THE 4TH INTERNATIONAL TOPICAL MEETING ON
NUCLEAR THERMAL HYDRAULICS, OPERATIONS AND SAFETY
April 6-8, 1994, Taipei, Taiwan

A RULE-BASED EXPERT SYSTEM FOR CONTROL ROD PATTERN OF BOILING WATER REACTORS BY HOVERING AROUND HALING EXPOSURE SHAPE

Pin-Wu Kao, Lian-Shin Lin and Jing-Tong Yang
Institute of Nuclear Energy Research
P.O. Box 3-3, Lung-Tan, Taiwan 325, R.O.C.
FAX.: (03) 471-1064

ABSTRACT

Feasible strategies for automatic BWR control rod pattern generation have been implemented in a rule-based expert system. These strategies are majorly based on a concept for which exposure distributions are hovering around the Haling exposure distribution through a cycle while radial and axial power distributions are dominantly controlled by some abstracted factors indicating the desired distributions. The system can either automatically generate expert-level control rod patterns or search for criteria-satisfied patterns originated from user's input. It has successfully been demostrated by generating control rod patterns for the the 1775 MWth Chinshan plant in Unit 1 Cycle 13 alternate loading pattern and Unit 2 Cycle 8 but with longer cycle length. All rod patterns for two cycles result in all-rod-out at EOC and no violation against the four criteria. The demonstrations show that the system is considerably good in choosing initial trial rod patterns and adjusting rod patterns to satisfy the design criteria.

I. INTRODUCTION

Many articles have been presented for automatic control rod pattern generation. The OPROD program[1-3] and Lin's program[4] basically used a heuristic algorithm to find the initial control rod pattern, which is a mathematical programming method to search for the optimal and suboptimal control rod patterns. The search direction in the mathematical programming algorithm is based on results of a three-dimensional core simulation code. Because the search direction is rough, the algorithm needs to run the simulation code many times , which requires considerable computing time.

Fukujaki et al.[5] developed a knowledge-based system to support control rod pattern design. Their system generates case data for a three-dimensional core simulation code to calculate the core status, then modifies the case data by considering the results of the calculation. Calculations and modifications are iteratively repeated until certain design criteria are satisfied.

Lin and Lin[6] developed a prototype of rule-based expert system for automatic control rod pattern generation. The system has two main components, a forward-chaining mechanism adopting Rete pattern matching algorithm[7] and a knowledge base containing some heuristic strategies for conforming to thermal limits, improving average axial power distribution, reaching target eigenvalue and obtaining initial control rod pattern.

In this paper, some feasible strategies are given to replace Lin & Lin's. Section II briefly describes the BWR control rod design criteria while the concepts of our strategies are described in Section III. Haling principle is usually taken for a primary core design since it can find a constant power shape through a cycle with minimum power peaking factor. The power shape obtained by following the Haling principle is called as Haling power shape. When a core is depleted with the Haling power shape, the exposure distribution for the core at any burnup is called as Haling exposure distribution. In order to be easier to satisfy thermal limits criteria, the strategies are based on a concept for which exposure distributions are hovering around the Haling exposure distribution through a cycle while radial and axial power distributions are dominantly controlled by some abstracted factors indicating the desired distributions. The strategies for finding initial patterns has been renewed by replacing the method of certainty factors with a simple model as an estimator. The performance of the expert system is presented in Section IV. Finally, the conclusion is provided in Section V.

II. ROD PATTERN DESIGN CRITERIA

There are about 100 control rods in a BWR core, which are conventionally divided into two groups, represented by A and B. The A group has eighth-core mirror symmetry while the B group has quarter-core mirror symmetry. The rods in the A and B groups are further divided into subgroups A1, A2, B1 and B2.

