Fuzzy Logic in Nuclear Engineering

Da Ruan
Belgian Nuclear Research Centre (SCK•CEN)
Boeretang 200, B-2400 Mol
E-mail: druan@sckcen.be

Abstract

Nuclear engineering is one of the areas with a large potential for applications of fuzzy technologies, in which, however, the development is still in its infancy. The nuclear power industry requests special demands on plant safety, surpassing all other industries in its safety culture. Due to the public awareness of the risks of nuclear industry and the very strict safety regulations in force for nuclear power plants (NPPs), fuzzy logic applications in nuclear engineering present a tremendous challenge. The very same regulations prevent a researcher from quickly introducing novel fuzzy-logic methods into this field. On the other hand, the application of fuzzy logic has, despite the ominous sound of the word "fuzzy" to nuclear engineers, a number of very desirable advantages over classical methods, e.g., its robustness and the capability to include human experience into the controller. In this paper, we first briefly outline nuclear applications of fuzzy logic in the world. We then review some relevant applications of fuzzy logic in nuclear engineering. Finally, we present an on-going project on application of fuzzy logic control of the first Belgian Reactor (BR1) and other related applications of fuzzy logic at the Belgian Nuclear Research Centre (SCK•CEN). We conclude that research in fuzzy technologies has reached a degree where industrial application is possible. Investigations into this direction and particular in nuclear engineering are still very rare, but some existing results seem promising.

Keywords: nuclear engineering, industrial applications of fuzzy logic, fuzzy control application, BR1 reactor.

1 Introduction

Nuclear engineering is the branch of the engineering profession concerned with the practical applications of *nuclear energy*, that is, the energy which, in one form or another, originates in and emanates from the atomic nucleus.

Despite the existence of hundreds of commercial power plants (mostly of the light-water type), which in some countries like France or Belgium represent as much as 60% of the electrical power generation capacity, there is a slump almost everywhere in the attendance of nuclear engineering university programs and in its corollary, innovative research by talented young people in quest of doctoral degrees. Several nuclear engineering departments in American universities have been closed, while others have merged with mechanical- or chemical engineering departments for technical and economical reasons. The situation is not very different in European universities, where nuclear programs also attract smaller audiences. Nevertheless, researchers interested in starting a PhD thesis or in carrying a post-doc project should not conclude too hastily that the subject is dead: nuclear engineering in a large sense (i.e., encompassing *reactor* engineering) still offers plenty of interesting scientific and technological challenges.

Nuclear engineering is one of the areas with a large potential for applications of intelligent systems including fuzzy logic, in which, however, the development is still in its infancy [27, 31]. Most nuclear engineers today are involved in the development of nuclear power installations, either stationary power plants for the generation of electricity or plants for the propulsion of mobile systems. The Chernobyl accident and its cross-border consequences have reminded us that nuclear safety remains a short-term priority, both at home and abroad, as nuclear technology has not reached the same maturity in all countries. The need for on-line reactor operator decision support systems has become evident after the Three Mile Island accident in 1979. Since then, considerable attention has been paid by the engineering, scientific, economic, political communities and by society at large to prevent this type of event by using state-of-the-art artificial intelligence techniques.

Among the available techniques, fuzzy-logic control (FLC) has been recently applied to nuclear reactor control. Having acquired the accumulated skill of many operators, FLC can assist an operator in controlling a complex system. One of the advantages of FLC is to derive a conceptual model of the control operation, without the need to express the process in mathematical equations and to assist the human operator in interpreting and validating incoming plant variables and arriving at a proper control action. Several interesting FLC results were reported in the area of nuclear reactor control [10]: the high-temperature reactor (HTR) nuclear power plant model control [4], automatic operation method for control rods in boiling-water reactor (BWR) plants [14], the Feed-water-control system in Fugen heavy-water reactor (HWR) [40], the steam generator water-level in pressurized-water reactor (PWR) [15], and PWR-type nuclear power plants [1]. The best known work in this area is the successful application of FLC to the 5 Mega-Watts thermal (MWt) Massachusetts Institute of Technology (MIT) research reactor [3]. A rule-based, digital, closed-loop controller that incorporates fuzzy logic has been designed and implemented for the control of power on the MIT research reactor. The advantage of rule-based systems is that they are generally more robust than their analytic counterparts in the above work [3]. Therefore, the rule-based and analytic technologies should be used to complement each other, with rule-based systems being employed both as backups to analytic controllers and as a means of improving the man-machine interface by providing human operators with the rationale for automatic control action.

