Nuclear fuel cycle scenarios at CGNPC

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Abstract *–Established in 1994, China Guangdong Nuclear Power Holding Co. (CGNPC) now owns two power stations GNPS and LNPS Phase I, with approximate 4000MWe of installed capacity. With plant upgrades, advanced fuel management has been introduced into the two plants to improve the plant economical behavior with the high burnup fuel implemented. For the purpose of sustainable development, some preliminary studies on nuclear fuel cycle, especially on the back-end, have been carried out at CGNPC. According to the nuclear power development plan of China, the timing for operation and the capacity of the reprocessing facility are studied based on the amount of the spent fuel forecasted in the future. Furthermore, scenarios of the fuel cycles in the future in China with the next generation of nuclear power were considered. Based on the international experiences on the spent fuel management, several options of spent fuel reprocessing strategies are investigated in detail, for example, MOX fuel recycling in light water reactor, especially in the current reactors of CGNPC, spent fuel intermediated storage, etc. All the investigations help us to draw an overall scheme of the nuclear fuel cycle, and to find a suitable roadmap to achieve the sustainable development of nuclear power.*

INTRODUCTION

Established in 1994, China Guangdong Nuclear Power Holding Co. (CGNPC) is the only clean energy corporation in China which centers its business on nuclear power. Now it owns two power stations GNPS (Guangdong Nuclear Power Station) and LNPS (Lingao Nuclear Power Station) Phase I, with approximate 4000MWe of installed capacity. In the end of 1990's, GNPS started its research on fuel cycle to achieve more economical performance. And after 2001, the advanced fuel management has been successfully introduced into these two plants. The plant economical behavior has been improved with the advanced high burnup fuel.

With the great increase of the energy demand, the State Council has recently put forward the policy of "Actively Pushing the Development of Nuclear Power". A large amount of nuclear power stations will be in operation in the following decades. Enough fuel supply and well spent fuel treatment now become the key issue for the nuclear energy cooperation who owns more than 20 units. For the purpose of sustainable development, some preliminary studies on nuclear fuel cycle, especially on the back-end, have been carried out at CGNPC.

According to the nuclear power development plan of China, the timing for operation and the capacity of the reprocessing facility are studied based on the amount of the spent fuel forecasted in the future. Furthermore, scenarios of the fuel cycles in the future in China with the next generation of nuclear power were considered. Based on the international experiences on the spent fuel management, several options of spent fuel reprocessing strategies are investigated in detail, for example, MOX fuel recycling in light water reactor, especially in the current reactors of CGNPC, spent fuel interim storage, etc. All the investigations help us to draw an overall scheme of the nuclear fuel cycle, and to find a suitable roadmap to achieve the sustainable development of nuclear power.

Three main topics are presented in this paper: advanced fuel cycle implementation; spent fuel reprocessing and MOX fuel recycling; spent fuel intermediate storage. And a general conclusion on the nuclear fuel cycle is drawn based on those above studies.

ADVANCED FUEL CYCLE IMPLEMENTATION

Two different advanced fuel management have been successfully introduced, '18 month fuel cycle' in GNPS and advanced high burn-up '1/4 reload' in LNPS respectively. These two modification improved the plants performance. At the same time, these two projects pioneer the nuclear fuel upgrades in the Chinese nuclear power plant.[1]

18 month fuel cycle in GNPS

Started in the end of 1998, GNPS 18 month fuel cycle project was implemented to improve the plant capacity. After three years engineering verification and site modifications, the new fuel management has been successfully introduced at 2002, in cycle 9 of GNPS unit 2. At present the plant capacity factor is above 90% normally.
With the AREVA's new generation of AFA fuel assembly AFA3G, the equilibrium cycle length could reach 500 EFPDs with reload batch size by 72. The most important characteristics of AFA3G fuel are M5 cladding and Mid-Span-Mixing-Grids. The licensed burnup limit of AFA3G is 52000MWD/tU. And the fuel enrichment is 4.45%.

