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Designing an AI-Environment Prototype for the Automatic Startup of EBR-II

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OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
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Instrumentation and Controls Division

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NOTICE This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

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ABSTRACT

A status report on an artificial intelligence (AI) environment procedure-prompting prototype is presented. This program would permit replacement of hard copy of the Experimental Breeder Reactor-II (EBR-II) written operating procedures for plant startup with a computerized procedures manual. It is expected that with this approach, the computerized system would be able to assist reactor operators and managers by making procedures available rapidly, displaying the appropriate procedure steps, and performing on-line checks of plant parameters when required.

1. INTRODUCTION

Artificial intelligence (AI) methodologies and tools have already demonstrated their capabilities and benefits in the field of nuclear power plant operation. Particularly useful papers that document these facts are refs. 1 through 11. Operation of a nuclear power plant in the regulatory environment set up by safety rules is at present a complex task. A large number of rules, technical specifications, and site-specific procedures are required to be observed to start up a reactor. Each day, operators and managers are challenged to interpret the requirements, act on their interpretation, and consider all the potential relationships of the rules without failing. The large volume of information and its complexity make this a difficult task. The structure of traditional written operating procedures is normally step and instruction based (i.e., a procedure consists of a set of steps, each step consisting of one or more instructions to the operator about checks to make or actions to take).

An effort to make this situation more manageable and safer is being made at Oak Ridge National Laboratory (ORNL) by developing an AI environment capable of assisting operators and managers in the startup operation of a reactor. The present work is designed to replace hard-copy procedures with a computerized procedures manual, which would be able to assist reactor operators by making procedures available rapidly, displaying the appropriate procedure steps, and performing on-line checks of plant parameters when required. The objective of the environment is to increase the safety of operation by:

1. reducing the time required to access and execute an operating procedure;

2. reducing the number of errors when accessing and performing them;

3. reducing the probability of "getting lost" in the procedures and thereby performing incorrect actions;

4. providing supplementary information when appropriate and/or on demand;

5. relieving the operator of routine tasks, allowing him to concentrate on more relevant problems; and

6. providing checks on the operation via plant responses monitored by the digital data acquisition system (DAS) of the plant.

The AI environment developed in this work is based mainly on the knowledge extracted from the Experimental Breeder Reactor-II (EBR-II) startup procedures.

EBR-II is a small but complete liquid-metal-cooled reactor power plant. It has a thermal power rating of 62.5 MWt and a corresponding electrical output of 20 MWe; it has been operated over the full range of power, as the experimental program needs have dictated, for over 20 years. This facility is located at the Argonne-West site of Idaho National Engineering Laboratory.

2. TOOLS FOR THE AI ENVIRONMENT

The main tools used for the environment are the Knowledge Engineering System (KES)* and SunUNIFY.† KES is a domain-independent support tool for building interactive expert systems. KES was originally written in Lisp (1982) and was later (1986) converted to C to make it easier to integrate with other conventional programming applications.[12,13] One of the major features of KES is its three inference engines: production rules (if-then reasoning), frames (hypothesize and test), and statistics (Bayesian method). The KES Production Rule Subsystem (PS) represents knowledge through the use of if-then reasoning, employing a backward chaining technique that models the world via an object-oriented approach. The KES Hypothesize and Test Subsystem (HT) uses reasoning by explanation, building expert systems without production rules. Knowledge is represented with framelike descriptions to solve the problems. The Bayes Subsystem relies on statistical reasoning to address and solve problems.

Another main feature of this system is that KES can be readily embedded in other programs, allowing the inclusion of knowledge-base components in conventional programming. The opposite is also true; that is, KES can call any other application programs or systems (e.g.; Fortran, C, or Lisp programs; data bases; graphics displays; monitoring instruments; etc.). For this prototype, the part of KES that is used represents knowledge by rules, that is, the PS inference engine. The HT inference engine could be introduced if it becomes necessary at a later stage of the project.

A PS knowledge base is organized in sections; each section is used for a specific purpose in the knowledge base and follows a pre-established order. Some of the more important sections are:

1. **Constants.** To store the text that will be used in the display to the user.

2. **Text.** To store extensive textual information that could be of interest to the end user.

3. **Patterns.** For string-matching templates.

4. **Attributes.** For entities that can take on values during the execution of the knowledge base. These values may be integers, real numbers, truths, and single and multiple values.

5. **Types.** For defining new attribute types when there are several attributes that share the same list of possible values.

6. **Classes.** To represent knowledge about related objects.

