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Simulation and Operation of the EBR-II Automatic Control Rod Drive System

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by

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ABSTRACT

An automatic control rod drive system (ACRDS) installed at EBR-II produces shaped power transients from 40% to full reactor power at a linear ramp rate of 4 MWt/s. A digital computer and modified control-rod-drive provides this capability. Simulation and analysis of ACRDS experiments establish the safety envelope for reactor transient operation. Tailored transients are required as part of USDOE Operational Reliability Testing program for prototypic fast reactor fuel cladding breach behavior studies. After initial EBR-II driver fuel testing and system checkout, test subassemblies were subjected to both slow and fast transients. In addition, the ACRDS is used for steady-state operation and will be qualified to control power ascent from initial critical to full power.

March 12, 1985

INTRODUCTION

The Experimental Breeder Reactor II (EBR-II) is an unmoderated, heterogeneous, sodium-cooled fast reactor operated by the Argonne National Laboratory for the United States Department of Energy at the Idaho National Engineering Laboratory. EBR-II is a pool type reactor with the core, the primary pumps, and the intermediate heat exchanger submerged in a sodium pool contained in the primary vessel. EBR-II has operated for over 20 years as a power producing (20 MWe) test reactor, serving as a fuels and materials irradiation facility. Recently the role of EBR-II has been broadened to accommodate the Operational Reliability Testing Program (ORT)[1]. The ORT program is designed to study the behavior of prototypic and experimental fast reactor fuels following cladding breach and under limited transient conditions, i.e., extending into the lower transient capabilities of the TREAT reactor[2]. A requirement of the test program is to subject test fuels to 10 %/s power transients starting from 50 percent of full power or less to full power. With enrichment changes and fuel shuffling this would achieve transients to as high as 90 percent overpower in test fuel.

In order to provide the required transient capability, an automatic control rod drive system (ACRDS) was designed, built, and installed in EBR-II[3]. The ACRDS is a computer controlled rod drive system replacing a standard EBR-II control rod drive assembly. Essential safety features (scram function) and the rod drive rack and in-core part of the control subassembly were retained as standard EBR-II equipment. Gearing and the drive motor were replaced and adapted to computer control. The ACRDS has two operating ranges and three operating modes. Rod drive speed ranges are selected by manually shifting gears in the drive train. Reactivity insertion rates can be varied within each of these two ranges by controlling the drive motor speed. Slow speed mode (SSM) controls reactivity insertion rates up to 0.006 $/s and the fast speed mode (FSM) up to 0.09 $/s. The computer controls movement by comparing actual power and rate of power increase with a demand curve, and outputs the appropriate signal to the drive motor.

Operation is automatic (i.e., computer controlled) in both SSM and FSM, and manual in the SSM only. In manual SSM, the rates and magnitude of reactivity insertion are the same as with a standard EBR-II control rod and drive system.

The ACRDS was initially installed as a prototype in late 1982 for purposes of checkout and plant qualification for oxide fuel transient testing. The ACRDS was used to subject the plant to a total of 13 power transients starting at 40 percent to 100 percent of full power at a linear ramp rate of 4 MWt/s. These tests were unique in the sense that they qualified a power producing fast reactor as a transient test facility. Capability was demonstrated to test fuels and materials under mild transients.

Following the qualification tests, the ACRDS was removed, modified, and then installed permanently as a qualified reactivity control system. The following sections discuss in more detail the design, the testing, and the simulation program, including the experience with the ACRDS in the EBR-II experimental program.

ACRDS HARDWARE

The ACRDS consists of a computer for automatic control, raise-lower power supplies for manual control, a motor controller, a two-speed gear train assembly, feedback signal sensors, and various operational and safety interlocks. A block diagram of the system is shown in Figure 1. Two keyswitches located on the reactor console determine the mode of ACRDS operation. With both keys removed the reactor is in manual SSM at which time it can only be manually operated and the ACRDS functions like the other control rods. With the auto/manual key inserted, control can be transferred to the computer. With both keys issued, automatic FSM can be initiated if the gear train is in fast speed range and other interlocks are cleared. FSM is entered only by special approved procedures and when reactor power is above 25 MWt.

Manual mode is permitted when the slow-speed gears are selected. Electrical switches on the gear-train drive interlock with the SSM permit circuit. When the ACRDS rod is selected for movement and the manual raise/lower switch is actuated, a signal applied to the controller raises or lowers the rod at normal control rod speed.