When the control rods in subgroup A1 are the major rods in an active core, the reactor is said to be operating in

A1 sequence. The control rod sequence is changed from one to another at about 1000 MWd/MT to flatten exposure distribution. Here, either one in the following two orders of sequences is chosen for rod patterns:

$$A2 \rightarrow B1 \rightarrow A1 \rightarrow B2 \rightarrow A2 \ldots$$

or

$$A1 \rightarrow B1 \rightarrow A2 \rightarrow B2 \rightarrow A1 \ldots$$

When the control rod patterns for a cycle of a reactor core are designed, the following criteria should be met:

1. The difference between the actual eigenvalue for a rod pattern and target eigenvalue is small enough at each burnup step.
2. Thermal limits, including critical power ratio (CPR), average planar linear heat generation rate (APLHGR) and linear heat generation rate (LHGR), are within the limit values at each burnup step.
3. At end of cycle (EOC), all control rods can be fully withdrawn.
4. The exposure index (EI), defined as the sum of difference between normalized actual axial exposure and Haling exposure at node n multiplied by (n - 12), should be between 0.2 to -0.5

Condition 1 and 2 must be satisfied while the last two conditions can be allowed to be unfulfilled. The intent of condition 3 is to generate more cycle energy, and that of condition 4 is to provide a guideline for reactor operation to ensure that operation remains within the bounds of the licensing bases relative to plant transients sensitive to control rod scram worth. If condition 3 is not satisfied, cycle energy is reduced. If condition 4 is not satisfied and EI is more positive, safety analysis should be redone for the more bottom exposure distribution than Haling one. It is noted that the optimum rod pattern is not attempted to reach. Hence, a rod pattern obtained by this expert system and satisfying the design criteria according to the above way is accepted.

III. CONCEPTS OF THE KNOWLEDGE BASE

A. Hovering Around the Haling Shape

The thermal limits criteria are more concerned than other citeria when control rod patterns are designed for a cycle because they are more sensitive and more difficult to reach. The smaller the local peaking, the better the thermal limits. It is a good operating strategy to minimize the local peaking in the core through the cycle by keeping power shapes to be close to the Haling shape. Generally speaking, patterns with more axial bottom-peak power shape than that of Haling shape are accomplished with the ones with less axial bottom-peak power shape during more core burnup. Furthermore, axial power shapes hovering around the Haling shape and with a little more bottom-peak can result in a near Haling exposure shape to ensure a higher possibility of reaching all-rod-out at EOC and enough scram reactivity at the bottom of the core.

B. Initial Power Shaping

It is necessary to eliminate intermediate rods of a control rod pattern if an axial bottom-peak power shape is desired. Generally, intermediate rods are not desired due to their complex influence on core power response. Moreover, the shallow rod can be easily obtained by adjusting a rod. Hence, in an initial pattern, only deep rods are considered while all the other rods are fully out. From the initial pattern, the trial pattern is adjusted until it meets the requirements. If an axial non-bottom-peak power shape is desired, some intermediate rods are needed. However, in an initial pattern, only deep rods are still considered.

All-rod-out radial power shape is the most important reference in power shaping. The radial peakings on high power regions under the all-rod-out condition are more concerned. One to three high power regions are defined while the number of high power regions is not over the number of deep rods. Number of deep rods is estimated by hot excess reactivity at the rated operating condition. Users can choose rod density index, which is defined as the average distance of deep rods to high power regions so that they may control the peaking factors in the high power regions. In the meantime, they can also control the axial power shape roughly since intermediate rods will be inserted during rod pattern adjusting if large peaking factors appear in the high power regions of the initial rod pattern.

C. Initial Rod Pattern

All patterns with different rod density index, which must be octal-core symmetric for A-sequence and quarter-core symmetric for B-sequence, are given in a pattern-list. If it is possible, B-sequence pattern is considered to be near octal-core symmetric. The rod patterns simulation are performed by the three-dimensional simulation code SIMULATE-3 until a rod pattern meets the desired CPR ratio to limit (FLCPR). Then, the rod patterns whose rod density indices are within a band of the rod density index corresponding to the satisfied rod pattern are choosed as the candidates of the initial pattern. The desired initial pattern is one of the candidates in which the fewest deep rods are located in the low exposure regions where exposures are less than the Haling exposures over a predetermined value, thus these regions can be expected to have more depletion at the burnup step.

D. Rod Pattern Adjusting

CPR value depends on bundle power; therfore, CPR violation at a bundle can be eliminated by deeply inserting a neighboring control rod or rods around the bundle. However, LHGR and APLHGR values depend on local power density, so the violations for a bundle can be eliminated by inserting a neighboring rod or rods around the bundle over the axial violation positions. If there are a lot of severe LHGR or APLHGR violations around a shallow rod, the rod needs to be inserted immediately as an intermediate rod to reduce computer time for rod adjusting. The toughest LHGR or APLHGR violation occurs at the location far away from any rods in the desired rod sequence. If the violation can not be eliminated by the above method, the rod, closest to the violation, in the same group but not in the desired sequence, will be inserted shallowly.

