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OPERATIONAL-SAFETY ADVANTAGES OF LMFBR's: THE EBR-II EXPERIENCE AND TESTING PROGRAM

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ABSTRACT

LMFBR's contain many inherent characteristics that simplify control and improve operating safety and reliability. The EBR-II design is such that good advantage was taken of these characteristics, resulting in a very favorable operating history and allowing for a program of off-normal testing to further demonstrate the safe response of LMFBR's to upsets. The experience already gained, and that expected from the future testing program, will contribute to further development of design and safety criteria for LMFBR's. Inherently safe characteristics are emphasized and include natural convective flow for decay heat removal, minimal need for emergency power and a large negative reactivity feedback coefficient. These characteristics at EBR-II allow for ready application of computer diagnosis and control to demonstrate their effectiveness in response to simulated plant accidents. This latter testing objective is an important part in improvements in the man-machine interface (MMI).

INTRODUCTION

Nuclear power plants have two traditional lines of protection, a highly reliable plant protection system (PPS) to protect the plant, and containment to protect the public. These are also further subdivided and described as "lines of assurance." Many of these features tradition-

ally rely on engineered systems that require mechanical motion and/or emergency power. A critically important feature of an LMFBR plant, however, is that it can be designed to provide inherent (passive) rather than engineered (active) features for plant protection, improving safety, reliability and operability. This also greatly affects the man-machine interface by improving the ability to diagnose and respond to upsets.

This paper describes how inherent features of an LMFBR can be used together with man-machine interface (MMI) concepts to simplify the design, control, and protection of large LMFBR power plants. We begin with a brief review of inherent safety-related features of LMFBRs, and discuss the use of some of these features to simplify and enhance plant control and protection. We then discuss how MMI concepts that were developed in other industries can be used in the design and operation of large LMFBR power plants. One such concept is that of analytic redundancy, which was originally developed for aerospace use. This concept involves sensor validation techniques and the use of fault-tolerant computer hardware and software, but it can also be used as a logic model for specifying an optimal instrumentation array for plant surveillance, control, and protection. We conclude with a description of the pertinent Experimental Breeder Reactor-II (EBR-II) operating experience and testing program and illustrate the use of MMI concepts at this facility.

INHERENT SAFETY FEATURES OF LMFBR's

LMFBR power plants have potentially inherent safety features that can be used to advantage in design.[1] We review the major features here, focusing on plants having the pool-type primary system configuration:

1. Sodium at temperatures well below its normal boiling point of 881°C is used as the coolant for the primary and intermediate systems; this allows these systems and their boundaries to operate at relatively low pressures ($\lesssim$ 150 psig). The major

consequences are that the primary system does not constitute a "pressure vessel" and that a breach of this boundary will not lead to severe depressurization and loss of coolant from the core.

2. Because of its high thermal conductivity a large thermal expansion coefficient, sodium is an excellent working fluid for removal of decay heat from the core by natural convection.

   Shutdown-heat removal can be accomplished without dependence on emergency power system.

3. The large inventory of primary sodium in the reactor vessel is an effective heat sink, allowing significant time for corrective action under upset conditions. Also, design advantage can be taken of this feature to minimize thermal shock to major components, such as pumps and intermediate heat exchangers.

4. If fuel-element cladding breach occurs, the primary sodium will trap the fission products of most concern biologically, such as iodine and cesium, preventing their release to containment or the environment.

5. Feedback reactivity effects are predictable and consistent, and reactor control is easily accomplished.

The foregoing inherent features lead to the conclusion that an LMFBR plant can be designed to be highly stable over a wide range of likely and unlikely operating conditions, but the plant must be designed to take advantage of these features. That is, the plant can be designed to be inherently capable of accommodating credible upset operating conditions as described in the following section.

USE OF INHERENT SAFETY FEATURES FOR LMFBR CONTROL AND PROTECTION

Three inherent features of an LMFBR plant are of paramount importance in enhancing its control and protection. These three features are the ability to remove decay heat by natural convection of the primary sodium, the large inventory of primary sodium to act as a heat sink under upset conditions, and the predictable, verifiable, and controllable feedback reactivity. The EBR-II design takes maximum advantage of each, providing significant safety and operating margin for operational reliability testing.