---

*KES is marketed by Software Architecture and Engineering Inc., Arlington, Va.
†SunUNIFY is a product of Sun Microsystems, Inc., Mountain View, Calif.

7. **Externals.** To communicate information from KES to the external world or vice versa.

8. **Rules.** To infer values for the attributes. Certainty factors also can be used on either side of the rule (antecedent or consequent).

9. **Demons.** To perform actions based upon events.

10. **Actions.** To keep control of the interaction between all the previous sections and the end user also.

SunUNIFY is a relational data base system built especially for Sun workstation computer systems.[14] In SunUNIFY, the relational model has been extended to allow more sophisticated user interfaces and logical data-integrity checking. It also provides development tools to help implement the applications.

Its interactive data-entry package, "ENTER," provides full screen interactive data-entry facilities. The query-by-form feature allows a wide range of queries to be answered in a simple way. The use of the Structured Query Language (SQL) is also supported. The "RPT," a report writer, is interfaced to both SQL and ENTER. In this way, applications reports can be made from either or both query methods. The menu-oriented user interface is also helpful, especially for the nonspecialist in data processing who can access all the tools through the menus.

It is possible to create any number of separate data bases by storing them in different directories. The data base application can be protected by different levels of security. Each user may be assigned a password to access the data base, and different menus and programs can be selectively authorized to different users. Hashing tables, B-trees, links for explicit relationships, and high-speed buffers by sequential access are the access methods provided by SunUNIFY. Global query optimization before execution is also contemplated.

3. DESCRIBING THE KNOWLEDGE

The major domain resource is the complete set of the EBR-II startup operating procedures, consisting of a large set of written instructions (hard copy) incorporating both reactor design and operational experience. EBR-II experience and wisdom were gained during more than 20 years of operation. To start up the reactor, the operators have to go through a list of procedures, each of which has to be marked with the initials of the operator to indicate that the instruction has been performed satisfactorily.

The complete hard copy set of instructions, also called procedures, is more than 15 in. high. This gives an idea of the scope of the operator's task. At present, the operator reads the instruction, interprets it, executes an action, and then writes his initials by this step of the procedure to indicate that it has been performed satisfactorily. The procedures are grouped in sections and subsections that refer to a particular system or to a particular state of the reactor. We can identify four categories of them, as follows.

1. **Preliminary Checkout Procedures (PCP).** These procedures verify the status and operability of major subsystems that will be, in a later stage, interacting with the plant startup; they are the

    Electrical System,
    Radiation Monitoring System,
    Auxiliary System,
    Reactor Control Checksheets,
    Fission Product Monitors,
    Sodium and CGCS System, and
    Primary System.

2. **Preparatory Procedures (PP).** These procedures verify that the reactor, primary, secondary, steam, and data acquisition systems are operational and in the required status, but no equipment is activated. There are 14 PP steps.

3. **Direct Procedures (DP).** These procedures call for and verify the startup of equipment in the primary and secondary systems, verify internal temperatures in the core, insert the keys for reactor operation, and move control rods to bring the reactor to a steady-state power level in the range of 50 to 400 kWt. There are 25 DP steps.

4. **Approach to Power (AP).** These procedures carry the reactor to 50 MWt of power in 10 MWt steps, and then take it to the authorized power. The turbine generator may be loaded at ~20 MWt, and all core parameters are recorded and/or plotted. There are seven AP steps.

For PCP, the operator executes the instruction and checks it on the same sheet where he reads it. It is kept as a record of the reactor operation. These instructions are usually short. Each subsystem is represented by a section.

For each of the other three procedures (PP, DP, and AP), detailed explanations of what has to be done are on one sheet, and on another sheet is a short form of the same instruction which is initialized by the operator and kept as a record. Each one of these three procedures is documented in a section. After a group of instructions has been completed, generally a section, they need some approval signatures, for example, plant operations manager, operations analysis manager (etc.).

According to the previous procedures descriptions, we can classify the procedures into two types, "simple" and "elaborate." The simple instructions (PCPs) represent the first phase of the procedures when the operator is making a general checkup of the plant subsystems before going into the reactor operation itself. The elaborate instructions represent more complex tasks, usually in direct interaction with the control of the reactor. Examples of both simple instructions and elaborate instructions are given in the appendix.

PCPs are documented in seven simple sections, each one corresponding to a particular subsystem. PP, DP, and AP belong to the class of elaborate instructions. Consequently, with the two different types of instructions, we have followed two different approaches in the process of modeling the knowledge into the knowledge base. These approaches are discussed in Sect. 4 of this report.