The significant influence of FLC in this field was also illustrated by the activities of **FLINS** (an acronym for **F**uzzy **L**ogic and **I**ntelligent Technologies in **N**uclear **S**cience) and by the response to FLINS'94 (The 1st international workshop on *Fuzzy Logic and Intelligent Technologies in Nuclear Science*, Mol, Belgium, September 14–16, 1994) [28]. A successful application of FLC to the feed-water control system of the 165 Mega-Watts electric (MWe) Fugen Advanced Thermal Reactor (ATR) has enabled operators to control the steam drum water level more effectively than with a conventional proportional-integral (PI) control system [11]. The Korea Atomic Energy Research Institute [12] piloted a real-time self-tuning fuzzy controller for a steam generator with a scaling factor adjustment. This improves the performance of the water-level controller; the controller is itself simulated by a compact nuclear simulator.

Many new results on this topic are followed and presented at FLINS'96 (The 2nd international workshop on *Intelligent Systems and Soft Computing for Nuclear Science and Industry*, Mol, Belgium, September 25–27, 1996) [29]. SCK•CEN started its own R&D project in this area on FLC nuclear reactors [30]. In this framework, the availability of the BR1 reactor greatly simplifies the effort to validate the used model description. This allows us to concentrate on the optimal implementation of the overall control. We remark that this project reflects a special application domain of fuzzy logic related to the highest safety requirement in nuclear areas. Research involved in this project will provide a real test bed and be the only step towards the future fuzzy-logic applications in NPPs.

2 Fuzzy algorithmic and knowledge-based decision support in nuclear engineering

Many of the real-world problems arising in the analysis and design of decision, control, and knowledge systems are far from simple. Intelligent technologies including fuzzy logic, neural networks, genetic algorithms, and others provide additional tools which significantly enlarge the domain of problems which can be solved. Nuclear engineering is one of the areas with a large potential for applications of intelligent technologies in which, however, the development is still in its infancy. Nevertheless, recent publications [32, 31] show a positive trend towards using intelligent systems in nuclear applications. As Chairman of the FLINS international scientific advisory committee, Professor Zimmermann delivered his opening lecture on "Fuzzy algorithmic and knowledge-based decision support in nuclear engineering." Among the existing intelligent technologies, the development of fuzzy technology during the last 30 years has, roughly speaking, led to the following application-oriented classes of approaches which are all, more or less, applicable to nuclear engineering [44]: model-based applications (e.g., fuzzy optimization, fuzzy clustering, fuzzy Petri Nets, and fuzzy multi-criteria analysis); knowledge-based applications (e.g., fuzzy expert systems, fuzzy control, and fuzzy data analysis), and information processing (e.g., fuzzy data banks and query languages, fuzzy programming languages, and fuzzy library systems).

Perhaps the most impressive fact about the present success of fuzzy logic is the breadth of application of this paradigm, ranging from consumer products to industrial process control and automotive engineering. In spite of obvious differences in scope and/or manner of implementation, fuzzy logic plays a similarly central role in creating a suitable rule-based, linguistic, control strategy. Moreover, fuzzy logic bridges the gap between symbolic processing and numeric computation, thereby expanding the domain of application of control engineering to areas that have hitherto fallen outside this scope. And specifically, fuzzy logic forms the basis for implementation of control strategies in a wider sense to include decision-making and supervisory control. Application areas in nuclear engineering are also elaborated on control in and of NPPs, safety management, accounting of nuclear waste, and nuclear energy and public opinion [44]. As a good example of nuclear application areas, Professor Wang presented his invited lecture on "Intelligent engineering and technology for nuclear power plant operation" [42]. The Three Mile Island (TMI) accident has drawn considerable attention from the engineering, scientific, management, financial, and political communities, as well as from society at large. The lecture surveys possible causes of the accident studied by various groups. Research continues in this area with many projects aimed at specifically improving the performance and operation of a NPP using the contemporary technologies available. In addition to the known cause of the accident, Professor Wang also speculated on other potential causes of the accident and suggested a strategy for coping with these problems in the future. Using the TMI experience, the paper [42] offers a set of specific recommendations for future designers to take advantage of the powerful tools of intelligent technologies that we are now able to master and encourages to adopt a novel methodology called fuzzy constraint network.

Professor Tanaka, the President of the Japan Society for Fuzzy Theory and Systems (SOFT), sent a special message to FLINS'96: *We know that higher mathematical tools would be necessary for nuclear science and engineering, safety engineering, as well as for environmental protection technology. These problems are closely related with social systems and constitute a complex problem. I am particularly pleased to see that the fuzzy system is considered as a model for such a complex field.*

In Japan, the "fuzzy" boom started from rather simple application of Fuzzy Logic Control to the electric household appliances. At present, however, Fuzzy Logic Control, which could be applied to more complex systems, is required. There are also some studies going on to introduce the possibility theory for risk analysis.