Tests to demonstrate adequacy of cooling by natural convection at decay heat power levels have been successfully carried out at EBR-II,[2,3] PHENIX, PFR, and FFTF. The heat transferred from the core to the primary sodium can be removed through the normal heat transport path, that is, through the intermediate and steam systems. It can also be removed through dedicated safety-grade loops that take it directly from the primary system or from the intermediate system ahead of containment isolation valves and reject it to the atmosphere. Such loops can be designed to operate completely by natural convection or by a combination of forced and natural convection to meet diversity and redundancy requirements. These dedicated loops thus provide a demonstrable capability for natural convective cooling, even with total loss of site electrical power. Moreover, their use precludes safety concern about vulnerability to disruption of the main heat removal path via the intermediate and steam systems. The intermediate sodium and steam systems need not be designed to be safety grade if the dedicated loops are provided representing a considerable savings in plant cost.

The large inventory of sodium in the reactor vessel (120,000-180,000 ft^3 in a 1000 MWe plant) is an effective heat sink under upset conditions. One example of this effectiveness involves an aspect of plant design and control, namely, limitation of component and piping fatigue due to stresses resulting from thermal transients. The most common thermal transient that has a significant potential for inducing fatigue is reactor scram. If the primary pumps are not run back to match flow to power during scram, a slug of cold sodium emerges from the reactor into its outlet region. If the outlet region is large enough, mixing of the cold slug with hot sodium reduces the rate of change in temperature experienced by the outlet region and intermediate heat exchangers (IHXs) to a point where fatigue is not a concern. Thus, advantage can be taken of the inherent heat capacity of the outlet region to avoid the use of engineered protective features. A similar mixing effect in the cold pool tends to mitigate the thermal stress consequences to the primary pumps and piping of loss-of-coolant flow in either the intermediate or steam system.

A second example relates to sizing of the heat exchangers in the dedicated safety-grade loops for removal of decay heat from the primary system. The large volume of primary sodium can store a great amount of decay heat, and, as the decay heat generation rate falls off rapidly with time. Thus, the larger the volume of primary sodium, the smaller will be the required surface area of both the heat exchangers in the reactor vessel and those that reject the heat to the atmosphere.

Predictable, verifiable, and controllable feedback reactivity is an inherent feature of an LMFBR that simplifies its control. It can also enhance the protection of the plant from highly unlikely but severe upset conditions. The feedback reactivity is due to density changes of core materials with temperature, axial growth and radial "flowering" of fuel and blanket assemblies, differential expansion between control rod drive lines and the core, diagrid expansion, and the Doppler effect. Both the French[4,5] and British[6] have conducted analytical investigations that suggest that a properly designed large LMFBR plant may be able to survive the highly unlikely event of a total loss of forced primary system flow with failure of the plant protection system to shut the reactor down. Here "survive" does not mean that there would be no plant damage, but rather that such damage would not be so severe as to lead to concern about public safety.

Two conditions would have to be met to prevent serious disruption of the core. First, primary flow coastdown would have to be slow enough to keep the power-to-flow ratio below an acceptable limit during an initial period of some tens of seconds. Second, sufficient inherent negative reactivity feedback would have to be introduced to drive the power down to a point where extensive sodium boiling in the core did not occur. Adequate feedback may be obtainable from thermal expansion of control rod drivelines and of the diagrid, as well as from "flowering" of the core.

MAN-MACHINE INTERFACE ASPECTS OF LMFBR DESIGN AND OPERATION

Man-machine interaction has been a subject much misunderstood and seldom addressed, except as a question for control-room design. It is now seen to be much more than a simple control room design issue; potentially it represents a thread that ties plant design issues together. That is, properly done, credit may be taken for increased safety-margin and increased reliability resulting from improved control systems and a design that takes maximum advantage of the inherent characteristics of LMFBR's described above. This is also facilitated by significant improvements in computer technology and greater understanding of operator capabilities.

A common assumption is that work underway for LWR plants to improve the man-machine interface is sufficient for LMFBR's. Upon close inspection, it is seen that the LWR work is indeed applicable but of a different emphasis than for LMFBR's. This difference exists because basic plant design approaches and criteria are different for LMFBR plants.

