DEMONSTRATION OF EBR-II POWER MANEUVERS
WITHOUT CONTROL ROD MOVEMENT*

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L. K. Chang, D. Mohr, H. P. Planchon, E. E. Feldman,
and N. C. Messick

Argonne National Laboratory
Argonne, Illinois 60439-4820
U.S.A.

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Demonstration of EBR-II Power Maneuvers
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Abstract

A group of five plant inherent control tests was successfully conducted in November 1987 in the Experimental Breeder Reactor II. These tests demonstrated that the plant power of a metal-fueled reactor can be passively controlled over a large power range by slowly changing the primary flow and the reactor inlet temperature. These variables are, in turn, regulated by the primary pump speed, the secondary flow, and the turbine inlet pressure. In all tests, control rods were not used to regulate power. It was demonstrated that the plant power can be controlled with reasonable accuracy without using control rods when the reactivity feedback characteristics of the reactor are well understood and the plant controllers are adequately designed.

Introduction

The shutdown heat removal tests (SHRT)^{1,2} in EBR-II have demonstrated that without external control systems a metal fueled liquid metal reactor (LMR) can be inherently and safely shut down for either a loss-of-flow-without-scrum (LOFWS)³ or a loss-of-heat-sink-without-scrum (LOHSWS)⁴ accident. As pointed out in Ref. 5 an LMR can also be inherently safe for transient overpower accidents or for other accidents involving controller

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failures which could negate an otherwise safe passive shutdown. Data obtained from tests involving primary flow perturbations⁶, reactor inlet temperature perturbations⁶, and steam pressure reductions⁷ in the SHRT program have indicated that the reactor power can be passively controlled by the primary flow, the secondary flow and/or the steam flow. These results suggest the possibility of alternate control schemes which would reduce or eliminate the need for control rods for normal reactor power control and for fuel burnup compensation. If the reactor power can be passively controlled in the power range using limited or no control rods, then the transient overpower without scram (TOPWS) accidents due to control rod runout can either be eliminated or greatly reduced in severity. The reactor safety with respect to failure of control rods or other controllers can thus be based on inherently characteristics of the plant such as reactivity feedbacks, limited rod reactivity, limited flow and heat transfer capability in the plant. A plant inherent control testing (PICT) program was thus developed⁸ to explore the innovative nuclear plant power control strategies which do not degrade plant inherent safety and will allow passive accommodation of TOPWS accidents.

The reactor power in the PICT series was controlled over a power range between ~ 40 to 96% by making very slow changes in the main control variables. These variables were regulated by the primary pump speed, the secondary flow, and the turbine admission valve (TAV) position. Once the initial conditions were set for a given test, the control-rod-drive mechanisms were deenergized (to prevent control rods motion) and the control variables were changed via the plant controllers.

EBR-II Plant Description, Control and Instrumentation

The EBR-II is a sodium-cooled, pool-type fast reactor designed to operate at a thermal power level of 62.5 MWt and a net electrical power output of

about 20 MWe. Rated sodium flows of the primary and the secondary systems are 485 and 320 kg/s, respectively. The plant is located in Idaho and is operated by Argonne National Laboratory for the U. S. Department of Energy. EBR-II has been in operation since 1964 and has served as a fast-flux irradiation facility, and more recently it also served as a safety testing facility.

The reactor primary system of EBR-II, Fig. 1, is contained in a double-walled tank. The tank contains about 340 m³ of sodium at 371°C under normal operating conditions. The primary coolant is well-mixed in the common outlet plenum of the reactor vessel which is connected to the reactor outlet pipe that transports the coolant to the intermediate heat exchanger (IHX). Flow exiting from the IHX mixes with the bulk sodium in the primary tank before it enters the two primary pumps on its way to the reactor inlet pipes and into the reactor vessel.

The reactor consists of 16 rows of hexagonal subassemblies, which form the core region (rows 1-6), reflector region (rows 7-10), and blanket region (rows 11-16). The typical EBR-II driver subassembly contains 91 pins of sodium-bonded metallic fuel. About 84% of the flow enters high pressure plenum to cool the core, and the remaining 16% enters to the low pressure plenum to cool the blanket and reflector subassemblies.