An axial power shape can be represented by a factor which is defined as an average power ratio (APR) of the lower 8 ft to 12 ft. The power ratio and the peak location of an axial power shape are the important indicators of the axial power shape when a control rod pattern is designed. With all control rods fully withdrawn at BOC, a BWR core shows an axial bottom-peak power shape with a larger axial power ratio. When core burnup increases, the power ratio becomes smaller due to more fuel depletion at bottom of the core. At each burnup step, a desired average axial power ratio, and its allowed range are given from the user's input, then the system is forced to make the average axial power ratio for the trial pattern within a range of the axial shape criteria. Usually, the intermediate rods are kept as few as possible, and shallow rods are withdrawn as fully as possible, if larger thermal margins than the specified values and a bottom-peak shape are found.

Core criticality is usually kept by re-adjusting positions of deep rods after rod movements are determined due to the thermal limit or power shape violations. A table of rod worths against rod locations, depths and core exposures is constructed to estimate rod movements to maintain criticality. A linear relation is assumed for multiple movements.

IV. RESULTS AND DISCUSSIONS

There are two main parts in the program: a three dimension core simulation code and the expert system based on the expert system shell, CLIPS version 5.1, developed by NASA. The framework of the expert system based on a HP/9000 workstation includes:

1. structured object forms to represent plant, control rods, rod patterns, constraints and core status.
2. meta-rules to control calculation flow and to guide the use of knowledge formed into object-level rules.
3. object-level rules:
   a. initial rules to generate initial rod pattern.
   b. adjusting rules to modify rod pattern.
4. an expert system shell.

In order to check the performance of our expert system, it was applied to generate rod patterns for the Chinshan nuclear power plants in Taiwan. The Chinshan power plant is a BWR/4 with rated power 1775 MWth and 97 control rods. For Chinshan Unit 1 Cycle 13, an alternate loading pattern was designed and studied to find whether the vendor's loading pattern can be improved. The cycle is operated in the spectral shift strategy, so rod patterns are designed in 100% power/90% flow from 0 to 8 GWd/MT while in 100% power/100% flow after 8 GWd/MT. In order to compare rod step through results, the expert system are used to find rod patterns for the alternate loading pattern. Another example which we choosed is Chinshan Unit 2 Cycle 8 , a previous operated cycle with longer cycle length. The resulting rod patterns for two cycles are shown in Figs. 1 and 2 respectively.

In Figs. 1 and 2, those fuel bundles marked with light dots are low exposure regions, those marked with grey dots are high power regions, and those with dark dots are both low exposure and high power regions. The locations of deep rods in the initial patterns for each burnup step are circled. The resulting rod patterns at the end of cycle (EOC) for all checked cycles are all-rod-out. In the real operating, the rod pattern for Chinshan Unit 2 Cycle 8 EOC is not all-rod-out with rod density 0.046. Therefore, the actual cycle length for this cycle is 9.224 GWd/MT while the cycle length for our rod patterns is 9.767 GWd/MT.

In Fig. 1, rod patterns are quite simple since only deep rods exist. The axial power shapes are bottom-peak before 6 GWd/MT, then the axial power shape becomes more and more top-peak. From this figure, we found the low exposure regions are always kept in the central core regions and high power regions under the all-rod-out condition are also in the same regions. Hence, the cycle length for our rod patterns is longer than the Haling cycle length , 8.643 GWd/MT vs. 8.372 GWd/MT, because low exposure in the central core region at EOC results in higher reactivity.

In Fig. 2, rod patterns for Chinshan Unit 2 Cycle 8 are much more complex. The axial power shapes are bottom-peak before 3 GWd/MT, they become middle-peak at 4 G-Wd/MT, and then become double-hump from 5 to 7 G-Wd/MT, and finally approach to near Haling shape. Low exposure regions appear only at 1 and 2 GWd/MT, so the depletion process is close to the Haling depletion. Hence, the cycle length, 9.767 GWd/MT, for our rod patterns is close to the Haling cycle length, 9.807 GWd/MT.

