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CHINA NUCLEAR SCIENCE & TECHNOLOGY REPORT

中国先进反应堆评价模型及分析

COMPARISON AMONG DIFFERENT DEVELOPMENT WAYS OF ADVANCED REACTORS IN CHINA

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中国先进反应堆评价模型及分析

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摘　要

面向21世纪的核能发展，从快中子增殖堆、高温气冷堆及混合堆三种堆型中，中国将研究开发一种能大幅度提高核燃料利用率、安全性与经济性好的堆型。考虑到先进堆评价涉及到很多不确定和较难量化的因素，采用了层次分析法(AHP)和专家咨询法。在层次分析法的指标体系中，选取了4个主要指标：安全性、技术成熟度、经济性和适用性。在广泛征求了专家们的意见和大量调研了国内外文献基础上，选取了氧化物燃料快堆、金属燃料快堆、铀燃料高温气冷堆、铀-钍循环高温气冷堆和混合堆的评价参数，并作了综合评价和排序。同时邀请了130位在政府部门和学术研究部门工作的专家和权威，对先进堆的发展进行了咨询。咨询答卷的回收率达到86%。并对咨询数据进行了计算机处理。从上述两种方法的评价结果中可以得到如下结论：快堆，特别是金属燃料快堆应成为中国21世纪核能发展的主要堆型。

COMPARISON AMONG DIFFERENT DEVELOPMENT WAYS OF ADVANCED REACTORS IN CHINA

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ABSTRACT

For the development of nuclear energy in the 21st century, China will select a new type reactor to develop which will have higher fuel efficiency, high safety and better economy. The selection is among the types of FBR (fast breeder reactor), HTGR (high temperature gas-cooled reactor) and FFHR (fusion-fission hybrid reactor). Since the evaluation of advanced reactors involves many uncertain factors and the difficulty of quantization, both the AHP (analytic hierarchy process) method and expert consultation are adopted. Four aspects are taken in the norm system of AHP, i. e. safety, maturity of technology, economy and appropriateness. By using questionaire method to experts and studying related documents, five types of advanced reactor are selected which are oxide fueled FBR, metal fueled FBR, uranium fueled HTGR, U-Th fueled HTGR and FFBR. Their evaluation parameters are comprehensively assessed and sorted. About 130 experts and professors who have been working in the research institutes and government agencies of nuclear field are asked to give their comments on the development of advanced reactors. The response rate of questionaries is 86%, and the data collected are processed by computers. From the evaluation result of AHP method and expert consultation the fast breeder reactor, especially, the metal fueled FBR, should have the priority in nuclear energy development in the 21st century in China.

INTRODUCTION

The China's primary energy production was about one billion TCE in 1989, but only 0. 87 TCE was China's primary energy consumption per capita, which was about one third of that of the world in the same year. From the points of view of the experts, China's primary energy consumption will reach 5 billion TCE in 2050, which is about 5 times as much as that in 1989. It is no doubt that developing nuclear energy is the vital key to solve the energy problem in the next century, Because of that the fossil and hydraulic resources per capita in China are not plentiful. In 1986 Chinese government drafted a high technology plan. As the resource-utilization efficiency of PWR is low, in order to meet the nuclear energy development in the 21st century, the decision was made in the plan to choose an advanced reactor, which should be safe, economical and of high resource-utilization efficiency and will be the major direction of China's nuclear energy development in 21st century, among Fast Breeder Reactor, High Temperature Gass-Cooled Reactor and Fusion-Fission Hybrid Reactor.

In 1980, Canadian Mr. Gritoph E. put foward a model of evaluating breeder and near-breeder systems[1]. A "merit function" was constituted in this model and was used as an evaluation criterion. The function calculated the discounted present value of the cumulative saving is realized by using the nuclear rather than non-nuclear source. He evaluated such reactor systems as Light Water Reactor, Canada Deuterium Uranium Reactor and Liquid Metal Fast Breeder Reactor by comparing the discounted present value of each reactor.