A schematic of the entire EBR-II plant showing important instrumentation and controllers is given in Fig. 2, in which C denotes the controlled components, T denotes temperature, F denotes flow, P denotes pressure and P_{ow} denotes power. The IHX transfers heat generated in the reactor to the secondary sodium system and ultimately to the steam generator and the turbine. The secondary sodium, driven by an A-C electromagnetic pump, returns to the IHX after passing through the secondary piping system, two parallel superheaters and seven parallel evaporators. During normal steady state

operation, the reactor power is regulated by control rods (C_1 in Fig. 2); primary flow (F_1) is controlled by pump speed (C_2) to a constant flow rate; voltage to the secondary pump (C_3) is controlled to have desired secondary flow such that a constant reactor inlet temperature (T_1) can be maintained; the steam header pressure (P_1) is controlled by the turbine admission valve (TAV) position, C_4 , using an Initial Pressure Regulator (IPR) and/or by the steam bypass valve (C_5). Of the controlled components currently used in plant operation, five of them are shown in Fig. 2. The rest, associated with the condensate and feedwater systems, are not explicitly shown.

The control systems for the five PICT tests involved Bailey 90 programmable (micro processor) digital controllers in the primary, secondary, and steam systems of the plant. While these have some differences in functional capacity and memory, all (except C_1) have the same basic configuration and they were interconnected (networked) by a personal computer located in the control room. The network allowed changing the input variables, down loading of the appropriate control algorithm, setting of controller constants, and the introduction of programmed setpoint disturbances. Each Bailey controller is related to its own Digital Control Station (DCS) which has one configuration mode for normal controller operation, and another mode to allow software changes to its associated controller while the plant is operating. The control rod controller C_1 , was disabled for all the tests, such that the reactor power would not be changed by the control rods during the tests. In the present test series, the secondary pump, C_3 , was either controlled to give a desired primary tank temperature (via a secondary flow/tank temperature controller) or the demanded steam header pressure (via a secondary flow/turbine pressure controller). The TAV, C_4 , was used to control either the steam header pressure (via the IPR) or control the turbine/generator output demand (via the load limit controller).

The EBR-II is well instrumented throughout the reactor, the primary system, and the balance of the plant. A total of nearly 900 instruments are available for data recording. Instrumentation in the primary system includes ion chambers, flowmeters, bulk-sodium thermocouples, pressure sensors, and reactor sodium inlet and outlet thermocouples. The primary-system flowmeters are located in the inlet and outlet pipes of the reactor. The bulk-sodium thermocouples are located at various axial and circumferential locations in the primary tank. Thermocouples measure the sodium outlet temperature of selected subassemblies. Reactor power is measured by ion chambers and is also calculated by heat balances based on flow and temperature measurements in the primary, secondary systems and steam system. The data acquisition system (DAS) uses an inverse kinetic routine to make a real-time calculation of excess reactivity based on power measured by an ion chamber. Both measured and derived data are recorded on the magnetic tape by the DAS. The secondary sodium and steam systems are also well instrumented with pressure gauges, thermocouples and flowmeters.

Design of the Tests

The thermal-hydraulic and neutronic computer code, NATDEMO,⁹ was used to predict the plant states and maneuvers associated with various reactor power plant control schemes tested. NATDEMO predictions served as the basis to evaluate EBR-II's compliance with the Technical Specifications and the plant safety during testing, which along with hardware/software operability and plant operational feasibility, are the essential elements in the PICT test design. NATDEMO is a nuclear plant system simulation code which was specifically designed for the prediction of EBR-II plant responses; the code is capable of simulating the dynamic response of the plant for a variety of transients ranging from normal operation to abnormal conditions caused by

major disturbances such as primary flow, reactor inlet temperature and steam pressure. The control functions previously discussed were modeled in the code to simulate plant responses for plant power maneuvers using various controllers. One of the important features of the neutronic portions in the NATDEMO code is its detailed model of reactivity feedbacks. This is essential for predicting of plant state following a controller action since the power response is intimately related to the reactivity feedback characteristics of the metal fueled EBR-II core.