I hope that the regional study group such as SOFT and the study groups in a specialized field such as FLINS would closely co-operate with each other and that, further, all "fuzzy" communities in the widely different fields would strongly develop in their studies on the application of fuzzy theory and other advanced methodologies.

In closing my comment I sincerely pray that the FLINS'96 international workshop may create a fruitful result for the future development.

3 A survey of nuclear applications at FLINS'96

The FLINS'96 proceedings consist of a series of invited lectures by distinguished professors and individual oral presentations, in total 52 papers selected out of 80, submitted from more than 20 countries. The volume is divided into three parts. The first part (Soft Computing Techniques) provides basic tools to treat fuzzy logic, neural networks, genetic algorithms, decision-making, and software used for general soft-computing aspects. The second part (Intelligent Engineering Systems) reports on engineering problems such as knowledge-based engineering, expert systems, process control integration, diagnosis, measurements, and interpretation by soft computing. The third part (Nuclear Applications) concentrates on the applications of soft computing and intelligent systems in nuclear science and industry. We only survey here the third part on nuclear applications of fuzzy logic.

The paper by Dulin and Kiselev [6] covered the problem of storing and retrieving information from large data bases, where the information has no exact structure and different objects have very thin (or weak) relations to each other. It is one of the biggest problems in decision-support systems, especially in those spheres, where the information is complicated and very changeable. One way to solve this problem could be to build a semiotic model of the sphere according to our goals. One of the important parts of systems based on semiotic modelling is the active knowledge base supplied with the special concordance mechanism of structural consistency. The authors deal with an active knowledge base condition considered by means of connections structure analysis of knowledge base components. They examined a set of subjects with connections that have a binary existence estimate, and distinguished consonant, dissonant, and assonant sets depending on whether the consonance criterion is satisfied. They also proposed an algorithm for reducing assonant and dissonant sets to a consonance state with minimum expenditures in terms of the general number variable estimates of the connections.

Nishiwaki [22] discussed various uncertainties involved in emergency conditions, and pointed out that uncertainties in many factors are fuzzy. As a result, he proposed to use fuzzy theory as an attempt for analysing cause and effects under emergency conditions such as in Hiroshima, Nagasaki, and other nuclear accidents, and for fuzzy failure analysis and diagnostics of NPPs.

In the event of a nuclear accident, any decision on countermeasures to protect the public should be made based upon the basic principles recommended by the International Commission on Radiological Protection. The application of these principles requires a balance between the cost and the averted radiation dose, taking into account many subjective factors such as social/political acceptability, psychological stress, and the confidence of the population in the authorities. In the framework of classical methods, it is difficult to quantify human subjective judgements and the uncertainties of data efficiently. Hence, any attempt to find the optimal solution for countermeasure strategies without deliberative sensitivity analysis can be misleading. However, fuzzy sets, with linguistic terms to describe the human subjective judgement and with fuzzy numbers to model the uncertainties of the parameters, can be introduced to eliminate these difficulties. With fuzzy rating, a fuzzy multiple attribute decision-making method can rank the possible countermeasure strategies. The paper [18] described the procedure of the method and presented an illustrative example.

To improve reliability in detecting anomalies in NPP performance, Schoonewelle *et al.* [36] presented a method based on acquiring various characteristics of signal data using autoregressive, wavelet, and fractal-analysis techniques. These characteristics are combined using a decision-making approach based on fuzzy logic. This approach is able to detect and distinguish several system states.

Kanai *et al.* [13] presented an application of fuzzy linear programming methods to the optimization of a radiation shield. They investigated possibilities for reducing the radiation effects attainable in hydrated, lead- and boron-containing materials of optimal compositions using the fuzzy linear programming.

In [21], Moon and Lee presented an algorithm for autonomous wall following movement of a mobile robot. It has eight ultrasonic range transducers, and is steered by separately driving the two front wheels. A smoothing based on fuzzy sets is applied to the detected wall tracks and a cubic spline function passing through the smoothed points is computed in each step successively. The spline function is used for computing the planned path and the rotational target. A set of fuzzy control rules is used to compute the two front wheel speeds.

Liu and Ruan [19] reported an FLC scheme to improve the power control stability of the BR1 reactor at SCK•CEN. The authors discussed the various possibilities to find the best or optimal FLC scheme for controlling the BR1's power level. Some experimental results reveal that the FLC scheme has the potential to replace nuclear reactor operators in the control room. Hence, the entire control process can be automatic, simple, and effective.