Not only the resource- utilization efficiency and economy but also technology maturity, application, safety and other factors will be considered when we evaluate FBR, HTGR, FFHR. Because the technology maturity of the three kinds of advanced reactors evaluated are quite different and none of them is commercially utilized now, if we only employ the "merit function", the influence of uncertain factors will increase and the results will be not true to the original. There is another important factor which can not be ignored, i. e. the influence of technology maturity upon the development speed of the advanced reactors. This also can't be described by the "merit function".

Considering the fact that it is difficult for the general econometrics methods to deal with quantitative study of uncertain factors, we adopted Analytic Hierarchy Process and expert consultation.

Analytic Hierarchy Process was put forward by the American operation research expert Thomas L. Saaty by the end of 1970's whi h is a comprehensive evaluation model applied in the systems of multiple hierarchies and multiple norms[2,3]. Owing to the development of economy, science and society, many factors which can not be quantitatively described but qualitatively described have been involved in such researching fields as society, economy, management and organization behavior, psychology, etc. Nevertheless, so as to make an optimal choice, the qualitative analysis is needed on one hand and the quantitative analysis on the other. AHP has given full play in the qualitative analysis and quantitative analysis of such kind system which is formed of many relating and interacting elements.

The major characteristic of AHP is that it can comprehensively analyse the system evaluated, divide the norms of the system into hierarchies in line with their logical relations and interacting properties and finally, get the evaluation results by evaluating and quantitating the more concrete norms. The advanced reactor development concerns many complicated factors such as policy, technology, economy, safety, resource. Some of them even are difficult to directly quantitated. In addition to AHP, expert consultation has been carried out, and the results of the two methods are completely consistent in this paper. We can conclude from the results that it is the inexorable and optimal choice for China to develop Fast Breeder Reactors especially Metal Fueled FBR in the next century.

1 ANALYTIC HIERARCHY PROCESS AND RESULTS

1.1 The Norm System

As we mentioned above, the influence of every factor needs to be comprehensively considered when we evaluate the advanced reactors. In the light of interacting properties and logical relations among the factors of the systems evaluated, we divide the different factors into several hierarchies. The norm system is described as Fig 1.

The norm system is divided into five hierarchies. Hierarchy A is target hierarchy, it expresses the comprehensive evaluation value of each advanced reactor. Hierarchy B is criterion hierarchy. Hierarchy C is norm hierarchy, as well as hierarchy D. Hierarchy E is scenario hierarchy. Oxide Fueled FBR, Metal Fueled FBR. Uranium Fueled HTGR, U-Th Fueled HTGR and FFHR are taken as the reactor types to be chosen in the scenario

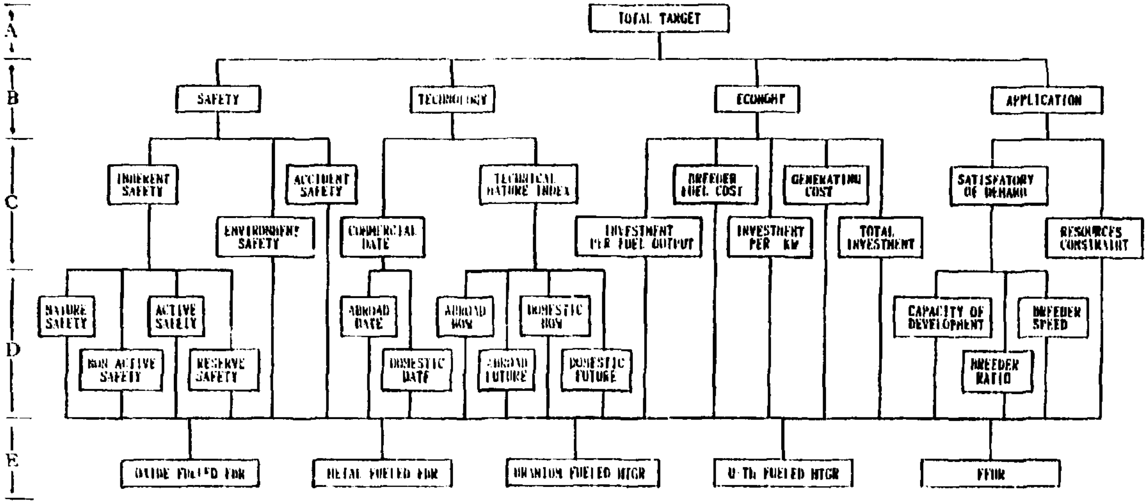

Fig. 1 The norm system of the hierarchy analysis process

A—the target hierarchy; B—the criterion hierarchy;