In automatic SSM, the computer is placed in the control loop. The computer monitors reactor power from a nuclear channel and

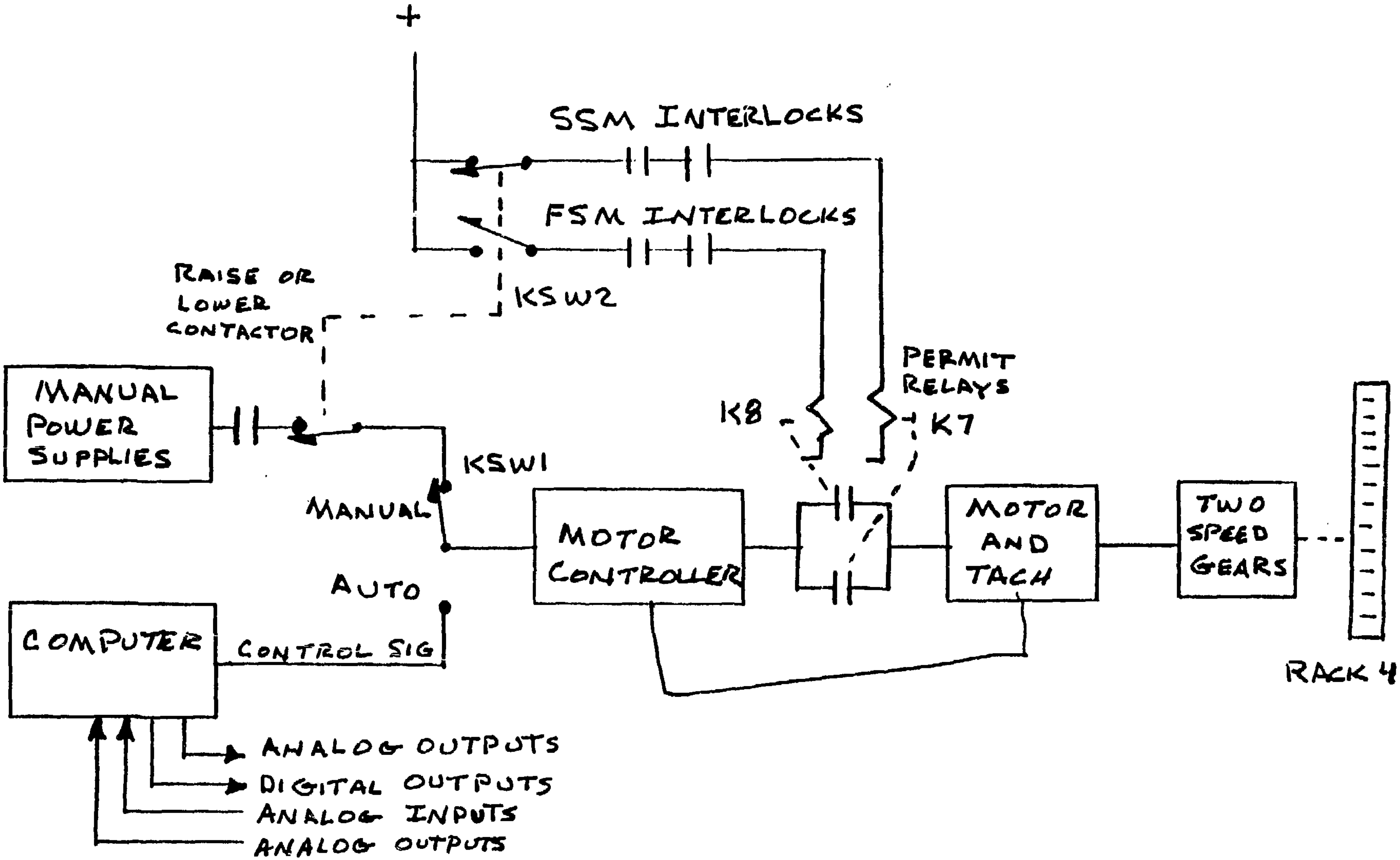

Fig. 1. ACRDS Functional Block Diagram.

permits automatic control only if the power is greater than 20 MWt. It also monitors another nuclear power channel and calculates an error signal. The computer outputs a varying control voltage which moves the rod at speeds between 0.508 mm/min (0.02 in/min) and 187 mm/min (5.0 in/min) in SSM or between 0.127 mm/s (0.005 in/s) and 30.7 mm/s (1.21 in/s) in FSM.

The control computer is a Digital Equipment Corporation PDP(MINC)11/23 with 16-bit wordsize and a floating-point processor. It performs 20 calculations per second updating the control signal 20 times per second. The computer receives four filtered analog signals, two from the nuclear channels, one from the ACRDS rod position, and one from the ACRDS rod speed. Each signal is conditioned with a 5 Hz antialiasing filter.

The ACRDS drive motor has an integral tachometer and the controller is pulse width modulated. The tachometer provides a velocity feedback signal to the controller error detector which is compared with the input control signal.