For nominal reactor operation, the reactor outlet and the reactor inlet temperatures are 473 and 371°C, respectively. In all of the tests, the reactor outlet temperature was limited to be within the nominal envelope (371-473°C) and the reactor inlet temperature was limited to 385°C. During the test the turbine was on line generating electrical power and the reactor power was controlled from about 40 to 96% power.

The reactor power change behavior of the tests can be explained by considering changes in reactivity ($\delta\rho$), power (δP), power/flow ratio ($\delta(P/F)$), and reactor inlet temperature (δT_i). Reactivity changes due to fissile atom depletion is neglected. A quasi-static (linearized) approximation for the reactivity perturbation can be expressed as:

$$\delta\rho = A\delta P + B\delta(P/F) + C\delta T_i, \quad (1)$$

in which A is the power coefficient representing reactivity feedbacks proportional to power change alone, B is the coefficient representing the reactivity feedbacks proportional to the power-to-flow ratio (P/F) change, and C is the coefficient representing reactivity feedbacks related to reactor inlet temperature variation. A detailed description of A, B, and C are given in Ref. 5.

Since the control-rod-drive mechanism was deenergized during the tests, the net reactivity change from one steady state to another would be zero ($\delta\rho = 0$). For the tests where reactor inlet temperature is kept constant, then $\delta T_i = 0$. By substituting $\delta T_i = \delta\rho = 0$ into Eq. (1), the relationship of P/F between two equilibrium states, 1 and 2, can be expressed as:

$$\frac{(P/F)_2}{(P/F)_1} = \frac{1 + (A/B)F_1}{1 + (A/B)F_2}, \quad (2)$$

where subscripts 1 and 2 denote the steady-state conditions 1 and 2, respectively. The A/B in EBR-II is estimated to be between 0.1 and 0.25 depending on reactor P/F, loading conditions and the bowing reactivity components. These values are consistent with measurements made in the primary flow perturbation tests,⁶ and are also consistent with the LOFWS tests.³

For the tests where the primary flow is kept constant (i.e., $F_1 = F_2$), and the reactor power is controlled by reactor inlet temperature, the relationship between power and reactor inlet temperature at two equilibrium states are:

$$P_2 - P_1 = C \times (T_{i1} - T_{i2})/(A+B), \quad (3)$$

where (A+B) is the approximate power reactivity decrement (PRD), i.e., the reactivity addition required to raise the power from zero power hot critical to 100% power at 100% flow. The PRD in EBR-II is about 0.28\$ depending on loading conditions, and C is about 0.007\$ per °C based on data gathered from reactor inlet temperature perturbation tests⁶ and LOHSWS tests⁴ in EBR-II. The final equilibrium conditions of the PICT tests can be estimated using Eqs. (1) to (3).

Conduct of Tests and Results

Five tests, referred to as PICT's 1, 3, 4, 5 and 6, were included in the test series.* The tests were conducted in the test window extending from November 11 through November 18, 1987.

PICT 1

The purpose of this test was to study the feasibility of controlling reactor power using primary flow. During the test, the primary pump speed (C_2) was controlled to a prescribed speed by computer software, and the secondary flow was regulated by the secondary EM pump (C_3) through a secondary flow/tank temperature controller to maintain a constant reactor inlet temperature. The IPR was used to maintain a constant steam header pressure by adjusting the TAV position (C_4).