C—the first norm hierarchy; D—the second norm hierarchy; E—the scenario hierarchy.

hierarchy. The criteria of hierarchy B are SAFETY, TECHNOLOGY, ECONOMY, APPLICATION. Hierarchy D is the sub-norm hierarchy of C which is the sub-norm hierarchy of B. For instance, COMMERCIAL DATE and TECHNICAL MATURITY of hierarchy C are the sub-norms of TECHNOLOGY——the norm of hierarchy D, they also have sub-norms—— ABROAD DATE, DOMESTIC DATE and ABROAD NOW, ABROAD FUTURE, DOMESTIC NOW, DOMESTIC FUTURE—— which belong to hierarchy D. ABROAD DATE represents abroad commercial utilization date, ABROAD NOW represents abroad technical maturity now. The others can be deduced from the above explanation.

1.2 The Judgment Matrices

One of the important steps in AHP is to constitute the pairwise comparison judgment matrices of every norm hierarchy. In this paper, the parameters of the judgment matrices were determined by effectively taking advantage of the available data and information. The uncertain factors in the advanced reactor development have been forecasted and estimated, too. At the same time we have tried hard to decrease the influence of the uncertain factors upon the results and make full use of the differences among the certain norms of the different advanced reactors. So the results will tend to more rational.

On the basis of extensively soliciting the opinions from the experts and according to the estimation in the period between 1990~2050 in which we considered[4~7], we have assigned the values to the parameters.

It does not need to take the dimension relations of the norms into account through the process of assigning the values to the parameters and calculating the results. This is a characteristic of AHP.

Now the judgment matrices are given in Table 1 to Table 9.

The numerical values of Table 1 are the measures of the relative importance of the norms. In this model, the ratio scale 1~9 are adopted as the reflection of the relative importance between every two norms. The numbers 1, 3, 5, 7, 9 are separately defined as that a norm has eaqual importance, moderate importance, strong importance, demonstrated importance and absolute importance, compared to another norm. 2, 4, 6, 8 are the intermediate values between the two adjacent judgments. In the matrices, reciprocals of all scaled ratios that are >1 or $=1$ are entered in the transpose position, i.e. when above nonzero numbers are assigned to norm i compared with norm j, then norm j has reciprocal value when compared with norm i. So we can get a series of values which

< 1.

Table 1 The judgment matrix of A TOTAL TARGET

CRITERION	B1 SAFETY	B2 TECHNOLOGY	B3 ECONOMY	B4 APPLICATION	EIGENVECTOR
B1 SAFETY	1	1/3	1/3	1/2	0.174
B2 TECHNOLOGY	3	1	1	2	0.295
B3 ECONOMY	3	1	1	2	0.282
B4 APPLICATION	2	1/2	1/2	1	0.249

In Table 1 the values of the first column have the meanings as follows:

The first row is 1, which means that SAFETY has equal importance compared with SAFETY. The second and the third row are 3, which mean that TECHNOLOGY and ECONOMY have moderate importance compared with SAFETY. The fourth row is 2, which means that APPLICATION has the importance bewteen that of TECHNOLOGY and ECONOMY compared with SAFETY. The values of the first row are the reciprocals in the transpose positions of the first column. The meanings of the other values are on the analogy of this.

Now we give the reasons of assigning the above values. The safety of the advanced reactors are higher than that of PWR which has come up to the nuclear safety standards being set now. Therefore the relative importance of SAFETY decreases. Naturally TECHNOLOGY, ECONOMY, APPLICATION become the principal factors to affect the advanced reactor development, which makes the relative importance of them increase.

The weights of the four norms of hierarchy B are obtained by calculating the eigenvector of the judgment matrix, which are 0.174, 0.295, 0.282, 0.249. After that the consistency of the pairwise comparison judgment matrix is tested.

Table 2 and Table 3 are the pairwise comprison matrices relating SAFETY. The norm INHERENT SAFETY has more relative importance when it is taken as a sub-norm of norm B1 SAFETY, as INHERENT SAFETY produces an great impact on the vitality of the advanced reactors.