Figs. 3 and 4 show that axial cycle exposures at EOC are close to the Haling axial cycle exposures, especially in Chinshan Unit 2 Cycle 8. Tables 1 and 2 show that thermal ratios of our rod patterns for both cycles are satisfied and thermal ratios for the Haling depletion at EOC are listed as reference. At EOC, exposure index is 0.009 for Chinshan Unit 1 Cycle 13 alternate loading pattern, and 0.00454 for Chinshan Unit 2 Cycle 8. Therefore, both of them satisfy exposure index criteria.

V. CONCLUSIONS

For the initial pattern, the strategies of determining locations of deep rods by the rod density index, the average distance from deep rods to high power regions, are adequate. Radial and axial power shapes are outlined by appropriate average distance from high power regions. Hence, once deep rods are determined in the initial pattern, few of deep rods will be adjusted to be shallow. If a lot of severe thermal violations occur around a shallow control rod, the expert system will observe this situation, and then the rod will be inserted to be intermediate immediately. The expert system was demonstrated for two cycles control rod pattern generation of Chinshan nuclear power plants. All rod patterns for two cycles result in all-rod-out at EOC and no violation against the four criteria. Hence, the expert system is proved to be a powerful and practical tool for automatic rod pattern generation for Chinshan boiling water reactor.

ACKNOWLEDGEMENTS

INER wishes to thank Taiwan Power Company for providing the information for Chinshan Nuclear power plants, which enabled these analyses to be performed.

REFERENCES

1. T. KAWAI, H. MOTODA, T. KIGUCHI, and M. OZAWA, "A Method for Generating a Control Rod Program for Boiling Water Reactors," Nucl. Technol., 28, 108 (1976).
2. T. HAYASE and T. MOTODA, "Boiling Water Reactor Control Rod Programming Using Heuristic and Mathematical Methods," Nucl. Technol., 48, 91 (1980).
3. S. TOKUMASU, M. OZAWA, H. HIRANUMA, and M. YOKOMI, "A Mathematical Method for Boiling Water Reactor Control Rod Programming," Nucl. Technol., 71, 568 (1985).
4. C. LIN, "An Automatic Control Rod Programming Method for a Boiling Water Reactor," Nucl. Technol., 92, 118 (1990).
5. L. S. LIN, C. LIN, "A Rule-Based Expert System for Automatic Control Rod Pattern Generation for Boiling Water Reactors," Nucl. Technol., 95, 1 (1990).
6. J. C. GIARRATANO, CLIPS Reference Manual, NASA's Software Technology Branch (1991).
7. C. FORGY, "On the Efficient Implementation of Production Systems," PhD Thesis, Carnegie-Mellon University (1979).

Table 1. Thermal ratios of rod patterns for Chinshan Unit 1 Cycle 13 Alternate Loading Pattern

Exposure GWd/MT	MFLCPR	MAPRAT	MFLPD
0.0	0.888	0.885	0.917
1 0	0.901	0.902	0.913
2.0	0.814	0.782	0.845
3.0	0.862	0.854	0.915
4 0	0 874	0.843	0.925
5 0	0.892	0.907	0.915
6.0	0.844	0.874	0.889
7.0	0.891	0.875	0 913
8.0	0.897	0.736	0.818
9.7666	0.848	0.745	0 859
Haling	0.849	0.672	0.838

Table 2. Thermal ratios of rod patterns for Chinshan Unit 2 Cycle 8

Exposure GWd/MT	MFLCPR	MAPRAT	MFLPD
0.0	0.757	0.909	0.857
1.0	0.779	0.874	0.832
2.0	0.741	0 849	0.815
3.0	0 770	0.901	0.862
4.0	0.731	0.871	0.839
5.0	0 781	0.815	0.795
6.0	0.778	0.829	0.856
7 0	0.872	0.861	0 881
8.0	0.828	0.822	0.864
8.6432	0.779	0.795	0.920
Haling	0 793	0 767	0.808