Sharif Heger *et al.* [37] present a method for self-tuning of fuzzy logic controllers based on the estimation of the optimum value of the centroids of its output fuzzy set. The method can be implemented on line and does not require modification of membership functions and control rules. The main features of this method are that the rules are left intact to retain the operators' expertise in the FLC rule base, and that the parameters that require any adjustment are identifiable in advance and that their number is kept to a minimum. Therefore, the use of this method preserves the control statements in the original form. Results of simulation and actual tests show that this tuning method demonstrates a similar improvement for power up and power down experiments, based on both simulation and actual case studies. For these experiments, the control rules for the fuzzy logic controller were derived from control statements that expressed the relationships between error, rate of error change, and duration of direction of control rod movements.

Chung *et al.* [5] proposed an improved method for multiple-fault diagnosis in large-scale NPPs. The authors showed a way for getting the dominant feed-forward control loop with multi-path and also gave the corresponding fault diagnosis. As an illustration, they demonstrated the usefulness of the proposed method in the primary system of the Kori nuclear power plant unit 2.

Considering the fuzzy nature of impact signals detected from the complex mechanical structures in a NPP under operation, Oh *et al.* [23] proposed the Loose Part Monitoring System (LPMS) with a signal processing technique utilizing fuzzy logic. In the proposed

LPMS design, comprehensive relations among the impact signal features are taken into account in the fuzzy rule bases for the alarm discrimination and impact event diagnosis. The test results show that some information provided by the LPMS is easily understandable by a plant operator. Thus, the proposed approach for the loose part monitoring and diagnosis has been revealed to be effective not only in suppressing the false alarm generation but also in characterizing the metallic loose-part impact event from the aspects of Possible Impacted-Area (PIA) and Degree of Impact Magnitude (DIM) in NPPs.

In [35], Schildt described a fuzzy controller for safety-critical process control, especially for applications in the field of NPPs. One can show that the size of necessary rules is relatively small. Thus, there exists a real chance for verification and validation of software due to the fact that the whole software can be structured into standard fuzzy software (like fuzzification, inference algorithms, and defuzzification), real-time operating system software, and the contents of the rule base. The author also implemented fundamental principles of safety techniques like *dynamization principle, monitoring function,* and *watch dog function* into a special fuzzy control design. As a conclusion in [35], up to now some theoretical knowledge of *stability proof* is available so that we see a real good chance for applying a fuzzy controller in the field of safety-critical process control.

Na *et al.* [16] presented a real-time expert system which was implemented using Artificial Intelligence (AI) and object-oriented technology for alarm processing and presentation in a NPP. The knowledge base is constructed based on some schemes to process and display alarms to the plant operators. The activated alarms are dynamically prioritized by the reasoning rules, and then presented on the process mimic overview and by some other means. To demonstrate the proposed system, the alarm processing and presentation is carried out in a simulated environment of the TMI-2 accident.

The work of Guido *et al.* [9] explored some of the developing states of an *Expert Environment* (EE) for plant failures *Diagnosis Systems* starting from *Knowledge Base Systems.* The main goal of the EE is to develop a diagnosis tool performing an intelligent monitoring of some process variables, detecting system faults, and deducing the possible causes of the anomaly symptoms. The authors presented a prototype system that carries out an inspection of anomalous symptoms and a diagnosis process on a simplified model of the steam generators feed-water systems of a Pressurized-Heavy-Water Reactor (PHWR).

Nuclear power plants, like other complex systems, are involved with heterogeneous data to describe their operational state, e.g., real-time process data (analog and binary), design data, graphics, and relational data. The control room operators of these plants need tools to unify the information and presentation of these data in only one consult and navigation paradigm. Erwin *et al.* [7] described the distribution and visualization system of the Atucha I NPP in Argentina. This object-oriented system offers facilities to build, test, and use visualization screens about systems, subsystems, and components of the plant, organized in a hierarchical form to overloading the operator with information. Each object that conforms a visualization screen includes a set of inner variables associated with tags in the plant, plant design data, or other inner variables of the same or different objects. These inner variables can be used to modify the object's behavior and/or functionality. The data management system is based on a distributed system, working on a local area network using TCP protocol to receive and send data to graphical clients.

4 FLINS activities at SCK•CEN

Clearly, recent developments show that fuzzy logic is a scientific revolution that has been waiting for decades. Research in this field has reached a degree where industrial application is possible. In nuclear industry, problems such as security, maintenance, monitoring, diagnosis, and environment are all related to humans and their society, and are the most important and difficult problems. These problems are so complicated that they can hardly be solved without a global approach. Therefore, soft and intelligent computing may be one of the most powerful tools available to us.