Table 2 The judgment matrix of B1 SAFETY

NORM	C1 INHERENT SAFETY	C2 ENVIRONMENT SAFETY	C3 ACCIDENT SAFETY	EIGENVECTOR
C1 INHERENT SAFETY	1	3	3	0.6
C2 ENVIRONMENT SAFETY	1/3	1	1	0.2
C3 ACCIDENT SAFETY	1/3	1	1	0.2

Table 3 The judgment matrix of C1 INHERENT SAFETY

NORM	D1 NATURE SAFETY	D2 NON-ACTIVE SAFETY	D3 ACTIVE SAFETY	D4 RESERVE SAFETY	EIGEN-VECTOR
D1 NATURE SAFETY	1	5	7	5	0.636
D2 NON-ACTIVE SAFETY	1/5	1	3	2	0.182
D3 ACTIVE SAFETY	1/7	1/3	1	1/2	0.068
D4 RESERVE SAFETY	'/5	1/2	2	1	0.115

Tables 4, 5, 6 are the pairwise comparison matrices about TECHNOLOGY. COMMERCIAL DATE is an essential factor which has much to do with the commercially utilizing the advanced reactors. Even DOMESTIC DATE is the decisive factor. Not only the domestic condition and the international condition but the tendency of the development and the growing speeds of technical maturity of the advanced reactors in the next 60 years need to be considered.

Table 4 The judgment matrix of B2 TECHNOLOGY

NORM	C4 COMMERCIAL DATE	C5 TECHNICAL MATURITY INDEX	EIGENVECTOR
C4 COMMERCIAL DATE	1	2	0.667
C5 TECHNICAL MATURE INDEX	1/2	1	0.333

Table 5 The judgment matrix of C4 COMMERCIAL DATE

NORM	D5 ABROAD DATE	D6 DOMESTIC DATE	EIGENVECTOR
D5 ABROAD DATE	1	3	0.25
D6 DOMESTIC DATE	1/3	1	0.75

Table 6 The judgment matrix of C5 TECHNICAL MATURITY INDEX

NORM	ABROAD NOW	ABROAD FUTURE	DOMESTIC NOW	DOMESTIC FUTURE	EIGEN-VECTOR
D7 ABROAD NOW	1	1/2	2	1/3	0.147
D8 ABROAD FUTURE	2	1	5	1/2	0.290
D9 DOMESTIC NOW	1/2	1/5	1	1/7	0.070
D10 DOMESTIC FUTURE	3	2	7	1	0.493

In Table 7, GENERATING COST is the most important one compared with the other norms which belong to norm ECONOMY, the reason is that it is of critical importance to the competitive ability of the advanced reactors on energy market.

INVESTMENT PER FUEL OUTPUT and BREEDER FUEL COST represent some aspects of the breeder fuel economics of the advanced reactors.

Table 7 The judgment matrix of B3 ECONOMY

NORM	C6	C7	C8	C9	C10	EIGENVECTOR
C6 INVESTMENT PER FUEL OUTPUT	1	1/2	1/3	1/5	1/3	0.066
C7 BREEDER FUEL COST	2	1	1/2	1/3	1/2	0.114
C8 INVESTMENT PER KW	3	2	1	1/2	1	0.232
C9 GENERATING COST	5	3	2	1	4	0.429
C10 TOTAL INVESTMENT	3	2	1/2	1/4	1	0.158

Table 8 and Table 9 are the pairwise comparison matrices about APPLICATION. In the period between 1990～2050, the development of the advanced reactors is for the sake of meeting the demand of energy as well as possible. Therefore the relative importance of SATISFACTORY OF DEMAND increases. RESOURCE CONSTRAINT concerns many uncertain factors, such as uranium deposit which can be economically exploited, fuel recycle, fuel reprocessing, active fuel fabrication, etc. In order to simplify the norm system, and due to wanting of data, only the major factor—— constraint effect of resource deposit on the advanced reactor development is taken into account. The relative importance of resource constraint is not strong. This is ascribe to the above factors and that China's energy system is an open system.