The initial reactor inlet temperature and turbine header pressure were controlled to the normal constant operating values of about 371°C and 8.6 MPa, respectively, and these values were controlled to remain essentially constants throughout the test. The initial conditions of the test (96% rated power (60 MWt), 110% rated flow) provide a comfortable margin below normal operating conditions. The reactor flow, the forcing function in this test, was reduced to about 42% at 1% per minute in three steps and then the flow was returned to 110% in a similar manner. The intermediate values were 77 and 58% flows. When the flow was reduced, the reactor temperature increased, which caused the reactor power to decrease due to negative reactivity feedback as explained in Eq. (2). The normalized flow and power profile of the test are illustrated in Fig. 3. In order to control the reactor inlet temperature, the secondary flow tended to follow the primary flow and power variation. It was noted during

*PICT 2 was not conducted.

the transient that the reactor inlet temperature remained nearly constant as demanded, with a deviation of no greater than 2°C as shown in Fig. 3. This deviation was somewhat reflected in the transient power response since the reactor power varies about 2.7% for every 1°C change. Although the reactor flow and the inlet temperature at the end of the test were very close to the initial conditions, the final power was lower than the initial power as shown in Fig. 3. This was caused by driver fuel burnup during the test period. It was noted in Fig. 3 that in PICT 1 the power-to-flow ratio was below the normal operation value throughout the test. The reactivity loss due to burnup causes the power decrease of about 3% over about 12 hr test. After the test a calibrated control rod was moved to obtain the initial power and thereby to measure reactivity loss due to burnup. If the reactor power was controlled to be constant by varying the reactor flow, the burnup would be manifested as an increase in primary flow.

The results indicated that reactor power can be regulated using primary flow, however, if a precise transient reactor power profile is required, the secondary flow/tank temperature controller should be more precisely tuned, if possible, such that reactor inlet temperature variation can be reduced during the power and flow maneuver.

PICTs 3 and 4

PICTs 3 and 4 demonstrated the slow reactor power change and load-following (reactor power follows the turbine-generator load demand) maneuvers involving reactor power, inlet temperature and turbine generator output demand changes. These plant disturbance, in turn, were controlled by the secondary pump (C₃) and the TAV position (C₄). The reactor power in these tests were maneuvered from 96% to about 50% (PICT 3) and then back to about 96% (PICT 4). For both tests, the primary pump speed was controlled to maintain a

constant reactor flow. In PICT 3, the demanded reactor inlet temperature setpoint was first set (see Fig. 4) and the secondary flow/tank temperature controller thus responded by regulating the secondary flow. At the same time, the IPR was used to maintain a nearly constant steam header pressure by adjusting TAV position. In PICT 4, the TAV was controlled to attain desired electric output. The secondary pump was controlled to keep the steam header pressure constant.

The primary flow and turbine header pressure of both tests were maintained constant at 96% and 8.6 MPa, respectively. The initial power of PICT 3 was 96%, and the test was initiated by increasing the reactor inlet temperature setpoint from the initial 363°C to 368°C at 0.56°C per minute. This was accomplished by changing the secondary flow as described above. As the reactor inlet temperature increased, the reactor power decreased due to negative reactivity feedback as indicated in Eq. (3). After the plant parameters stabilized, the reactor inlet temperature demand was increased to 375°C, and then to 383°C, which caused the reactor power to decrease. The reactor inlet temperature of PICTs 3 and 4 is given in Fig. 4. In the figure the first 6 hr, approximately, is PICT 3. The remainder is PICT 4. An increase/decrease in reactor inlet temperature corresponded to a decrease/increase in reactor and generator powers as indicated in Fig. 5. The results indicate that the power can be easily controlled by the reactor inlet temperature. The secondary flow controller realignment occurred between 6 and 7.5 hrs in the figures. In the realignment, the secondary flow/tank temperature controller and the IPR were replaced by the secondary flow/turbine pressure and the generator power controllers. The temporary disturbance shown at ~ 7 hr was due to the above controller changes.

PICT 4 which followed shortly after the completion of the controller realignments, is essentially a mirror image of PICT 3. The mode of control however, was changed between PICTs 3 and 4. PICT 4 was basically a load-following maneuver, the measured turbine power outputs at the intermediate steps recorded in PICT 3, as shown in early portion of Fig. 5, served as the demanded turbine load output for the corresponding steps in PICT 4.