The motor rotates 1600 rpm for the maximum voltage control signal in either SSM or FSM. The two-speed gear train determines the speed of the rod rack. In SSM the motor speed is reduced by a gear reduction ratio of 1200 to 1 and in FSM by 82.5 to 1. Changing gear ratios requires the removal of a padlock, removal of a bolt, pivoting of a reach-cluster gear assembly and reinsertion of the bolt. The gear assembly is padlocked to prevent unauthorized rotation to FSM.

The two speed gear train is shown in Figure 2. A 20-to-1 worm gear assembly is attached to the pinion gear. The worm gear assembly provides a right angle drive from the motor to the rack and more importantly, it provides a mechanical brake between the rack and motor. The downward force of the rack drive cannot be transmitted back through the worm gear. This allows the system to operate without a brake and to manually change gear ratios with the reactor at power.

One of the safety concerns addressed in the ACRDS motor-gear train design is motor overspeed that would cause excessive reactivity insertion rate. Two ways were identified to cause motor overspeed; (1) motor over voltage and (2) partial motor demagnetization. Overvoltage protection was provided in the controller output to clamp the motor voltage to an acceptable value in the case of a controller output voltage failure. Partial motor demagnetization would cause an increase in motor speed and could be caused by high motor current transients. The manufacturer of the controller provided a very fast transient suppression network to prevent this situation from occurring. A hardware motor overspeed circuit was also designed to independently stop motor movement should motor overspeed occur. This trip circuit compares the tachometer feedback signal with a maximum allowed setpoint signal.

There are several interlocks associated with the ACRDS. In all modes, the hardware motor overspeed prevents excessive insertion rate. In automatic SSM the software program monitors reactor power, power deviation, and rod speed, and opens an interlock contact

Fast Speed

$$\text{Reduction Ratio} = (20)(4.128) = 82.56:1$$

$$\text{Pinion Speed} = \frac{1700 \text{ RPM}}{82.56} = 20.59 \text{ RPM}$$

$$\text{Rack Speed} = (20.59)(3.500) = 72.068 \ \frac{\text{in.}}{\text{Min}}$$

Slow Speed

$$\text{Reduction Ratio} = (20)(4.128)(14.527) = 1199.349:1$$

$$\text{Pinion Speed} = \frac{1700}{1199.349} = 1.417 \text{ RPM}$$

$$\text{Rack Speed} = (1.417)(3.500) = 4.961 \ \frac{\text{in.}}{\text{Min}}$$

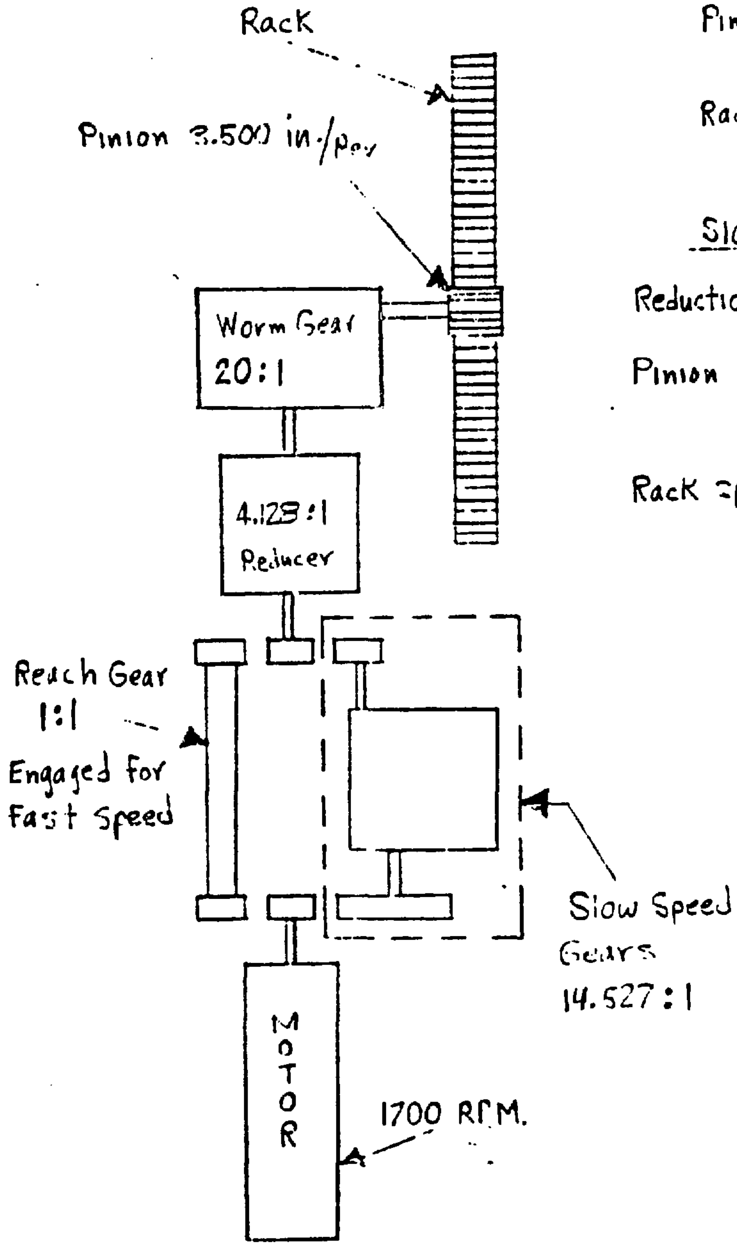

Fig. 2. ACRDS Two Speed Gear Train.