Table 8 The judgment matrix of B4 APPLICATION

NORM	C11 SATISFACTORY OF DEMAND	C12 RESOURCE CONSTRAINT	EIGENVECTOR
C11 SATISFACTORY OF DEMAND	1	2	0.667
C12 RESOURCE CONSTRAINT	1/2	1	0.333

Table 9 The judgment matrix of C11 SATISFCTORY OF DEMAND

NORM	D11 CAPACITY OF DEVELOPMENT	D12 BREEDER RATIO	D13 BREEDER SPEED	EIGE-NVECTOR
D11 CAPACITY OF DEVELOPMENT	1	3	5	0.648
D12 BREEDER RATIO	1/3	1	2	0.230
D13 BREEDER SPEED	1/5	1/2	1	0.122

We can get the weights by calculating the matrices. All the comprehensive weights were together shown in Table 10.

Table 10 The comprehensive weight of each norm

CRITERION B	B1	B2	B3	B4	NORM D	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13
NORM C					WEIGHTS OF NORM C													
C1	0.6				0.105	0.64	0.18	0.07	0.11									
C2	0.2				0.035													
C3	0.2				0.035													
C4		0.67			0.197					0.25	0.75							
C5		0.33			0.098							0.15	0.29	0.07	0.49			
C6			0.07		0.019													
C7			0.13		0.032													
C8			0.17		0.065													
C9			0.49		0.121													
C10			0.15		0.044													
C11				0.67	0.083											0.65	0.23	0.12
C12				0.33	0.166													
WEIGHTS OF CRITERION B	0.17	0.30	0.28	0.25	WEIGHTS OF NORM D	0.07	0.02	0.01	0.01	0.05	0.15	0.01	0.03	0.01	0.05	0.11	0.04	0.02

From Table 10 and Fig. 1, we can know that the evaluating marks of C9, D6, D11, i.e. GENERATING COST, DOMESTIC COMMERCIAL DATE and CAPACITY OF DEVELOPMENT play an important role in TOTAL TARGET. In fact the three norms reflect the critical factors of ECONOMY, TECHNOLOGY, and APPLICATION of advanced reactors. That keeps with the realistic conditions.

1. 3 Comparison of the Advanced Reactors

Having consulted many referances[4~14] of our country and of other countries, and consulted many experts, we evaluate the norms by using mark scale 0~100, as Table 11.

Table 11 The evaluation value of each norm

REACTOR TYPE	OXIDE FUELED FBR	METAL FUELED FBR	URANIUM FUELED HTGR	U-Th FUELED HTGR	FFHR
ENVIRONMENT SAFETY	80.0	80.0	80.0	80.0	60.0
ACCIDENT SAFETY	80.0	80.0	80.0	80.0	65.0
INVESTMENT PER FUEL OUTPUT	60.0	90.0	0.0	40.0	90.0
BREEDER FUEL COST	70.0	95.0	0.0	40.0	60.0
INVESTMENT PER KW	80.0	90.0	80.0	60.0	50.0
SYSTEM GENERATING COST	80.0	90.0	80.0	60.0	20.0
TOTAL INVESTMENT	85.0	80.0	70.0	20.0	5.0
RESOURCE CONTRAINT	80.0	90.0	10.0	60.0	95.0
NATURE SAFETY	90.0	90.0	90.0	90.0	70.0
NON-ACTIVE SAFETY	80.0	80.0	80.0	80.0	50.0
ACTIVE SAFETY	85.0	95.0	85.0	85.0	85.0
RESERVE SAFETY	90.0	90.0	90.0	90.0	60.0
ABROAD COMMERCIAL DATE	90.0	85.0	60.0	5.0	3.0
DOMESTIC COMMERCIAL DATE	80.0	95.0	60.0	0.0	0.0
ABROAD TECHNICAL NOW	90.0	60.0	70.0	5.0	2.0
ABROAD TECHNICAL FUTURE	90.0	90.0	80.0	5.0	2.0
DOMESTIC TECHNICAL NOW	30.0	15.0	30.0	3.0	1.0
DOMESTIC TECHNICAL FUTURE	60.0	90.0	60.0	0.0	1.0
CAPACITY OF DEVELOPMENT	60.0	95.0	10.0	3.0	2.0
BREEDER RATIO	60.0	90.0	0.0	40.0	95.0
BREEDER SPEED	60.0	95.0	0.0	5.0	10.0