In PICT 4, the test was initiated by increasing the turbine-generator output demand from 9.7 MWe to 13.4 MWe at 0.2 MWe per minute using the generator power controller. As the turbine-generator output demand was increased, the TAV was automatically opened to meet the output power demand. The increased steam flow from the TAV opening tended to decrease steam header pressure; the secondary flow/turbine pressure controller thus responded by increasing the secondary flow in an attempt to keep the steam header pressure constant at 8.6 MPa. The increase of secondary flow to meet the higher power demand caused the tank temperature to decrease and reactor power to increase because of reactivity feedback. The turbine-generator output demands for the three steps were 13.4, 16.5 and 17.7 MWe. The reactor and generator powers of PICTs 3 and 4 are given in Fig. 5 which show very similar response patterns, and indicate that plant efficiency drops only slightly at low power conditions. The results indicated that the nuclear power output can be adequately controlled by the combination of secondary flow and generator output controllers.

The final power of PICT 4 was originally planned to be the initial power of PICT 3. Fuel burnup and the attendant reactivity losses during the test were thus to have been accommodated for the planned condition with lower reactor inlet temperature. At the end of PICT 4 more secondary flow would therefore have been required than at the beginning of PICT 3 in order to

obtain the required (lower) reactor inlet temperature." Due to limited secondary pump capacity, however, the final power of PICT 4 was somewhat lower than planned. Had the test been run from a slightly higher initial reactor inlet temperature the control scheme would have adequately compensated for fuel burnup reactivity loss over the whole operating range.

PICTs 5 and 6

PICT 5 and first part of PICT 6 were designed to investigate the turbine-generator and steam plant performance under various steam pressure conditions, and secondary part of PICT 6 was designed to demonstrate further that the power of a nuclear plant can be controlled by steam header pressure and turbine-generator output demand. Again, the inherent reactivity feedback characteristics were used to regulate reactor power. The secondary flow/turbine pressure controller (C_3) and the TAV position controller (C_4) were used in both tests.

PICT 5 was started from 60 MWt reactor power with conditions similar to those of PICT 3 except that the reactor inlet temperature was increased from 363°C to 366°C. This was done to ease the impact of limited secondary pump capacity. The turbine pressure served as the forcing function and the TAV remained fixed at a constant position in the early portion of the test. The steam header pressure demand was reduced from the initial 8.6 MPa to about 5.5 MPa in three steps. The decrement was ~ 1 kPa per step and a ramp rate of 55 kPa per minute. The follow-on step was initiated as soon as a steady-state condition was reached in the previous step. As expected, the secondary flow/turbine pressure controller automatically reduced the secondary flow to meet a lower turbine pressure demand. This caused an increase of reactor inlet temperature and a decrease of reactor power. It should be pointed out that when the turbine pressure is reduced, the steam saturation temperature

will be reduced causing a decrease in IHX secondary flow inlet temperature. This effect alone would caused IHX primary coolant outlet temperature to decrease and consequently the reactor power to increase if the secondary flow remain constant. The demanded reduction of turbine pressure in PICT 5 thus has two opposing effects on reactor inlet temperature; the saturation temperature decrease which, in turn, reduced core inlet temperature and the secondary flow decrease (to achieve reduced pressure) which caused the reactor inlet temperature to increase. The net effect was clearly an increase in reactor inlet temperature and a decrease in reactor power as shown in Figs 6 and 7. During the secondary part of PICT 5 (2.5 to 4 hr in Figs 6 and 7), the TAV was slowly opened to a wide open position at 1% per minute while the turbine pressure was kept a constant at 5.5 MPa. As the valve opened, pressure tended to drop, in order to maintain a constant pressure, more secondary flow was required. This caused reactor inlet temperature to drop and power to increase as illustrated in the latter portions of Figs. 6 and 7, respectively.