Advanced high burn-up 1/4 reload fuel management in LNPS

Another advanced fuel management project at CGNPC is the advanced high burn-up 1/4 reload project, which has been implemented in LNPS since 2007. To achieve higher discharged fuel burn-up, an innovative AFA3G fuel was introduced, which is All M5 AFA3G with the M5 cladding, fuel skeleton and grids. The licensed burn-up limit of All M5 AFA3G is 57000MWD/tU. The equilibrium cycle length is 320EFPDs with reload batch size by 40. And the fuel enrichment is 4.2%.

Further investigation

In recent year, the Uranium price has been increased higher and higher. So many plant owner paid more attention on the fuel cost. There is a simple parameter, fuel factor (GWD/tU-235), which could indicate the fuel cost of one fuel management actually.
The fuel factor evaluation on typical yearly fuel cycle, 18 month fuel cycle, and advanced high-burn-up 1/4 reload showed that the current GNPS 18 month fuel cycle was the worst one. (see in Table 1) It could be concluded that, to produce the same energy, the current 18 month strategy in Daya Bay uses about 20% more U-235 than the 1/4 reload strategy.

Since with the higher plant capacity factor and more electricity output, 18 month fuel cycle strategy is still one good choice to improve the plant performance. Increasing the fuel enrichment could be the solution to achieve better fuel economics. A preliminary fuel management study with enrichment of 4.95% showed that the average discharge burnup could reach 52000 MWD/tU, the corresponding fuel factor is 1050. That could be the next fuel management innovation in GNPS or LNPS.

TABLE 1. Fuel Factor Evaluation

	12 month fuel cycle	18 month fuel cycle	1/4 reload
enrichment (% U-235)	3.2	4.45	4.2
Average batch discharge burnup (MWd/tU)	33000	44000	50000
FUEL (GWd/tU-235)	1031	988	1190

SPENT FUEL REPROCESSING AND MOX FUEL APPLICATION

Management of spent fuel arising from nuclear power production has long been considered an important issue due to the political, economic, and societal implications associated with it. In view of the large amount of spent fuel being progressively added to the cumulative inventory in the world, the significance of spent fuel management will continue to grow in the future. It's necessary to avoid spent fuel accumulation with the coming world-wide 'nuclear renaissance'.
Now a take-over mode for spent fuel was chosen by CGNPC. Since 2003, the China National Nuclear Corporation (CNNC) have received the spent fuel produced in GNPS annually. With the national nuclear energy plan, more than 20 1000MW PWR units will be in operation under CGNPC at 2020. The spent fuel management become a very important strategy issue for sustainable development of the company. The back-end scenarios at CGNPC are investigated.

Spent fuel Reprocessing (current situation)

In the classic approach to the back end of the fuel cycle, the closure of the fuel cycle by means of reprocessing and recycling in fast breeder reactors was regarded as a standard strategy[2].
A closed fuel cycle with reprocessing and recycling strategy has been decided for a long

time in China. A pilot reprocessing plant is under construction at Lanzhou Nuclear Fuel Complex (LNFC). The main reprocessing facility of the pilot plant has the maximal flow rate of 400kgHM/day with a modified PUREX process.

This plant could help people to demonstrate process, equipment and instrumentation for reprocessing of spent fuel from nuclear power plant under hot conditions, and to accumulate experience on design, construction, commission and operation for a commercial reprocessing plant in future. The pilot plant will avail itself a continuous production capacity of 100 tHM/ y after reprocessing 50 tHM spent fuels for a project of R&D and being replenished.

For a large scale commercial reprocessing plant, the available spent fuel is a necessity resources. It could be the key factor to determine the timing for operation and the sizing of the facility.