FLINS started as a new research project, launched in line with its objective to give young talented people the opportunity to carry out future-oriented research. FLINS was initially built within one of the postdoctoral research projects at SCK•CEN. At this moment, the FLINS group consists of several engineers, especially from nuclear science, and scientists who are currently working on various projects combined with their doctoral or postdoctoral research activities. Several research topics related to nuclear applications have been discussed and are being further worked upon by the members of the group: decision-making for radiation protection by fuzzy logic [25, 38, 41], fuzzy modelling of dynamic behavior in complex systems [24], and fuzzy engineering in nuclear applications [32, 33].

The main task for FLINS for the coming years is to solve many intricate problems pertaining to the nuclear environment by using modern technologies as additional tools, and to bridge a gap between novel technologies and the industrial nuclear world. Specific prototyping of FLC of the BR1 reactor has been chosen as FLINS' first priority. This is an on-going R&D project for controlling the power level of the BR1 reactor at SCK•CEN. The project started in 1995 and aims to investigate the added value of FLC for nuclear reactors.

4.1 BR1 reactor and FLC applications

BR1 is a graphite-moderated and air-cooled reactor fuelled with natural uranium metal. Its nominal power is 4 MW but it is generally operated at 0.7 MW to reduce the air pumping cost. The reactor is available for 8 hours per day; the time utilisation factor amounts to about 80%. About 50% of this total reactor time is used at the request of industry and universities for neutron activation analysis in a variety of applications. The other activities are related to international research programs.

The model presently used for the BR1 reactor actually is the point kinetics model. It can be described by a non-linear system with a set of differential equations with six delayed neutron groups [2]:

$$\frac{dn}{dt} = \frac{\rho - \beta}{\Lambda} n + \sum_{i=1}^{6} \lambda_i c_i$$

$$\frac{dc_i}{dt} = \frac{\beta_i}{\Lambda} n - \lambda_i c_i, i = 1, \ldots, 6$$

Where
n is the neutron density at rated power (%);
c_i is the ith group precursor concentration;
β_i is the ith group delayed neutron fraction;
β is the total delayed neutron fraction;
λ_i is the ith group delayed neutron decay constant (s^{-1});
Λ is the neutron generation time (s);
ρ is the reactivity due to the control rod ($\Delta k/k$). (Note: Reactivity is defined as the difference between the effective multiplication factor and unity divided by the effective multiplication factor).

The neutron density is related to the power level, and depends on the reactivity of the reactor and the number of delayed neutrons. The control requirements of BR1 are to keep the reactivity $\rho(t)$ near zero or to exhibit a certain transient behaviour for a required power transient. At the required steady-state conditions, if $\rho(t)$ is different from zero, the controller inserts or withdraws the regulating rods to return $\rho(t)$ to zero. However, since $\rho(t)$ is not easily measurable, we use input signals such as the Difference of Power (DP) (difference between the real and the desired power) and the reactor period (T). (Period is defined as the power level divided by the rate of change of power. Thus, a period of infinity corresponds to steady state, while one is equal to a small positive number indicating a rapid power increase). For the BR1 reactor, there are two types of control rods, namely, A-rods (for the fine-tuning of reactivity, indicated as MOPA) and C-rods (mainly for the compensation of other reactivity effects, indicated as MOPC). Fine tuning is performed by 1 single A-rod while the coarse tuning is performed by 8 C-rods, all moving togather. Therefore, in the paper we identify them as A-rods and C-rods. Basically, the controller reads DP as input. This input signal is electronically transformed into an analogue command signal. Its sign and magnitude command the selection of the direction and speed of the A-rods. The controller is efficiently limited by a certain delay due to neutronics and the thermal behaviour of the reactor. Whereas FLC no longer requires an explicit model of the reactor, it can take into account the knowledge of the operators for controlling the reactor.

Whereas in the classical control of BR1, A- and C-rods are moved separately, FLC has the advantage that it allows A- and C-rods to move simultaneously. This introduces a new concept in nuclear reactor control. From the economical and safety aspects of control, the rod movements should be as small as possible. Therefore, the FLC system seems to be a better solution. The resulting output controls the motion of rods. Figure 1 is a simplified version of the BR1 controller.