4. IMPLEMENTING THE DATA BASE

Let us focus our attention on the PCP and have a closer look at the electrical system procedures (See Appendix). Using data base terminology, we could describe this information as a table, where the operator checking-initials, the signatures, and the dates are data that will be entered in this table. With this in mind, we can define 27 string fields (operator initials), 5 data fields, 1 numeric field, and 4 special string fields. These are special in the sense that not everybody can access them, only operators and/or managers with a predefined, exclusive keyword.

The "Paint Screen Forms" utility of SunUNIFY was used to create a screen that appears to the user, where the access is allowed only to define fields in which operators and/or managers are to enter the pertinent data.

The utilities referring to "group privileges" and "individual privileges" were used to allow different kinds of access to menus and data. The operator accesses a screen where he cannot see the values of the fields that are the responsibility of a manager. He can retrieve, add, or modify data, but not delete them. Managers can do all the above as well as delete data.

The run number has been defined as a primary key, and the corresponding date of the checkup operation is entered automatically by the system.

Field security has been implemented for some cases through a program using the SunUNIFY advanced field attributes. For example, the manager-of-plant-operation approval field requires a keyword to be filled in. The system will not accept the data entered if the expected keyword is not used. The same applies to the manager-of-operation-analysis approval field and all other fields for which an approval is needed.

Similar to the electrical system are the radiation monitoring system, auxiliary system, reactor control checksheets, fission product monitors, sodium and CGCS system, and primary system. These six parts are required to have three to five signatures each in order to be considered approved to begin the reactor startup.

We will see in Sect. 5 that a keyword only must be entered, or it will not be possible to continue with the reactor startup. This is necessary because it is required by PP that PCP be completed first.

5. MODELING THE KNOWLEDGE INTO THE KNOWLEDGE BASE

At the present state of our prototype, the PS inference engine of KES is being used, and it may be considered the "brain" that controls the flow of the information displayed to the operators for the startup of the reactor. When the plant operator begins the startup session, the KES program welcomes the user, and, through an external, the data base system (SunUNIFY) is called and presents the menu that follows:

Please choose a system to check.

1. Electrical System
2. Radiation Monitoring System
3. Auxiliary System
4. Reactor Control Checksheets
5. Fission Product Monitors
6. Sodium and CGCS System
7. Primary System

The operator chooses the systems in any order, enters the required data, and decides when to quit the data base and come back to "the expert." This should be done after the data for all seven systems have been entered, and the managers have authorized the operation to continue. The KES program will not allow continuation unless the operation has been completed and documented satisfactorily. KES monitors the status through keywords defined in special access fields in the data base.

The data for these seven subsystems procedures are stored in the data base, as explained in Sect. 4, and it can be displayed on the screen at any time.

The other six systems that make up part of the PCP may be treated in the same way as the Electrical System. These systems are spread over the plant in many different physical locations and can be checked by different plant operators simultaneously. To optimize this part of the operation, it may be necessary to record the information on portable computers and later download the data to the main computer.

When the operators have finished entering the data for the seven subsystems and have decided to continue with the operation, KES will verify that all subsystems have received their corresponding approval from the different managers. This is done by a backward and forward communication with the data base. Through an external, KES runs an executable file which accesses RPT and, by combining a data input file and a command report file, will produce the data file needed by KES. In this file, KES finds the information necessary to verify that approval from the managers has been obtained. The procedure described above may be used to check any other data recorded in the data base.

Now, if the data for the seven subsystems of the PCP have been completed, the expert will guide the operator through PCPs. From then on, KES will keep control of the operation step by step. It will prompt the operator, on the screen, for each instruction, one at a time. It can be noticed here that the strategy of the control has been changed. This has been done for the reasons that follow.

In analyzing the PP, DP, and AP procedures, we observe that although some of the instructions may be done out of sequence, many others require a strict sequential order. In this case, a careful step-by-step control of the operation is necessary. At this point, a link between the time-dependent parameters of the reactor, some of the instructions from the procedures, and a reference simulation could be used for a better and more efficient control of the operation. KES would be particularly useful to take account of these facts.

Each detailed explanation instruction prompted to the operator is stored as a file in a directory. The same is done, in another directory, for the short form of the instruction and the data recorded by the operator (these are the data record logsheets).

The detailed explanations are prompted on the screen, step by step, to the operator. He will take actions accordingly, then initialize it with or without some comments. In the short form of the instruction, the operator response, date, and time are recorded on a file that is kept as a record of the reactor operation. This kind of recording will replace the hand-recorded logsheets used at present. All communications to and from the files are done through external definitions.