The major objectives of MMI work is to produce a control system for which improvements in plant operating reliability can be demonstrated and for which credit can be taken in licensing. In order to achieve this, the following issues must be addressed.

Develop criteria for control system designs to prevent and accommodate anticipated plant faults without challenging the shutdown system.

Define and demonstrate control system concepts that improve reliability.

- Model the human operator to define his capabilities and limitations.
- Improve sensor reliability and checking by automatic systems.
- Develop supervisory software for computer control and diagnosis; define optimum control strategy.
- Demonstrate diagnostic and control-system concepts in actual plants, for both normal and off-normal conditions.

Improve plant designs that limit demands to the control system.

- Identify design features to increase simplicity and inherent safety margins.
- Analyze response to potential accidents and relate to control system response.

The EBR-II operating experience, as well as the test programs underway, are providing information to address each of these areas.

Of particular interest for improvements in the man-machine interface is the proper application of computer technology. Probably no other technical field is advancing faster than computer hardware design and capability. It is being used extensively in the aerospace industry, including automatic control for commercial aircraft,[7] and is gaining increased acceptance in the nuclear industry. The key question is how computers can be best applied to nuclear plants to ensure improved reliability.

Computers are good at:

Examining many inputs
Remembering data
Conducting rapid calculations
Following precise instructions
Avoiding "mindsets"
Reducing data to meaningful forms
Maintaining attention.

Human operators are good at:

Integrating inputs to define problems and required action.
Making decisions in face of incomplete or confusing data.

Computers are poor at:

Making decisions in the face of incomplete or confusing data.

Operators are poor at:

Responding to many inputs
Remembering data
Conducting rapid calculations
Following precise instructions
Avoiding "mindsets"
Maintaining attention.

It is seen that the combination of computer and man can avoid many of the deficiencies of each alone, if properly integrated. With that in mind, the following concepts can be developed for an overall control and diagnostic system:

Computers should be used to:

a. Receive all sensor inputs.

b. Check reasonableness and "accuracy" of data.

c. Alert the operator if data received is suspected to be inaccurate.

d. Operate on plant data to infer reactor conditions not directly measured, identify trends, describe status of reactor in terms of its safety-state, etc.

e. Prioritize data to alert the operator to conditions of most concern, i.e., critical parameters, trends, anomalous behavior.

f. Alert the operator to conditions considered most relevant, including plant behavior outside of expected behavior.

g. Require decisions of the operator that can be considered supervisory in nature, leaving precise (detailed) action to automatic control systems or, alternately, providing the operator with detailed instructions.

The human operator should be used to:

a. Supervise the computer and automatic control system, making those decisions that are strategic in nature.

b. Continually communicate with the computer systems, maintaining cognizance of plant status, including auxiliary systems, in order to maintain an overall understanding of plant behavior.

This strategy applies across a full spectrum of reactor conditions (operating modes). For example, the computer systems would be especially useful during recovery from an accident involving degraded plant components. The automatic control system would be designed to maintain the reactor plant within its safety envelope in the event of anticipated faults (failure of individual components, loss of electric power, local faults in core, etc.). Obviously, the computer, as well as the operator, requires data that are of high quality to achieve these goals. Accordingly, much emphasis must be placed on the use of computers to check and validate data and on the use of engineering simulation and analysis to ensure that the necessary sensors have been provided in the original design.

EBR-II OPERATING EXPERIENCE AND TESTING PROGRAM

EBR-II, operating since 1964, has served as a prime example of a system which takes advantage of the inherent capabilities of a properly designed LMFBR. These features provide considerable flexibility in developing and testing systems appropriate to man-machine interface concerns. EBR-II is a 62.5 MWt (20 MWe) LMFBR system. The reactor/primary system is a "piped-pool" type with the reactor located in a sodium pool of about 87,000 gals. In contrast to later designs, the reactor system incorporates a piped outlet from the reactor to the Intermediate Heat Exchanger (IHX).