The kernel of FLC is a fuzzy knowledge base in fuzzy control applications. Normally, the rules in fuzzy control can be derived from: (1) the operator's experience; or (2) the

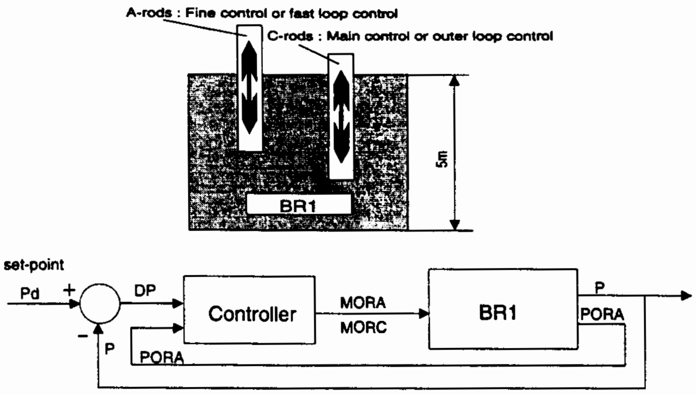


Figure 1: Two types of control rods at BR1: A-rods for the fine-tuning of reactivity (MOPA), and C-rods mainly for the compensation of other reactivity effects (MOPC).

operator's control actions; or (3) a crisp or fuzzy model of the process to be controlled, and or (4) training sets. The most common approach appears to be the first one, using the subjective input of control specialists, such as nuclear reactor operators. The second approach is used in industrial problems. As an example of the third approach, we refer to Sugeno's fuzzy control of a model car [39]. And for the fourth approach, we refer to Mamdani et al.'s implementing rule-based control of industrial processes [20]. For the BR1 project, we however use at this time both the first and second approach. Our current aim is to control the reactor in steady-state operation. According to observations and experience, if the difference between the real and the desired power (DP) is larger than 0.2 % but smaller than 0.8 %, the A-rods do not insert as far; by contrast, if DP is larger than 0.8 %the , A-rods insert further. For a negative value of DP, A-rods withdraw to an extent depending on the magnitude of the DP perturbation. This rule base remains true for as long as the A-rods have enough space to move. However, when the A-rods reach their insertion or withdrawal limit, they start to move in the opposite direction to return to their initial position. In the meantime, the C-rods are controlled to equilibrate the reactivity by slow insertion or withdrawal. This sequence of actions can be modelled in the more sophisticated rule base presented in table 1.

In this project, we aim to be of benefit to the existing control systems by applying fuzzy logic as an additional tool for both the safety and economic aspects in NPPs. Although the FLC briefly described in here is already a significant improvement compared to the classical BR1 controller due to its ability to control the A- and C-rods simultaneously and thereby expanding the dynamic control range, we believe that there is still room to further enhance the robustness of the FLC. To validate the correctness of the rule base in detail however, the closed-loop testing is necessary. The BR1 facilities will be further used to calibrate fuzzy logic technology for applications in nuclear industry. However, the licensing aspect of this technology as nuclear technology could be more

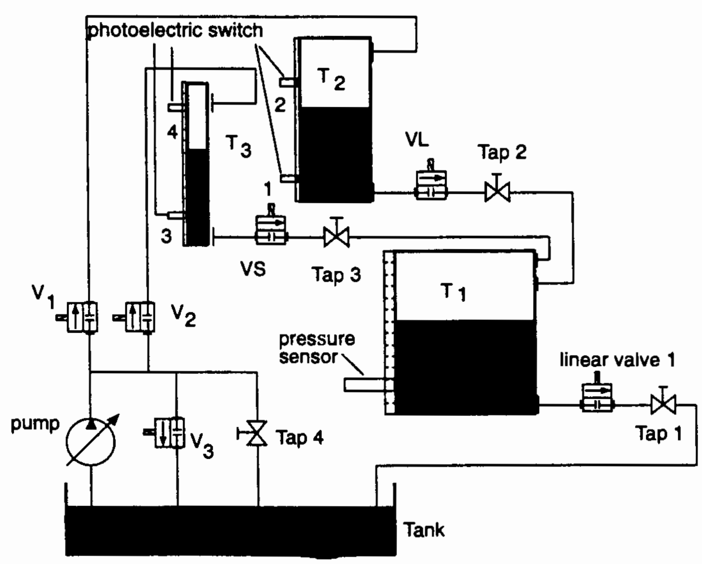
Table 1: Rule base of FLC with two inputs and two outputs

PORA	IL		NIL		AC		NWL		WL	
DP	MOPA	MOPC	MOPA	MOPC	MOPA	MOPC	MOPA	MOPC	MOPA	MOPC
NL	WB	NA	WB	NA	WB	NA	WS	WS	NA	WB
NM	WM	NA	WM	NA	WM	NA	WS	WS	NA	WS
NS	WS	NA	WS	NA	WS	NA	WS	NA	NA	WS
NZ	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PS	NA	IS	IS	NA	IS	NA	IS	NA	IS	NA
PM	NA	IS	IS	IS	IM	NA	IM	NA	IM	NA
PB	NA	IB	IS	IS	IB	NA	IB	NA	IB	NA

challenging and time consuming.