The experts deemed highly of the advanced reactor safety, compared with PWR. Some experts regard that it is easy to some degree to evaluate the safety of FBR and HTGR. As to FFHR, some experts insisted that its safety is high, as result of the subcriticality of its wrapper, however, some experts held that it is in potential danger, because it is possible for a part of its wrapper to reach criticality once led by some causes, there is no corresponding facility to guard. Therefore its safety still needs to be detected. After comprehensively considering the experts' opinions, we gave slightly low marks to SAFETY of FFHR, and that of the others are nearly same.

A new fuel cycle will need to be constructed if U-Th Fueled HTGR is developed, which will result in increasing the investment greatly. Then its evaluation mark of ECONOMY is relatively low. Uranium Fueled HTGR can not breed nuclear fuel, so its norms about breeder fuel were evaluated as zero mark. The breeder properties of Metal Fueled FBR and FFHR are the best of them, even the economy is better in former case. According to the economic evaluation of Metal Fueled FBR by the American experts[4,13,14], the investment per generating unit and other economics norms will be competitive with PWR in the early stage of next century, and some of them will be even better than that of PWR. So ECONOMY norms of Metal Fueled FBR were given higher evaluation marks. The total investment of FFHR before commercial utilization is much more great than that of the others, and FFHR couldn't be commercially utilized before 2050, so its ECONOMY norms were given lower evaluation marks.

The advanced reactors are at various stages of development. Oxide Fueled FBR is at the stage of commercial demonstration. Some American experts, Japanese experts and Chinese experts reckon Metal Fueled FBR as main advanced reactor type, because of its good breeder properties. The Metal Fueled FBR evaluatioin marks of COMMERCIAL DATE, the norms about technology development in further are relatively higher. On the other hand, the development prospects of U-Th Fueled HTGR and FFHR are limited (by the year of 2050). So the corresponding evaluation marks are lower.

Generally speaking, it is not possible for FFHR to develop to commercial stage in the considering period, so its satifying ability of nuclear energy development is not good. On the contrary, FBR has good properties in APPLICATION and the evaluation marks are higher.

On the basis of the weights noted in Table 10 and evaluation marks noted in Table 11, we obtained the priority of the advanced reactors by calculation, as Table 12.

Table 12 The evaluation results

REACTOR TYPE	OXIDE FUELED FBR	METAL FUELED FBR	URANIUM FUELED HTGR	U-Th FUELED HTGR	FFHR
EVALUATION RESULTS	76.6	89..0	52.9	36.0	33.0
ORDER	2	1	3	4	5

According to the result Table, the comprehensive evaluation results of FBR are the best. If safety, economy, technology and other factors are considered, FBR should give a priority of development. As a result of fast breeder speed and low cost, the scenario of choosing Metal Fueled FBR as the main advanced reactor type in the next century in China is the optimal one. The comperhensive evaluation result of FFHR is the smallest. Under the condition of lacking energy construction fund, it is not practical for China to develop FFHR ahead of time. Uranium Fueled HTGR has its unique characteristics in high temperature heat providing. It can be a complement of the China's advanced reactor development scenario. It is unreasonable for China to develop U-Th Fueled HTGR beyond time and fund, for there are many technological and economical problems to solve if China build an industry system of U-Th fuel cycle.

2 EXPERT CONSULTATION

Expert consultation has widely been used in decision-making process. As we know, the Delphi model in prognostics was based on this method.

We selected some controversial questions and different representive opinions as consult questions (totalled 12 items) which have been existing in advanced reactor research field of our country recently.