if an out-of-bounds condition exists. In automatic FSM, the computer monitors reactor minimum power, power deviation, and rod speed, and opens an interlock contact if an out-of-bounds condition exists. A reset timer circuit monitors the computer operation and opens a contact should the computer not cycle through the program every 150 ms. A separate hardware monitor provides a minimum power interlock in fast speed automatic mode. The input signal is from a linear nuclear channel.

In automatic mode, the ACRDS computer has a digital output signal that can release (scram) a drop rod. Releasing this rod helps to shape the power signal for rapid power decrease at the end of a transient.

TESTING AND SIMULATION OF THE ACRDS

The testing of the ACRDS was done in the fall of 1982 and consisted of 1) bench testing the computer algorithm with an EBR-II control rod, 2) in-reactor testing with a low reactivity worth control rod (about 0.02 \$), and 3) in-reactor testing with a full worth EBR-II control rod (about 0.83 \$). Following the demonstration of the correct computer algorithm, 13 power transients were done starting at 40 % of full reactor power up to 100 % power at a linear rate of 4 MWt/s. Power was held at 100 % for 12 minutes in each test and then reduced to 40 % at a rate whose magnitude was at least 4 MWt/s. During rapid power reduction, it was necessary to decrease reactivity with another control rod as a rod drop to reduce power fast enough to maintain a rate with magnitude at least 4 MWt/s. The tests 1) verified the efficiency and accuracy of the computer algorithm, 2) showed the usefulness of the ACRDS as a fuels and materials testing device, and 3) qualified a power producing fast reactor as a unique transient testing facility. A typical power and demand power trace from this test series is shown in Fig. 3.

The capability to test preconditioned fuel in mild power transients fills a needed deficiency between steady-state fuel irradiation experiments and fast transient experiments of the Category V reactor type[4] such as are done at the TREAT reactor[2].