Based on the China nuclear energy development plan, the capacity is forecasted in basic, realistic and optimistic ways:

TABLE 2. Forecasting Nuclear Power Capacity (GWe)

year	Basic	realistic	optimistic
2020	40	50	60
2025	51	68	96
2030	65	92	138
2035	80	120	180
2040	104	170	237
2045	127	213	293
2050	150	250	350

The accumulation of the spent fuel could be anticipated:

TABLE 3. Accumulation of spent fuel (tHM)

year	Basic	Realistic	optimistic
2020	5639	6319	6885
2025	9885	11845	14321
2030	15447	19581	25704
2035	22358	29796	41037
2040	31229	43921	61144
2045	42262	62337	86562
2050	55464	84490	117300

There are two design of site spent fuel pool: normal storage (10 years capacity) and densification storage (20 years capacity). Spent fuel will be moved from the fuel pool to treatment in reprocessing plant 7 years after discharged from the reactor for normal design and 17 years for densification design. So the spent fuel available in reprocessing plant could be forecasted:

TABLE 4. Spent fuel available in reprocessing plant

(tHM)

year	Amount
2006	396
2010	718
2015	1138
2020	1608
2025	2272
2030	3087
2035	5040
2040	9366

It can be seen that, better sizing of one reprocessing plant started-up in 2020 should be 400tHM/year to assure full load operation in first 20 years, and 800tHM/year could be better for the plant started-up in 2030.

Road Map for Long Term Reprocessing Technology

The reprocessing facilities are very expensive and take very long time to research, establish and to operate. So, the technical solution of the reprocessing facilities for the application both for PWR NPPs and Fast Breeder Reactors should be advanced enough to meet the purposes of lo long term sustainable development, minimize the amount and life time of the long term transuranium waste.

The technical difference among different processes for reprocessing should be compared and investigated such as PUREX, UREX and COEX. The best combination of the fuel cycle facilities should be investigated and define to establish the most efficient way for the closed fuel cycle. The following issues should be investigated and defined:

- Process that meets needs of Uranium and plutonium utilization with high efficiency, and spent fuel consumption.
- The best reprocessed technology that meets the long term application of FBRs.
- Transmutation facilities that both produce energy and minimize the life time of final the radiological waste.
- The best combination of reprocessing plant, transmutation facilities and fuel plant, and the MOX fuel plant for PWR and FBR.

With the illustration of the research agencies, the next generation of reactor, such as fast reactor, will be in commercial operation around 2040. Since lack of natural uranium, the fast breeder reactor (FBR) in Gen IV could be a good choice for China. To achieve this goal, efforts should be made in China to develop the new fast reactor technology, and also the reprocessing technology of partitioning or transmutation should be demonstrated. In fact, the current reprocessing technology PUREX might not be suitable to FBR fuel， and the fast reactor is far away from commercial operating due to some technical difficulty. But it's really a chance for China, including CGNPC, to reduce the distance between Chinese nuclear energy industry and that of developed countries.

MOX fuel recycling in PWR

A major reason for choosing the option of reprocessing has been the efficient utilization of uranium resources. The plutonium recovered by reprocessing can be recycled in LWRs as mixed oxide (MOX) fuel, replacing a nearly equivalent amount of enriched uranium and thus avoiding the need for considerable mining and enrichment operations. These advantages are not so significant as long as uranium is available at a relatively low price.

In the longer term, however, the recycle of nuclear fuel, including MOX in fast reactors, may play an important role both in global energy supply and as a technical basis for the partitioning and transmutation of minor actinides with a view to reducing environmental stress and contributing towards the sustainable use of nuclear energy.

Since it's long way to have the fast reactor technology been fully developed, MOX fuel recycled in PWR is still one realistic choice in China due to the planned a large number of PWRs. However, the MOX application in PWR has very limited utilization of the uranium and plutonium resources.