4.2 FLC demo model

Based on the background of FLC application in the BR1 reactor, we have also made a real FLC demo model 2. The demo model is suitable for us to test and compare our new algorithms of fuzzy control, because it is always difficult and time consuming due to safety aspects to do all experiments in a real nuclear environment. Particularly, this demo model is designed to simulate the power control principle of BR1 [17].



The Demo Model Structure

Figure 2: The working principle of the demo model

This demo model for the water level control has been made at SCK•CEN in cooperation with OMRON Belgium. It is made of transparent plexiglass material with coloured water inside, and it is a good visual equipment for testing different control algorithms, especially for fuzzy logic control strategy.

The demo model consists of two parts. One is the water level control system including one tank, three towers, five sensors, valves and pipes. Another is a box in which electrical control elements are installed such as PLC, Fuzzy unit, A/D & D/A unit, and power supply etc.

In this demo system, our goal is to control the water level in tower T_1 at a desired level by means of tuning VL (the valve for large control tower T_2) and VS (the valve for small control tower T_3). The pump keeps on working to supply water to T_2 and T_3. All taps are for manual tuning at this time. V_1 and V_2 are used to control the water levels in T_2 and T_3 in some areas. For example, when the water level in T_2 is lower than photoelectric switch sensor 1 the on-off valve V_1 will be opened (on), and when the water level in T_2 is higher than photoelectric switch sensor 2 the on-off valve V_1 will be closed (off). The same is true of V_2. Only when both V_1 and V_2 are closed will V_3 be opened, because it can decrease the pressure of the pump and prolong its working life. So far we have not used the linear valve 1. It will be used in simulating some complex system. The pressure sensor is used to detect the height of water level in T_1. So for T_1, it has two entrances and one exit for water flow. This is a typical dynamic system, and it is very difficult to control it by a traditional way [17].

For this tower T_1, see Figure 3, it has an infow and an outflow. Suppose the height of the water is h, the size (area) of water is A and the size of output hole is a, we may find the basic relationship between the inflow and the outflow. The basic function is:

$$\frac{Adh}{dt} = inflow(t) - outflow(t)$$

$$\frac{Adh}{dt} = f(t) - ka\sqrt{2gh}$$

where $outflow(t) = ka\sqrt{2gh}$ and k is a constant coefficient. In the current demo model, however,

$$f(t) = f_1(t) + f_2(t),$$

where $f_1(t)$ is the outflow of T_2 and $f_2(t)$ is the outflow of T_3, and they are nonlinear variables with some random disturbance. So the system is a nonlinear and time varying system.

In this system, we choose D and DD as inputs of the fuzzy logic controller, and VL and VS as the outputs of the fuzzy logic controller, where $D = P - S$, that is, Difference (D) between the practical value (P) of water level and the set value (S). $DD = D(t) - D(t-1)$, that is, Derivative of D (DD), in other words, the speed and direction of the change of water level. VL and VS represent the current signal to VL (large valve) and VS (small valve), respectively.

Table 2 contains all control rules. In this table, for example, PL/ZE at row 2 and column 3 means: if D is NS and DD is NL then VL is PL and VS is ZE. In other words, if the practical water level is *a little lower* (NS) than the desired level and the speed of the water level *falling down* is *large* (NL) then VL will *open largely* (PL) and VS will *not change* (ZE).