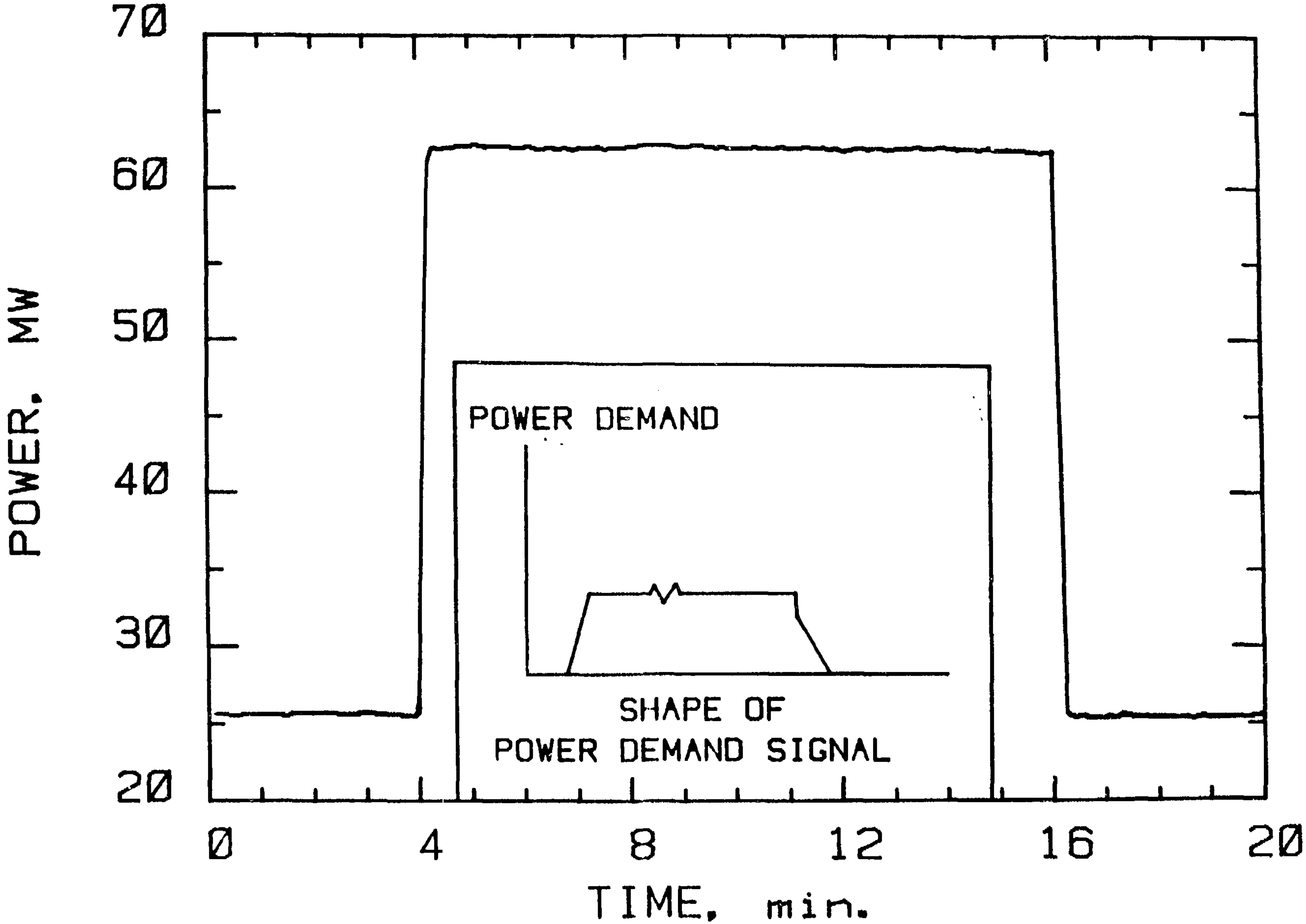

Fig. 3. Power Response and Demand Signal Shape
for ACRDS Transient. ANL Neg. No. 103-AA5267

The control computer of the ACRDS senses rod velocity, rod position, and reactor power. Then with an error signal derived from the difference between reactor power and demand power, an algorithm, whose form in z-transform is

$$F(z) = 80.64/Pd$$

is applied to this error signal. Here Pd is the power demand in MWt and is applied as a modification to the proportional controller[3]. The demand signal for the series of tests outlined above is then

$$Pd = \begin{cases} P1(t) & 0 < t < 9.05 \text{ s} \\ 2.38Po & 9.05 < t < t1 \\ P2(t) & t1 < t \end{cases}$$

where P1(t) is a linear ramp and P2(t) is chosen to produce the required power decrease. The holding time, t1, is about 720 s for the driver fuel qualification transient tests, but is whatever practical, say 40 s, in simulations of the tests.

The position of the ACRDS during the transient of Fig. 3 is shown in Fig. 4. The position increase near t = 12 min is done by decreasing reactivity with a control rod; the ACRDS rod then compensates by inserting to maintain constant power and ends up in a higher position in preparation for its movement during the down ramp. This time dependent position is typical of the tests described in Ref. 3..