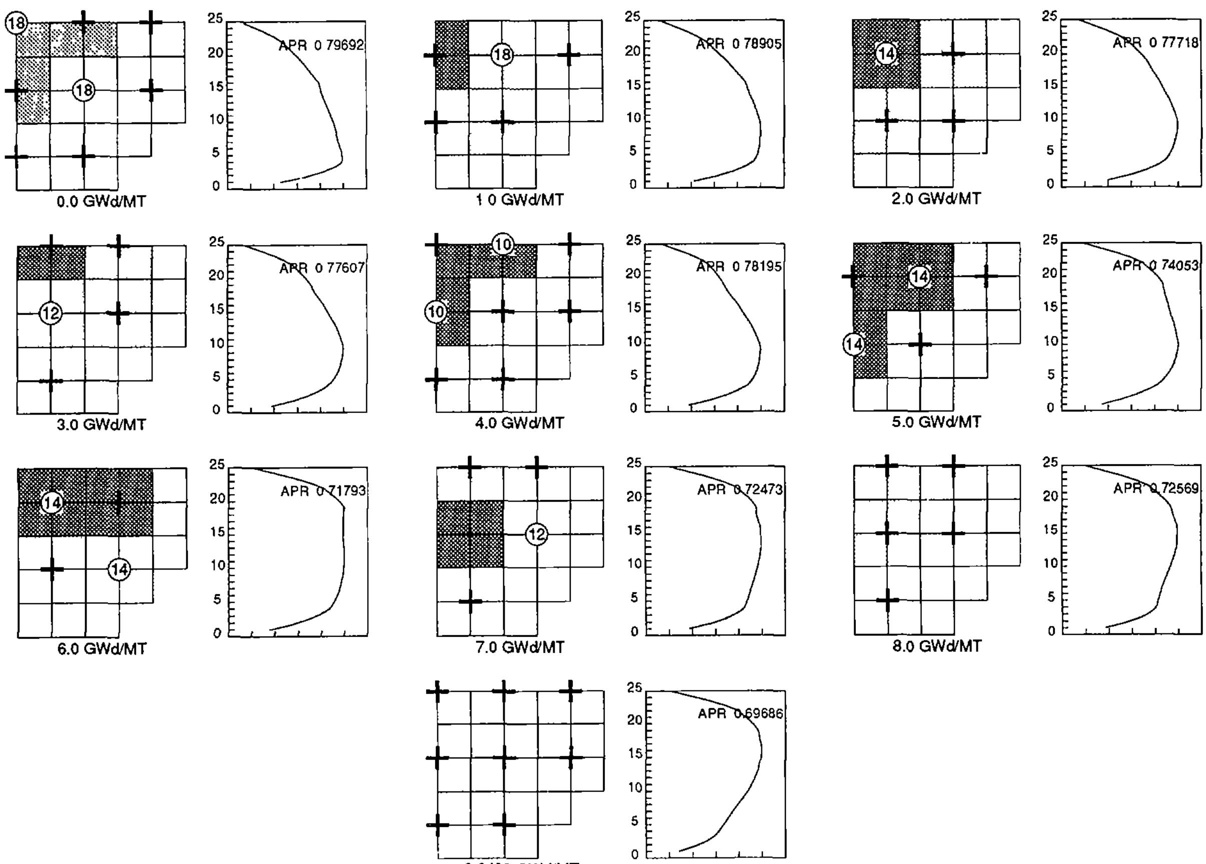

Fig.1 Control rod patterns and corresponding axial power shapes for Chinshan Unit 1 Cycle 13 Alternate Loading Pattern