6. VERIFICATION AND VALIDATION

A preliminary verification of the AI environment was made informally through a review of the system by operators of EBR-II and other Instrumentation and Controls (I&C) Division engineers who were interested in this research subject. A more extensive verification and validation is planned in the near future by an experienced operator who will test the system on the I&C Division computers. A final validation is programmed to be done in situ by a crew of operators at a later advanced stage of this AI environment.

7. CONCLUSIONS

Although at present we are in an early stage of the AI environment prototype for the automated startup of EBR-II, creation of a useful tool appears feasible. This tool will assist reactor operators and managers in startup activities.

This AI environment is expected to increase safety operations by: reducing the time required to access and execute the procedures, minimizing the errors in accessing and executing the instructions, reducing the possibilities of getting lost in the procedures, helping the operator in routine tasks so he will be able to concentrate on more demanding problems of the operation, providing supplementary information when appropriate, and/or providing checks (on demand) on the operation via plant responses monitored by DAS.

Concerning the tools used for this prototype, we can say that KES seems to be a good expert system shell for this application. The flexibility of the language, the capability of communication with other programs and systems, and the variety of sections (constants, attributes, demons, actions, etc.) through which any kind of idea or concept may be suitably described and expressed make this shell an appropriate instrument to build the kind of application we need. However, we were expecting KES to provide other capabilities such as graphics and a better user interface. Such capabilities are not yet available.

On the other hand, our experience with SunUNIFY has been a disappointment. While we were pleased with many of its features, it was very cumbersome to use (vs most current data base management systems), and we encountered several "bugs" and inadequacies that frustrated our progress. Also, the resources consumed by the software appeared to seriously degrade the performance of our entire Sun workstation network.

It is important to note that our earliest efforts utilized KES software on an IBM-compatible AT-386 computer. Relative to the implementation on the SUN workstation, we discovered that all the operations are significantly slower than working on the AT-386 machine. This fact not only would be extremely important at a later stage when the automatic acquisition or simulations would be implemented, but it was also bothersome during the development process of the present application.

For the reasons given previously, we are evaluating other data base systems including DBase-4 and INGRES, and we also are considering continuing this work on the AT-386 machine instead of the Sun workstation.

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APPENDIX

APPENDIX

I. EXAMPLE OF A "SIMPLE" STARTUP CHECK SHEET

Technical Specification Surveillance Log

APPROVED

____________________________ ________
Manager, Plant Operations Date

____________________________ ________
Manager, Operations Analysis Date

LOG NO. 1-A (SECT. 1) (REV. 13) Reactor Run No. ______

Date ________________

ELECTRICAL SYSTEM

This checksheet is to be completed prior to Plant Startup. Refer to Section II B, Plant Startup. All items must be initiated by the person completing the check. Items marked * are Technical Specification Surveillance Items.

NOTE: Before proceeding obtain the key to the continuous power UPS cabinets (Key 69) from the Shift Supervisor.

______ 1. The Continuous Power supply Uninterruptible Power system No. 1 and No. 2 are in operation. (Refer to Section IX D.)

______ 2. Test the Continuous Power Supply Uninterruptible Power System No. 1 and No. 2 as follows:

Note: While performing the transfer tests on the Continuous Power Supply UPS units, there should be no loss of plant instrumentation or annunciation of alarms due to continuous power perturbations. After completing each transfer operation, check with the reactor control console operator to verify that instrumentation and alarm annunciation is operating normally. Continuous power abnormal alarms will be received in the control room as the checks are performed.

_______ a. Transfer the Continuous Power UPS No. 1 and No. 2 SBS's to BYPASS by depressing the "Static Bypass Switch (SBS) Bypass Pushbuttons."

_______ b. Transfer the manual bypass switches on both UPS units to the "BYPASS" position.

_______ c. Open the AC Input Circuit Breakers (CB-51) on Continuous Power Supply UPS No. 1 and No. 2.

_______ d. Verify control power is being supplied to the Continuous Power Supply UPS No. 1 and No. 2 by observing that the output voltage of both inverters is normal.

_______ e. Close the AC input circuit breakers (CB-51) on Continuous Power Supply UPS No. 1 and No. 2.

Caution: When operating breaker CB-2, which is mounted inside the UPS cabinet adjacent to exposed terminals which are energized, wear a pair of lineman's gloves. The lineman's gloves may be obtained from the Operation equipment locker on the mezzanine level of the Power Plant. After completing the test on the continuous power supply, return the lineman's gloves to the Operations equipment locker.