Two natural circulation shutdown cooling systems provide for removal of decay heat from the primary sodium through two sodium to NaK heat exchangers in the primary tank coupled to two NaK-to-air heat exchangers located outside the reactor containment building. The shutdown cooler air-operated dampers are designed to open upon a high sodium temperature in the primary sodium tank or upon loss of instrument air pressure or electric power in the classic "fail-safe" mode.

Although EBR-II was designed in the 1950s, the present day concerns for reactor safety were handled in a straightforward manner with the result that, in many respects, EBR-II design philosophy represents state-of-the-art. For example, it is most desirable to limit the required operator actions under plant upset conditions, in order to minimize errors. At EBR-II, because of the natural circulation shutdown coolers and the pool-type system, there is no emergency core-cooling system, and no requirement for emergency power for core protection upon loss of normal heat removal capabilities. Uncovering of the reactor core is a virtual impossibility with a guard tank surrounding the main primary sodium tank - and with the biological shield (6 ft of reinforced concrete with steel liners) surrounding the outer guard tank.

Passive safety design was extended to the secondary sodium-steam generator as well. The EBR-II reactor is located below grade level as is the IHX. The steam generator is located at a higher elevation thus providing for a strong (about 6% of full flow) convective flow in the secondary sodium system with the pumps off.

Operationally, the EBR-II places less demand on the reactor operator than a comparable LWR plant for the following reasons:

1. Inherent cooling of the reactor core is virtually assured during plant upsets.
2. The large thermal inertia of the primary sodium pool provides a nearly constant inlet temperature to the reactor, thus minimizing the possibility of significant temperature transients to piping and pumps.
3. Primary piping system and reactor vessel within the primary sodium tank need not be leaktight.
4. Coolant thermal conductivity and a large margin from operating temperatures to boiling provide comfortable operating margins and no pressure boundary concerns.
5. Fewer control rods with simpler operational procedures.
6. No emergency core-cooling system, such as high pressure injection.
7. No chemical shim system.
8. No reactor coolant makeup system
9. No pressurizer.
10. Simplified primary coolant purification.
11. No low-pressure injection system.
12. No core flood tanks.
13. No partial-length control rods.
14. No H_2 burners

15. No containment spray system
16. No operational considerations required for xenon problems

These and other considerations point out considerable operational advantages for EBR-II and similar facilities. When the inherent advantages are understood by the operator, plant upsets are unlikely to panic him when he realizes that he has no basic worries about maintaining core integrity and his attentions can be focused on solving the plant abnormality.

Fewer systems mean fewer problems in most cases and EBR-II has had a good operational record. Plant capacity factor has averaged over 70% since 1975. Plant maintenance has been straightforward; one primary pump was removed in 1970 after six years of operation. Minor modifications and repairs were made and the pump returned to service. The second primary pump was removed in the spring of 1982 after 18-1/2 years of operation for inspection and repairs and was returned to service. Significantly, there appears to be complete compatibility of the sodium coolant and the system materials. Virtually no evidence of sodium corrosion nor impeller erosion was noted after 18-1/2 years of operation in sodium at 700°F (flow rate of about 4500 gpm).

In the operating experience of EBR-II, several testing programs have been pursued as LMFBR program objectives have evolved. Initial operation was for demonstration of successful operation of LMFBR power plants. In about 1965, EBR-II began to assume the load of irradiations experiments for fuels and materials, which has continued to some extent to today. Over 10,000 specimens of fuels and other materials have been irradiated in EBR-II.