PICT 6 contains two parts. The first part of the test was conducted immediately following the completion of PICT 5. The test was initiated by increasing the steam header pressure setpoints (in the secondary flow/turbine pressure controller) from ~ 5.5 MPa to 6.9 MPa at 55 kPa per minute in three steps, while the TAV was fixed at wide open position. The increments are 1, 0.24 and 0.069 MPa. The purpose of the decreasing pressure increment was to "inch up" in pressure to approach (but not exceed) the 96% reactor power as carefully as possible. This increased the reactor and the generator powers to close the 96% power condition as illustrated in Fig. 8. PICT 5 and the first part of PICT 6 indicated that the power change resulting from a TAV position variation from normal to 100% opening was equivalent to the power change caused by ~ 1.7 MPa turbine header pressure change in EBR-II.

The tests provide important performance lines for the turbine-generator and steam plant. The results show the plant can operate satisfactorily over a pressure swing of 6.9 to 5.5 MPa. It was particularly important to verify that the feedwater and condensate heaters operated satisfactorily. It should be noted that the purpose of the first parts of PICTs 5 and 6 is to study plant performance rather than a form of plant control scheme. In the second part of PICT 6, a combination of generator output controller and secondary flow/turbine pressure controller were used to regulate the plant. The essential condition to be tested here was the effect of increasing turbine pressure while decreasing the plant output power. The turbine power demand was reduced from 18.6 to 9 MWe in three steps with intermediate steps of 16 and 12 MWe. When the generator power demand was decreased, the TAV responded by closing the TAV, which first caused the turbine pressure to increase. In order to maintain a constant pressure, secondary flow was reduced, which caused reactor inlet temperature to rise and reactor power to fall. Following each demanded power decrease, the turbine pressure demand was increased by 0.59 MPa, so that a 8.6 MPa (normal operating condition) was achieved at the end of the test. Increased pressure demand caused secondary flow to increase, reactor inlet temperature to decrease, and power to increase. Thus, in order to maintain constant power, the TAV tended to automatically close somewhat at each pressure increase step. The reactor and electric power response in Fig. 8 indicated that at each step, the power goes up or down too far before leveling out at a constant value. This is somewhat caused by an overshoot in the secondary flow which affects power via reactor inlet temperature. This may have been avoided by finer tuning of the secondary flow/turbine pressure controller.

PICTs 5 and 6 characterized the relationship of reactor power, generator power, pressure and admission valve position for different sets of imposed operating conditions. The tests indicated that plant power can be well controlled by a combination of automatically controlling the TAV position and turbine pressure. The change of steam pressure alone (with secondary flow remains constant) is not a large effect on reactor power in EBR-II because the secondary flow is considerably less than primary flow, however, in plants in which the primary flow-to-secondary flow is close to one, changes in steam pressure causes variation in evaporator outlet temperature, which more effectively reflects in reactor inlet temperature and reactor power.

Conclusion

The tests demonstrated (1) load-following capability of EBR-II, the measured reactor and turbine powers of the tests indicated that the turbine efficiency varied only slightly over the power range considered, and the plant could adequately operate at the both high and low power level, and (2) the plant power can be controlled over a wide power range without moving control rods. The implication would be the possibility of greatly reducing the excess reactivity invested in control rods for reactor power maneuvering. The severity of overpower transient due to control rods runout can thus be reduced. The data obtained from the tests characterized the relationships of major plant variables and they can be used to design an integrated plant control system for more rapid dynamic tests in the future, and to explore automated control schemes for innovative metal fueled LMRs.

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Figure 1. EBR-II Primary System

Figure 2. Schematic of EBR-II Plant and Control System

Figure 3. Normalized Power Flow and Reactor Inlet Temperature of PICT 1

Figure 4. Normalized Reactor and Generator Power Response of PICTs 3 and 4

Figure 5. Inlet Temperature of PICTs 3 and 4

Figure 6. Normalized Reactor and Generator Power Responses of PICT 5

Figure 7. Reactor Inlet Temperature Response of PICT 5

Figure 8. Normalized (to PICT 5 Initial Condition) Reactor and Generator Power Responses of PICT 6