First of all, a rational choice on experts should be made carefully when we began to consult experts. In our case, the expert colony whose knowledge range could cover various fields of nuclear industry were seleced. 130 experts were invited to take part in the consult investigation and 112 experts answered. They have been holding key posts of government and nuclear industry, such as, some of them work at Ministry of Energy, Research Center for Economic Technologcal and Social Development of State Council of P. R. China, State Planning Committee, China National Nuclear Corporation, and some of them work at research and design institutions, universities, nuclear power plants, etc. In consultation we specially asked those who care about the development of our country's nuclear industry and the problem that our country's nuclear industry is facing with currently. Most experts have been engaged in the work of nuclear industry for more than 30 years. Through long term practice they have become famous professors, senior or general engineers. They not only have abundant experience of practice but also have their own original views. So, they can be regarded as a group of experts with the authoritativeness, representativeness, and extensiveness. The ages of them were between 45~82 years old, and the average age was 56. It is to be mentioned that so wide expert consultion was the first one in our country's nuclear industry field.

The information from the consultation was processed by using personal computer. The statistical figures are listed in the following three parts.

2.1 The Statistics of Experts' Views

In this part, the statitstical figure of each question was shown with percentage of three different statements in Table 13: agreement, abstention and disagreement.

Table 13 Expert consultaton statistical figures

CONSULT CONTENTS	AGREEMENT	ABSTENTION	DISAGREEMENT	INDEX
1. Economics of FBR is better	75	13.4	11.6	82
2. Economics of HTGR is better	31.3	13.4	56.3	38
3. Economics of FFHR is better	18.8	13.4	67.8	25
4. Safety of FBR is better	67.0	8.9	24.1	71
5. Safety of HTGR is better	52.7	8.9	38.4	57
6. Safety of FFHR is better	25.9	8.9	65.2	30
7. Developing advanced reactor should focus on FBR	71.4	14.3	14.3	79
8. Developing advanced reactor should focus on HTGR	11.6	14.3	74.1	19
9. Developing advanced reactor should focus on FFHR	6.3	14.3	79.5	13
10. Building experiment reactor should select FBR	72.3	15.2	12.5	80
11. Building experiment reactor should select HTGR	10.7	15.2	74.1	18
12. Building experiment reactor should select FFHR	3.6	15.2	81.2	11

2.2 The Comprehensive Evaluation of Experts' Views

First, set up matrix about the results of consultation, usually, it can be expressed as follows:

$$B = \begin{array}{r} \\ \text{ques. 1} \\ \text{ques. 2} \\ \cdot \\ \cdot \\ \cdot \\ \text{ques. } n \end{array} \begin{bmatrix} \text{ccass 1} & \cdots & \cdots & \text{class } k \\ b_{11} & b_{12} & \cdots & b_{1k} \\ b_{21} & b_{22} & \cdots & b_{2k} \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ b_{n1} & b_{n2} & & b_{nk} \end{bmatrix} \quad (1)$$

Where the element b_{ij} represents the total number of experts who estimate question " i " at " j " class.

In our case, the experts' views were classified into three classes, i. e. $k = 3$, to which three different estimation values : 1. 0, 0. 5, 0. 0 were assigned, representing three kinds of attitude of experts for each question separately, that is, agreement, abstention and disagreement. If there are m experts to attend consultation, the evaluation index vector can be determined as follows:

$$R = (1.0,\ 0.5,\ 0.0) \times 1/m \times B' \quad (2)$$

Where B' is a transposed matrix of matrix B. In our case, $m = 112$, $n = 12$, $k = 3$, then the evaluation index vector can be calculated with Eq. (2), shown as follows:

$$R = (r_1,\ r_2, \cdots \cdots r_{12}) = (1.0,\ 0.5,\ 0.0) \times 1/112$$

$$\times \begin{bmatrix} 84 & 35 & 21 & 75 & 59 & 29 & 80 & 13 & 7 & 81 & 12 & 4 \\ 15 & 15 & 15 & 10 & 10 & 10 & 16 & 16 & 16 & 17 & 17 & 17 \\ 13 & 62 & 76 & 27 & 43 & 73 & 16 & 83 & 89 & 14 & 83 & 91 \end{bmatrix} \quad (3)$$

$$= (82,\ 38,\ 25,\ 71,\ 57,\ 30,\ 79,\ 19,\ 13,\ 80,\ 18,\ 11)$$

The evaluation index for each question is shown in Table 13.

2. 3 The Comprehensive Estimation on Three Types of Advanced Reactor

There were four respects involved in consult questions according to which the three types of reactor were contrasted, that is, a. economy; b. safety; c. developing tendency; d. experiment reactor's priority. The comprehensive estimation value of each type of advanced reactor was obtained by summing up all of the experts' opinions in accordance with the above four respects. In result, further comparsions among the three types of reactor were made.