_______ f. Open the bypass power supply Circuit Breaker CB-2 on Continuous Power UPS Units No. 1 and No. 2.

_______ g. Verify control power is being supplied to the SBS on each of the Continuous Power Supply UPS units by observing that the output voltage of both inverters is normal.

_______ h. Close the bypass Circuit Breaker CB-2 on each UPS unit.

_______ i. Transfer the manual bypass switch back to the "UPS" position on each UPS unit.

_______ j. Transfer both SBS's to their normal inverter (forward transfer) by depressing the SBS normal invert pushbuttons.

_______ k. Transfer the No. 1 Continuous Power UPS SBS to its alternate inverter by depressing the alternate inverter pushbutton on the No. 1 UPS SBS.

_______ l. Verify that the No. 2 UPS unit assumed the No. 1 UPS load by observing that the No. 2 UPS A.C. load (A.C. ammeter) has about doubled.

_______ m. Return the No. 1 Continuous Power UPS SBS to its normal inverter by depressing the normal inverter pushbutton (forward Transfer) on the No. 1 UPS SBS.

_______ n. Verify that the No. 2 UPS A.C. load has returned to normal.

_______ o. Transfer the No. 2 Continuous Power UPS SBS to its alternate inverter by depressing the alternate inverter pushbutton on the No. 2 UPS SBS.

_______ p. Verify that the No. 1 UPS unit assumed the No. 2 UPS load by observing that the No. 1 UPS A.C. load (A.C. ammeter) has about doubled.

_______ q. Return the No. 2 Continuous Power UPS SBS to its normal inverter by depressing the normal inverter pushbutton (Forward Transfer) on the No. 2 SBS.

_______ r. Verify that the No. 1 UPS A.C. load has returned to normal.

_______ *s. All transfers were made satisfactorily, and the Continuous Power Supply UPS unit No. 1 and No. 2 are in operation per Section IX D of the Operating Instructions.

_______ t. Return the key to the constant power UPS cabinets to the Shift Supervisor.

_______ *3. Electrical Operating Log No. 5-B is current, and has been reviewed by the Shift Supervisor for Technical Specification surveillance compliance.

_______ 4. All 13.8 kV, 2400V and 480V protective relay targets have been reset.

_______ 5. Initial either (a) or (b), as applicable for Control room electrical Panels E-1 through E-7.

_______ a. All annunciator windows are in the proper ON or OFF condition, and light when tested.

_______ b. The Shift Supervisor has reviewed all malfunctioning annunciators to verify they are not Technical Specification related. Malfunctioning annunciators has been caution tagged and logged in the Console Log and in the comments section of this checksheet.

COMMENTS:

______________________________ __________
Operator Date

______________________________ __________
Shift Supervisor Date

II. EXAMPLE OF AN "ELABORATE" STARTUP CHECK SHEET (EXCERPTS)

Preparatory Procedures

(1) If this startup is the result of a forced shutdown, the Plant Operations Manager must brief the Associate Director of Operations, the Manager of Core Surveillance, and the Manager of any other applicable department of the unscheduled reactor shutdown and subsequent corrective actions and receive their concurrence to perform a plant startup.

(2) Verify the current Reactor Run Plan and Authorization (Run Plan) is available in the control room.

(3) Verify the Master Startup Checksheets, Log No. 1-A, Section 1 through 7, are complete and satisfactory. Complete Sections 8, 9, and 10 concurrently with startup.

(4) Review all outstanding work requests in the work request index log for problems that may affect plant operation.

(5) Verify that Danger and Caution tags have been cleared as necessary for plant operation.

(6) Verify that bulk sodium temperature is within the range of 695 to 705°F.

(7) Verify the DAS is in operation. Refer to Section II M, Digital Data Acquisition System (DAS).

(8) Verify that precritical test and experimental data has been taken per the applicable tests and experiments listed in the Run Plan.

(9) Take the startup NITF Automatic Data Retrieval system (ADRS) data in accordance with Section II M, DAS, approximately two hours prior to the approach to critical.

(10) Verify the DAS alarms are set at the values specified in the "subcritical" section of Log No. 8-T.

(11) Verify the DAS display for FPTF Delayed Neutron Detector RMS voltage is greater than 0.25 VRMS.

NOTE: This check is applicable only when a fueled test or experimental subassembly is installed under the FPTF.

(12) Verify that the BFTF Delayed Neutron Detector RMS voltage is greater than 0.40 VRMS as read locally on the voltage monitor (refer to Section BFTF, Subsection 2.b.).

NOTE: This check is applicable only when a fueled test or experimental subassembly is installed under the BFTF.

. . .

(End of sample. There are more instructions in PP.)

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