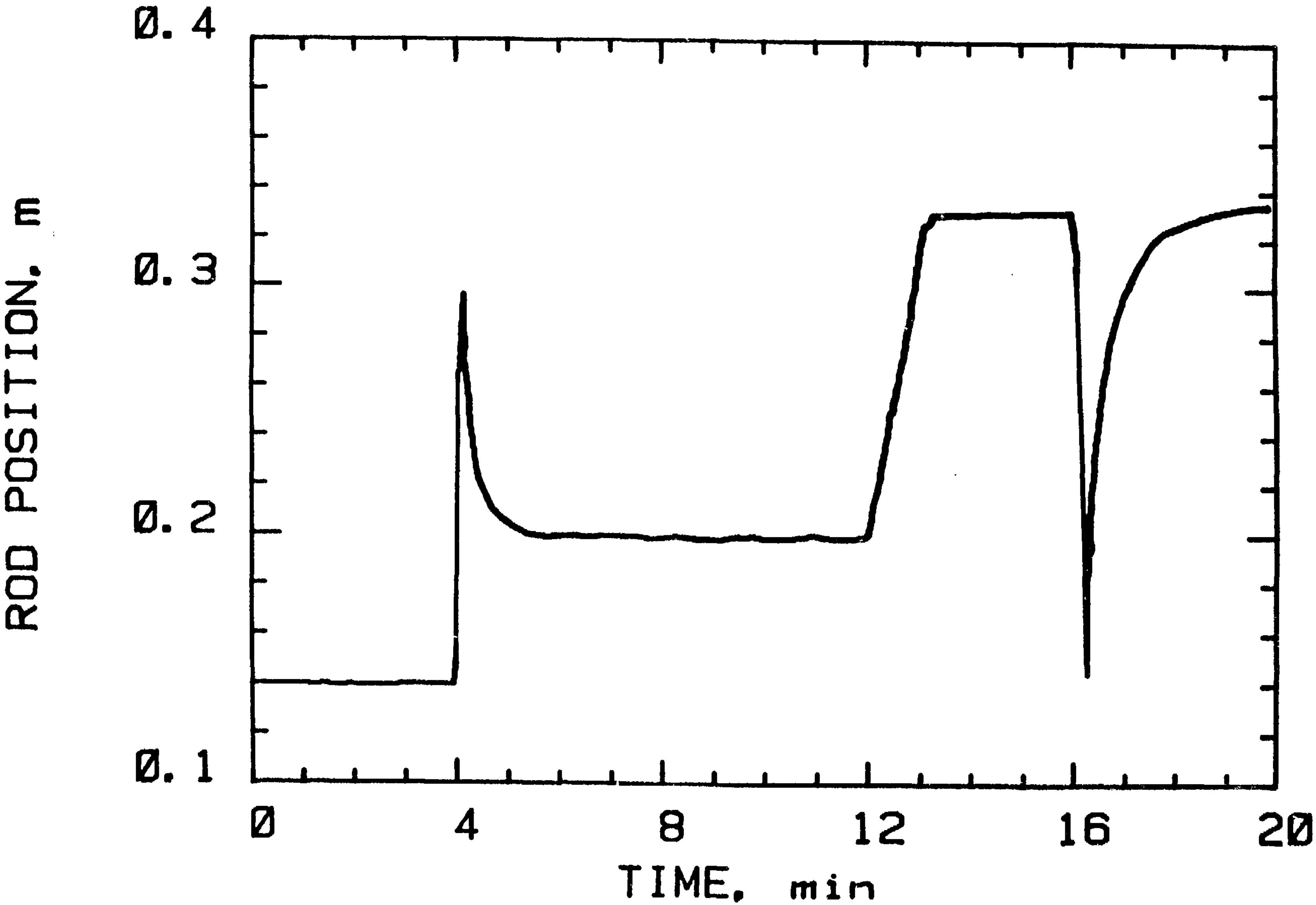

Fig. 4. Position of ACRDS Rod During Transient
Shown in Fig. 3. ANL Neg. No. 103-AA5266

The computer algorithm, acting on error signal above, changes rod position and velocity to accommodate power demand. The actual time-dependent power demand shape is quite arbitrary from a computer software standpoint, but practical considerations of rod worth, motor acceleration capability, and reactor safety place an upper limit on reactivity addition rate[3]. Included in the computer algorithm is the necessary intelligence to communicate with reactor operators for transient start signals, etc.

During the development and testing phase of the ACRDS, off-line simulation programs were used to design and predict its behavior. The modeling was done with:

1. a hybrid computer which was used to design the software algorithm[5,6].
2. an analog simulator used to simulate the EBR-II reactor (including feedback) during the bench testing phase[3].
3. finite difference computer codes which were used for the development and separation of EBR-II feedback coefficients[7,8].
4. continuous system modeling codes CSMP[9] and DSNP[10] for prediction and verification of system behavior.

The finite difference codes were used because they have been quite useful and effective for EBR-II core simulations in the past. The hybrid simulations provided the right combination of analog simulations (e.g., reactor sensory equipment) and digital simulations (e.g., the control computer) to promote good design.

The continuous system codes were used because of the ease of representing the mechanical parts of the ACRDS with the kinetics and feedback, including the control system. One of the continuous system codes includes balance-of-plant simulation capabilities [10].

The combination of computer code simulation and experiment was quite useful during the development and testing of the ACRDS. Intra-code comparison provided confidence that correct development was being done. In addition, the various computer codes, along with prior experience with EBR-II behavior, provided sufficient confidence to make the safety argument for the range of transient tests and automatic control desired in EBR-II. Comparison of code and experimental results provided confidence in future predictions of experiments. The experiments themselves also provided necessary data tc certify the EBR-II driver fuel for the range of transients expected in the future.

A rather detailed look at the ability of the computer codes to predict ACRDS behavior is reported elsewhere[3, 6]. We include here a comparison of the error signal for one such experiment in Fig. 5. The experiment was a typical one for this test series, i.e., a linear ramp in power at 4 MWt/s starting at 26.1 MWt and leveling off at constant (maximum authorized) EBR-II power of 62.5 MWt. Both the experiment and the two continuous system code representations with CSMP and DSNP indicate a larger error at the start of the transient where the prediction of delayed neutron behavior introduce an intertia resisting change in the system power.