It is obvious that the four factors should be weighted with different value. The more important the factor is, the bigger the weight is. A weight vector W was introduced: $W = (w_1, w_2, w_3, w_4)$. Then the comperhensive estimation value of each advanced reactor $V(i)$ was calculated with $R \times W$.

In our case, the vector W was supposed as : $W = (0.2, 0.2, 0.3, 0.3)$, meanwhile, the R for each type of reactor can be gυten from Eq. (3):

$$R(\text{FBR}) = \begin{bmatrix} r_1 \\ r_4 \\ r_7 \\ r_{10} \end{bmatrix} = \begin{bmatrix} 82 \\ 71 \\ 79 \\ 80 \end{bmatrix}$$

$$R(\text{HTGR}) = \begin{bmatrix} r_2 \\ r_5 \\ r_8 \\ r_{11} \end{bmatrix} = \begin{bmatrix} 38 \\ 57 \\ 19 \\ 18 \end{bmatrix}$$

$$R(\text{FFHR}) = \begin{bmatrix} r_3 \\ r_6 \\ r_9 \\ r_{12} \end{bmatrix} = \begin{bmatrix} 25 \\ 30 \\ 13 \\ 11 \end{bmatrix}$$

The value of comprehensive estimation for each type of reactor was shown as follows:

$$V(\text{FBR}) = (w_1, w_2, w_3, w_4) \times \begin{bmatrix} r_1 \\ r_4 \\ r_7 \\ r_{10} \end{bmatrix}$$

$$= (0.2, 0.2, 0.3, 0.3) \times \begin{bmatrix} 82 \\ 71 \\ 79 \\ 80 \end{bmatrix} = 78$$

$$V(\text{HTGR}) = (w_1, w_2, w_3, w_4) \times \begin{bmatrix} r_2 \\ r_5 \\ r_8 \\ r_{11} \end{bmatrix}$$

$$=(0.2,\ 0.2,\ 0.3,\ 0.3)\times\begin{bmatrix}38\\57\\19\\18\end{bmatrix}=30$$

$$V(\text{FFHR})=(w_1,\ w_2,\ w_3,\ w_4)\times\begin{bmatrix}r_3\\r_6\\r_9\\r_{12}\end{bmatrix}$$

$$=(0.2,\ 0.2,\ 0.3,\ 0.3)\times\begin{bmatrix}25\\30\\13\\11\end{bmatrix}=18$$

Because the determination of weight was completely dependent on people's understanding of the relation between influential factors and expounded issue. So, some artificial effect on value $V(i)$ would be created in analysing. How much the influence on $V(i)$ would be ? It was explained through calculating several values of V with various weights. The results are shown in Table 14.

Table 14 Weight's influence on advanced reactor's comprehensive evaluation

NO.	WEIGHT COEFFICIENT				CALCULATION RESULTS		
	w_1	w_2	w_3	w_4	V (FBR)	V (HTGR)	V (FFHR)
1	0.25	0.25	0.25	0.25	78	33	20
2	1	0	0	0	82	38	25
3	0	1	0	0	71	57	30
4	0	0	1	0	79	19	13
5	0	0	0	1	80	18	11

From the Table 14, we can find out that no matter how the weights were changed, the conclusion was identical, that is, most consulted experts support to develop FBR, in other words, FBR is more rational choice to develop nuclear power in next stage in China.

3 CONCLUSIONS

From the study included in this article, the conclusion can be obtained by using AHP model and expert consultation. It should be helpful in a decision-making process.

General conclusions are :

• The FBR, especially the Metal Fueled FBR is an optimal choice to develop nuclear power in next stage in China.

• The HTGR, due to its unique characteristics, will become complementary reactor gradually in Chinese advanced reactor system.

• Since the FFHR is economically limited and not mature on technology, it seems to be impossible that the FFHR will be commercially utilized by 2050's.

The conclusion drawn with different methods is entirely corresponding, which indicates this conclusion is reliable and satisfied. The results of our study have been taken seriously by relavent government departments.

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