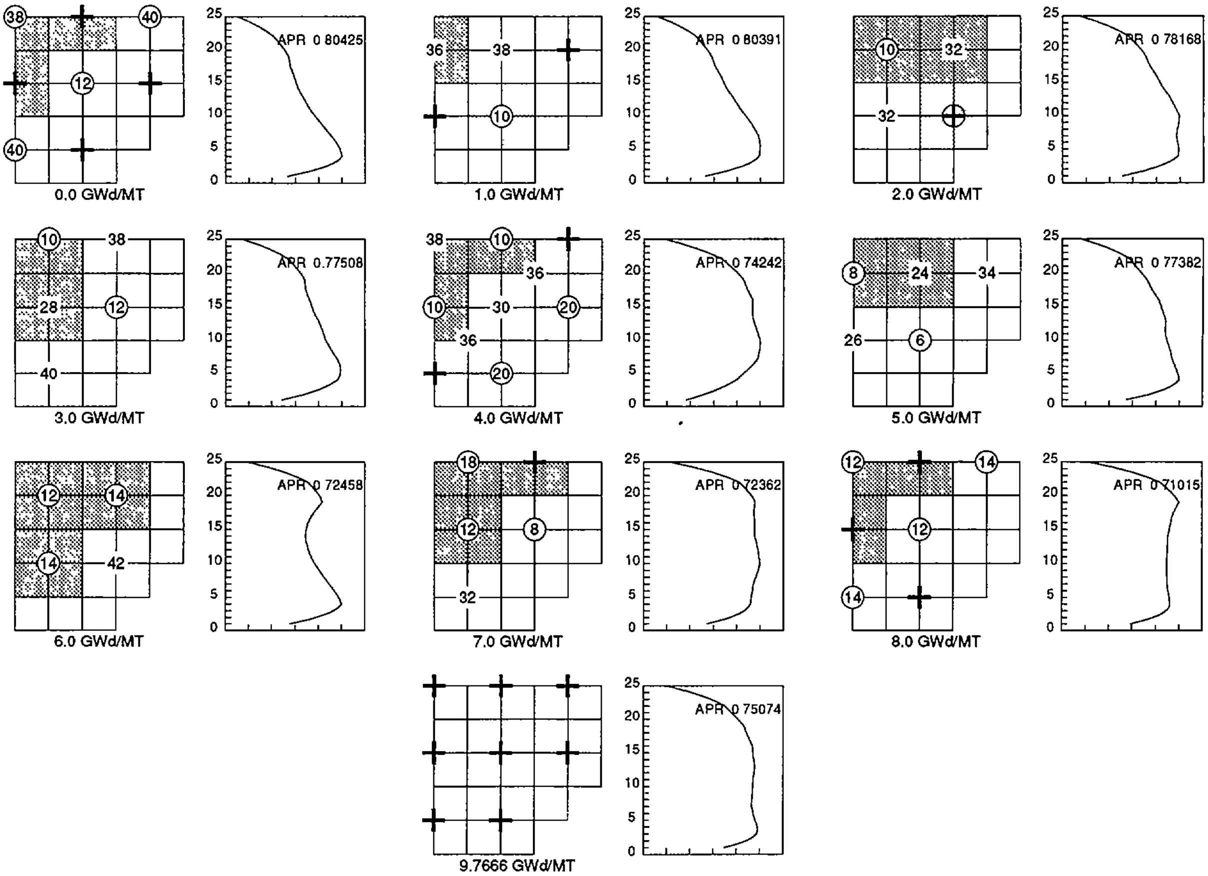

Fig.2 Control rod patterns and corresponding axial power shapes for Chinshan Unit 2 Cycle 8

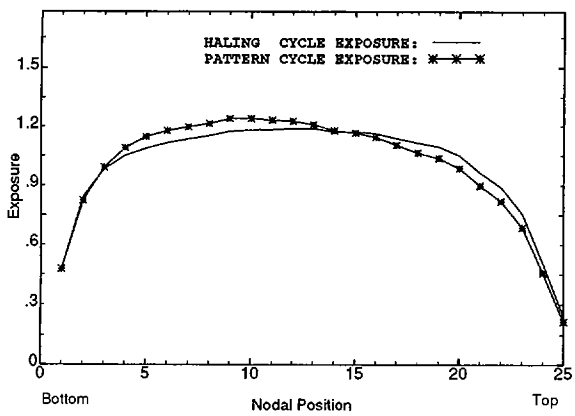

Fig. 3 Axial cycle exposure distributions of Chinshan Unit 1 Cycle 13 Alternate Loading Pattern

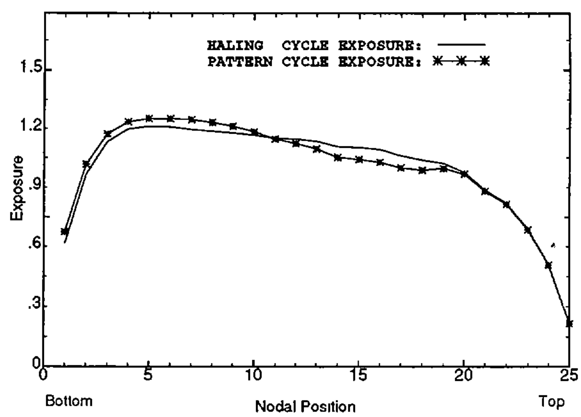

Fig. 4 Axial cycle exposure distributions of Chinshan Unit 2 Cycle 8

Session 41
Advances in Man-Machine Interface Design & the Related Human Factors Engineering-II