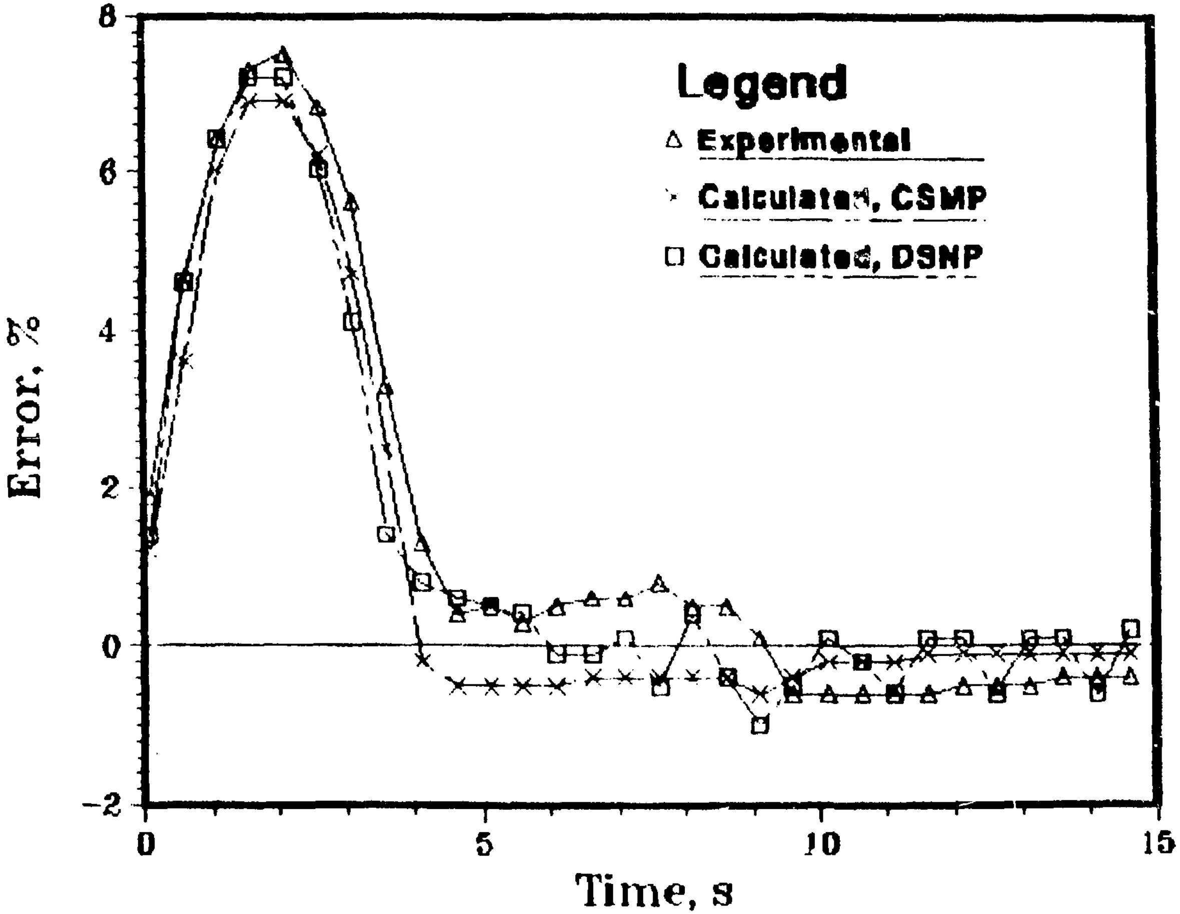

Fig. 5. Error, |Pd - Pow|/|Pd|
ACRDS Test, EBR-II, November 1982.
ANL Neg. No. 103-BB5154

Clearly, for the rapid up-portion of the experiment and the stead-y-state behavior following, the two computer simulations are quite accurate and adequately represent this experiment. In support of this statement one might note that the error signal is probably the most sensitive measure of comparison.

EXPERIENCE WITH THE ACRDS AT EBR-II

Following initial testing and training, the ACRDS was used to initiate power transients in oxide and metallic test fuels during reactor run 129. The first of these transients was used to quickly elevate a metal fuels eutectic experiment to desired test conditions thereby precluding failure during a gradual ascent to power. The test subassembly was held at 50 % reactor power for a pre-conditioning period and then the ACRDS was used to raise the reactor power to 100 % of full reactor power in 8 seconds. Following the desired irradiation period, the power was reduced manually.

A second transient test involved 19 preirradiated mixed-oxide fuel pins of several designs. This test was part of the USDOE-PNC program on reliability testing of oxide fuel. By fuel shuffling and enrichment the test assembly was subjected to an equivalent 90 % overpower transient. Following a seven-day preconditioning period at 32.7 MWt, the ACRDS initiated a transient to full reactor power at a linear rate of 4 MWt/s. The actual power transient achieved in shown in Figure 6. The desired transient power was achieved indicating more than satisfactory performance.

Since these initial transient experiments the ACRDS has been used routinely to subject test fuel to simulated upset conditions.