Beginning with LingAo phase II project, PWR reactors under the national objectives of "self-reliance in design, manufacturing, construction and operation", so called CPR1000 unit, will be constructed in batch, for example Hongyanhe project in Liaoning province, Ningde project in Fujian province, and Yangjiang project in Guangdong province. These reactors are similar to GNPS and LNPS, especially the parameters of the core are quite the same, and 18 month fuel cycle will be adopted by most of the owners. A preliminary judgment is made in this paper.

To introduce the MOX fuel in GNPS, LNPS, or the following nuclear power plant, the reactor safety will be the critical issue. The experience feedback from EDF, who depletes the most MOX fuels in PWR in the world, showed that MOX fuel may impact the plant safety analysis by following aspects:[3,4]

1) Slower decrease of reactivity BU, which impact on LB LOCA accident

2) Decrease of reactivity control efficiencies, lead to higher CB and additional RCCA banks required

3) Large thermal flux gradients at the interfaces between MOX and UO2 FA, result in FA zoning to limit core peaking factors increase

4) Slower decrease of the residual heat after reactor shutdown, impact on size and cooling of the spent fuel assembly pool, and on LOCA analysis

5) Fuel thermal conductivity is decreased, leads to higher fuel pellet temperature for a given power, and pellet clad temperature (PCT) is increased in case of LB LOCA

Specific calculations for GNPS with MOX fuels are made, the reload core is composed of 72 fresh assemblies (16 MOX assemblies).

The equilibrium cycle length is 474 EFPDs, the maximum FDH is 1.66, the shutdown margin is 2265 pcm. To compare with full UO2 fuel reactors (for the Unit 2 of GNPS, the shutdown margin is 3060 pcm, enthalpy rise factor is 1.64), the MOX fuel reactor have a less shutdown margin, and more penalizing radial power distribution. The tendency of FDH with burn-up in MOX fuel core is more complicated than UO2 core. (showed in Fig. 1 and 2).

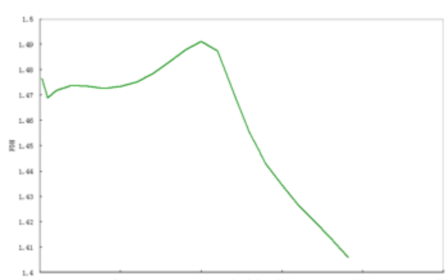

Fig. 1 the tendency of FDH with burnup in MOX reactor

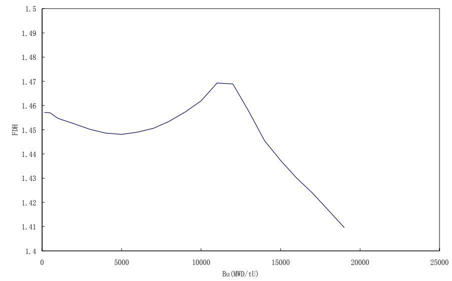

Fig. 2 the tendency of FDH with burn-up in UO2 reactor

There more residual power in MOX core than UO2 core. (see in Figure 3 and 4)