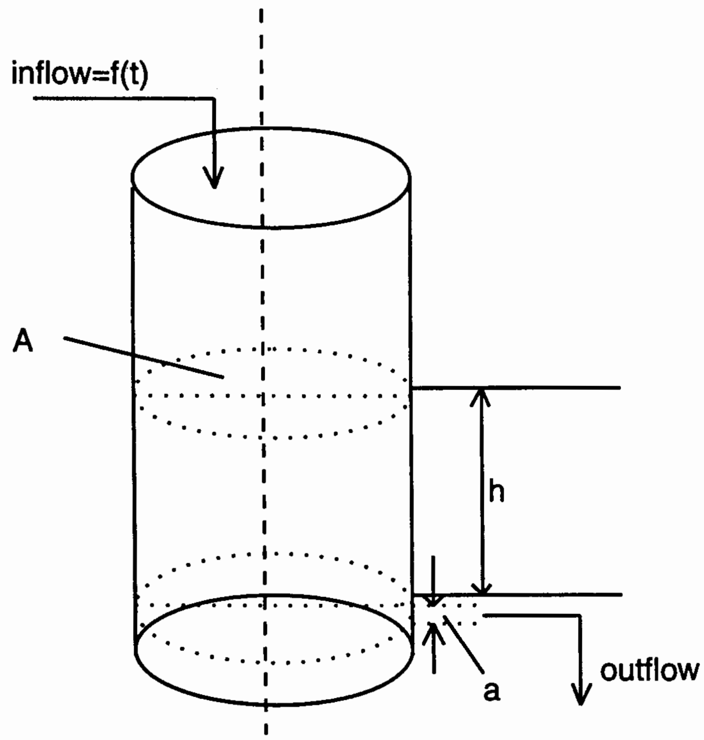


Figure 3: The dynamic analysis of the tower

With the help of the fuzzy control rules in Table 2, we get the control effect illustrated in Figure 4 (the thick curve). In this figure, the thick curve records the trajectory of the water level in T_1. From 0-5 minutes, the set value is 15 cm (S1=15); from 5-10 minutes, the set value is 25 cm (S2=25); from 10-15 minutes, the set value is 15 cm (S3=15). This is the best result of all experimental tests. Before this result, normally, we always find the control effect is either curve a or b. Curve a means a big overshot but with a fast response. Curve b means no overshot but with a slow response. It is well known that it is difficult to achieve a control result with a fast response and no overshot. Our result has already overcome this dilemma.

5 Concluding Remarks

As pointed out in [43], the nuclear power industry puts special demands on plant safety, surpassing all other industries in its safety culture. The regulatory environment in which nuclear power plants operate reflect these needs, and also the demands of the public for high levels of assurance about safety and regulatory compliance. This culture is not one which encourages innovation in control systems and philosophy, yet

Table 2 Control rule table

DD\D	NL	NS	ZE	PS	PL
NL	PL/ZE	PL/ZE	PL/ZE	PS/ZE	PS/ZE
NS	PL/ZE	PL/ZE	PS/NS	PS/PS	PS/NS
ZE	PL/ZE	PS/PS	ZE/ZE	NS/PS	NS/PS
PS	PS/ZE	ZE/NS	NL/ZE	NL/NL	NL/NL
PL	ZE/ZE	NL/NL	NL/ZE	NL/NL	NL/NL

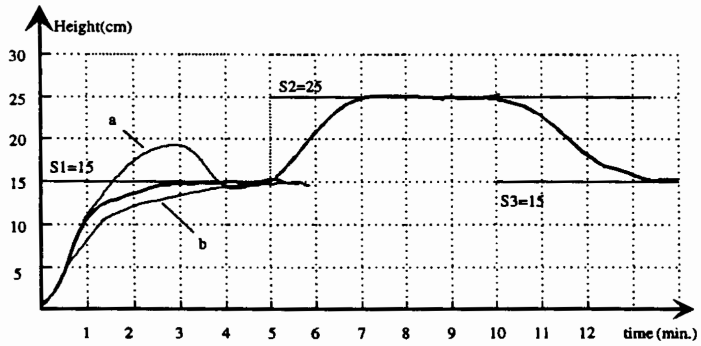


Figure 4: The trajectory of fuzzy logic control water level

nowhere are there greater potential benefits from high reliablility systems, automated fault recognition and rationally supported decision making. A demonstration of the use of intelligent control in an actual plant is a vital needed step in prototyping the next generation of nuclear power plants. These must prove not only the ability to safe survive major disturbances, but also the ability to operate efficiently and reliably in normal operation and to recover smoothly from the minor events that will occur on a regular basis, without challenge to future operations.

In this paper, we report the real R&D project on fuzzy logic application to the BR1 research reactor as a test bed. We aim to be of benefit to the existing control systems by applying fuzzy logic as an additional tool for both the safety and economic aspects in nuclear power plants. Although the FLC described in this paper is already a significant improvement compared to the classical BR1 controller due to its ability to control the A- and C-rods simultaneously and thereby expanding the dynamic control range, we believe that there is still room to further enhance the robustness of the FLC. To validate the correctness of the rule base in detail however, the closed-loop testing is necessary. The BR1 facilities will be further used to calibrate fuzzy logic technology for applications in nuclear industry. However, the licensing aspect of this technology as nuclear technology could be more challenging and time consuming.

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