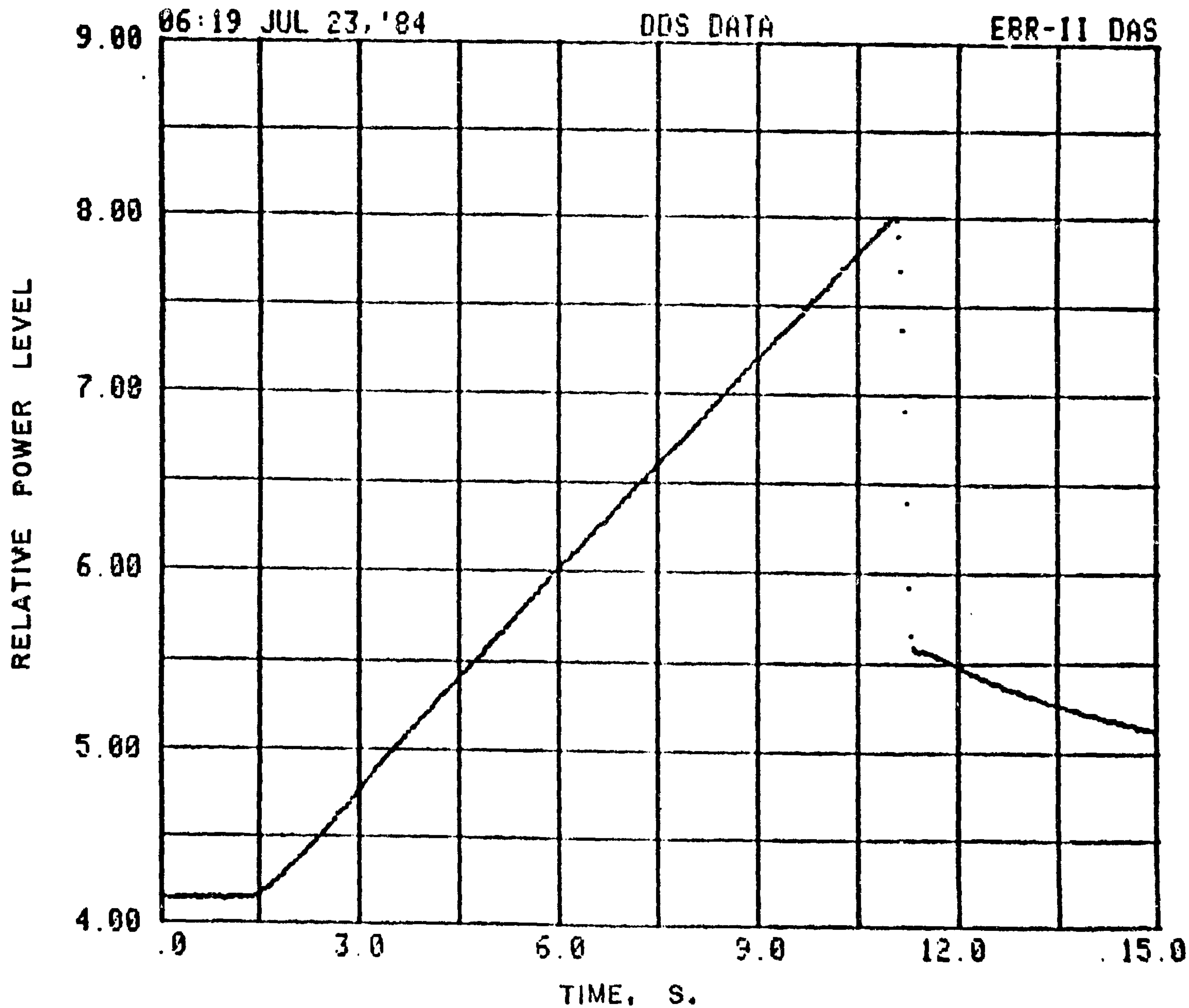

FIG. 6. TOPI-IB POWER TRANSIENT

At the conclusion of each reactor run, the reactor power is increased from the experiment conditioning power level to full power in 30 s. The reactor is held at full power for 5 min and then reduced to the conditioning power in 30 s and held for 4 hours prior to shutdown. The purpose is to simulate periodic mild overpower transients designed to simulate VIIB events considered in fuel qualification for liquid metal reactors. They duplicate design duty cycle events in driver fuel test pins and the results will be used to calibrate the LIFE4 fuel behavior code.

In addition to providing "tailored" power transients, the ACRDS has been used to maintain steady-state power level during routine operation for the past two reactor runs, and will in the near future be programmed to take EBR-II from zero-power to full authorized power automatically. It can also be used to provide "tailored" reactivity transients for special transfer function experiments and fuel irradiations.

SUMMARY

In summary, satisfactory operation of the ACRDS has extended the capabilities of EBR-II to a transient test facility, achieving automatic transient control. Test subassemblies can now be irradiated in transient conditions overlapping the slower transient capability of the TREAT reactor.

March 12, 1985

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