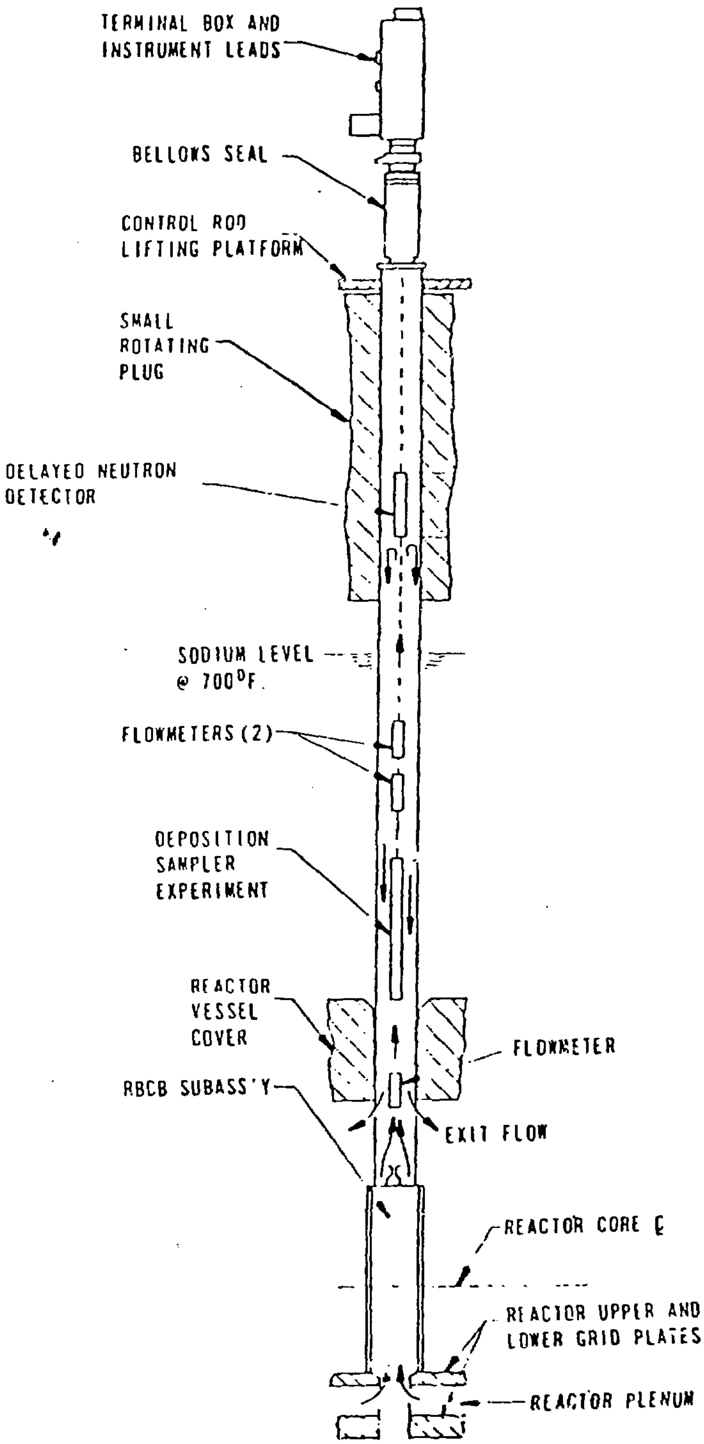
The irradiation program evolved to run-to-cladding breach tests, convective flow testing, and present and future programs of run-beyond-cladding-breach tests, shutdown heat removal tests, local faults testing, and improved reactor control (Man-Machine Interface) activities. These have provided, and are providing, much useful information on off-normal performance of LMFBR power plants for use in both design and safety.[8]

Two major changes made to the EBR-II reactor in order to carry out these programs were the design and installation of in-core test facilities to accommodate breached fuel[9,10] and development of a transient-overpower capability using a computer driven, automatic control-rod-drive system.[11] These capabilities have also required changes in core loading strategy, including tailoring the flux to meet the needs of individual experiments. In addition, two in-core instrumented subassemblies will be installed to provide measurements of the thermal-hydraulic performance of the core during convective flow testing. The significance of these modifications to man-machine interface testing is that they will allow a full range of off-normal conditions to be simulated, from local subassembly faults in the core-to-whole-plant upsets, including transient overpower and loss of flow. Simulation of these events, coupled with application of modern techniques of computer diagnosis and control, will provide a good demonstration of the controllability of LMFBR plants assisted by modern MMI techniques.

Because of their importance to the testing program, the special facilities and associated reactor capabilities are described below.