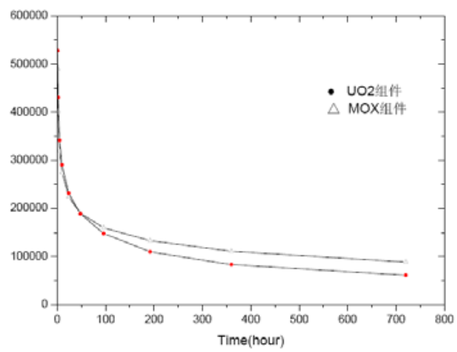

Fig. 3 The decay heat of the comparison between UO2 fuel and MOX fuel

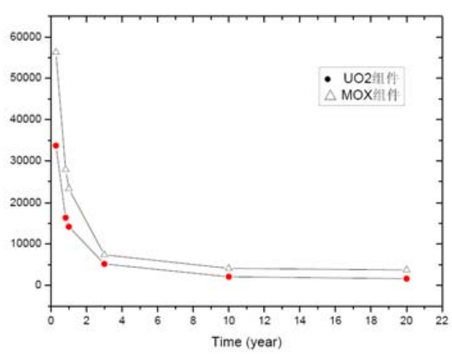

Fig. 4 The decay heat of the comparison between UO2 fuel and MOX fuel

The above specific calculations for Daya Bay show the same rules in MOX core as in EDF. The reactor core in GNPS is upgraded from the original EDF CPY units initially, and further innovated with higher burn-up, new fuel and high burn-up new fuel management. Therefore, compare to EDF plants, the available margin for MOX fuel will be more critical in GNPS. It means that more comprehensive engineering evaluation should be taken to introduce MOX fuel in GNPS or CPR1000 units.

MOX for FBR.

For long term sustainable development, MOX for FBR will be an efficient way in the closed fuel cycle, and should play important role.

INTERIM STORAGE OF SPENT FUEL

Today, in fact, there are still some divergences among many countries in what should be actually done with spent fuel, reprocessing or direct disposal? Resources or wastes, different understanding about the spent fuel decided the way it will be treated. The different perspective have been debated for decades, and are not likely to be resolved soon. But a quiet consensus has developed for the short term solution, simply storing spent fuel while continuing to develop more permanent solutions is an attractive approach.

Interim storage of spent fuel have been demonstrated to be a safe, secure, flexible, and cost-effective short term approach to spent fuel management. Whether spent fuel is treated as resources or wastes, interim storage can save enough time to improve technologies and policy approaches to achieve an optimized solution of the spent fuel management. Indeed, since 1970s most of the spent fuels have been stored, and the spent fuel management in some countries has been always changed with political, technical, or environmental reasons.

China is still in the early stages of its nuclear power program, with 11 reactors in operation, the total capacity is about 8700MW at present. As in many other countries, the reactors now in operation were built with limited fuel pool storage capacity, with the idea that spent fuel would be reprocessed. GNPS was the first plant that transferred the spent fuel out-site. About 220tHM spent fuel has been transported from on-site fuel pool out to an AFR storage facility, a 550tHM storage pool facility in Lanzhou. Since the very long distance, the climatic reason and the plant production plan, the timing of the spent fuel transportation is critical. Any delay or cancellation of the transportation will be unacceptable. A second facility for intermediated storage could be one selection to deal with this difficulty.

On the other hand, according to the mid- and long-term national nuclear power development schemes, there will be at least 40 units in operation by 2020, and about 900tHM PWR spent fuel and 150tHM CANDU spent fuel will be generated each year. An development plan of the commercial spent fuel reprocessing plant associated with spent fuel interim storage should be well arranged. The experience feedback shows that the interim storage of spent fuel ought to be seen as one essential part of the national spent fuel reprocessing policy.

In China, the nuclear power is increased very rapidly, so the flexibility should be the most important element in choosing the storage approach. With investigation of the different methods to store spent fuel, the dry cask storage technology is evaluated as better solution. This kind of centralized interim storage facility could meet the regular or urgent demands.

The site of centralized interim storage should located beside the reprocessing plant, or just as a part of reprocessing plant, to control the cost and avoid the risk of multi-transportation. Since most of the nuclear power plants in China are located beside the sea, the centralized interim storage facility is located on the coasts maybe a good choice.

CONCLUSIONS

With the discussion in this paper, the nuclear fuel cycle scenarios on CGNPC could be concluded that,

i) more enriched fuel into the core for the next plant upgrade;
ii) spent fuel reprocessing development plan should be in consistent with national nuclear energy development plan, and it must decided under the whole fuel cycle policy associated with other choice, such as interim storage;
iii) MOX fuel recycled in PWRs is one realistic choice in China, but a complete evaluation should be made, and scheduled with the national reprocessing plan.
iv) A sustainable way of for the establishment of large scale reprocessing facility and corresponding MOX fuel plant should be investigated and defined in China.

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