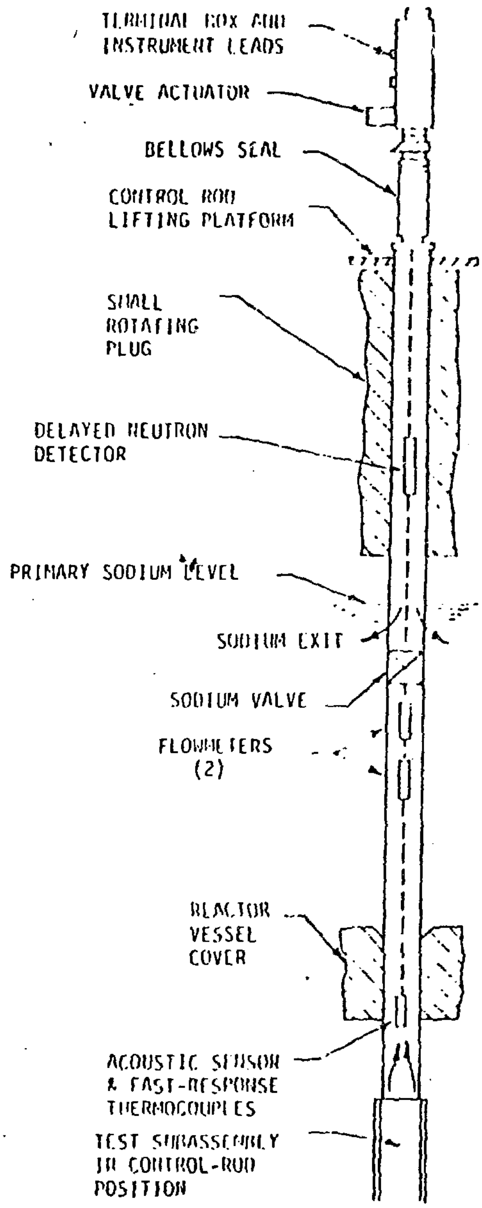
The in-core test facilities shown in Figs. 1 and 2, are open loop facilities which penetrate the reactor cover and mate with a subassembly below. They contain instrumentation to monitor sodium flow, temperature, delayed-neutron content, and acoustic signals. In addition, one facility, the fuel-performance-test-facility (FPTF) provides for control of sodium flow through the subassembly and the other, the breached-fuel-test-facility (BFTF) provides for collection of fission products and fuel released from breached elements. These are collected on a "deposition sampler" downstream of the test subassembly.

The instrumented subassemblies, designed to measure in-core thermal-hydraulic behavior, are similar to previously designed instrumented subassemblies for EBR-II, except that both a fueled and a structural (nonfueled) subassembly are included. Providing both will allow comparisons to be made between the behavior of fuel and blanket subassemblies



BREACHED-FUEL-TEST FACILITY (BFTF)

Figure 1



FUEL PERFORMANCE TEST FACILITY

Figure 2

during loss-of-flow transients. Both subassemblies are instrumented with thermocouples and flowmeters suitable for measuring flow at the very low levels associated with convective flow.

The transient-overpower testing at EBR-II consists of three distinct phases; 1) duty cycle operation, simulating periodic extended n-1 loop operation followed by a return to full power, 2) protected overpower transients, simulating periodic 15% overpower transients, and 3) extended overpower transients, carrying fuel elements to power levels where damage is predicted to occur. The primary objective is to demonstrate that advanced fuel-element designs can survive anticipated power ramps associated with off-normal LMFBR operation.

The program of man-machine interface testing involves the application of techniques designed to validate the accuracy of data from individual sensors, an extremely important consideration since much of the EBR-II instrumentation is aging and some, in the primary tank, is not replaceable. The first use of computers for automatic control at EBR-II will take place with installation of a system to control movement of a control rod to simulate "anticipated" power transients (at reactivity insertion rates of up to 10¢/s) as part of the future testing program.

CONCLUSIONS

The long life of EBR-II, its flexibility in pursuit of LMFBR improvement, and its successes argue strongly for examining more closely the inherent characteristics of LMFBR systems that make them simple and safe. The EBR-II testing programs are intended to do just that, demonstrating predictable and benign response to a wide range of plant or core upsets. Demonstration of computer application to diagnosis of off-normal plant conditions should lead to greater acceptance of this technology. Ultimately, these systems will be used for more extensive automatic control. Their reliability and applicability must be demonstrated.

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