USING VISTA FOR THE EVALUATION OF MOX FUEL TRENDS

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ABSTRACT

The nuclear fuel cycle may be broadly defined as the set of processes and operations needed to manufacture nuclear fuels, to irradiate them in nuclear reactors and to treat and store them, temporarily or permanently, after irradiation. Several nuclear fuel cycles may be considered depending on the type of reactor and the type of fuel used and whether or not the irradiated fuel will be reprocessed. Since the early 80s, the IAEA has been collecting and analyzing information on the nuclear fuel cycle. Much effort has been given to the development of a computerized database system, the Nuclear Fuel Cycle Information System (NFCIS). This centralized information system is an international directory of civilian nuclear fuel cycle worldwide. Its purpose is to provide information to the IAEA and its Member States on existing and planned nuclear fuel cycle facilities throughout the world. This task is accompanied by a new computer tool, the Nuclear Fuel Cycle Simulation System, VISTA. VISTA is a computer model, which can be applied to a given scenario portraying the history and future of nuclear power and its fuel cycle, and generate results for the front-end as well as the back-end of the nuclear fuel cycle. This paper presents the new results obtained by using VISTA, and includes a comparison to data taken from NFCIS.

1. INTRODUCTION

VISTA, a new model for the estimation of fuel cycle service requirements has been developed by the IAEA. The model has been designed to bring about the calculation of long-term nuclear fuel cycle requirements and actinide arisings, thus assisting in the investigations of future trends including spent fuel management.

There are a number of models and computer tools available for calculating uranium and fuel cycle service requirements. These models are based on sophisticated databases that include information on each nuclear power reactor in the world. Such models are suitable for estimating short-term open cycle requirements, but become complex for the closed cycle, where recycle of separated fuel material is to be taken into account. The incentive for the development of the new model was to simplify long-term, open or closed cycle estimations, while integrating information available from other existing databases in the IAEA.

The main assumption in the model is that it is possible to simulate the nuclear fuel cycle by taking into account the evolution of using different types of reactors during the years, without the precision of using reactor by reactor database. The reactor types taken into consideration are PWR, BWR, PHWR, AGR, GCR, RBMK, WWER-440 and WWER-1000.

The input parameters are divided into three groups:

- Strategy parameters - nuclear capacity variants and reprocessing-recycling strategies, reactor mixture and load factors, all on an annual basis;
- Fuel parameters - average discharge burnup, average initial enrichment and average tails assay on an annual basis; and
- Control parameters - share of mixed-oxide fuel in the core of reactors using this type of fuel, lead and lag times for different processes and the number of spent fuel reprocessing cycles.

VISTA’s results are divided into the following groups:

- Natural uranium, conversion and enrichment service requirements;
- Fresh fuel requirements and spent fuel arisings;
- Total plutonium arisings;
- Reprocessing and mixed-oxide fuel fabrication service requirements; and
- Separated plutonium utilization;

In this paper, the assumptions and results achieved by VISTA are presented investigating MOX-use trends. The incentive for developing the new model, as well as basic model description are given. This investigation involves two projections of future nuclear power capacity in combination with three reprocessing-recycling strategies. The results shown and discussed include comparison of spent fuel arisings with storage capacity, comparison of reprocessing requirements and capacities and comparison of MOX fuel usage trends with regards to MOX fuel fabrication capacities.

2. MOX FUEL TRENDS

Any discussion on trends has to rely on the availability of information. The IAEA nuclear fuel cycle databases project is targeting such requirements by implementing two parallel tasks. The first is by continuously collecting and analyzing information on existing and planned nuclear fuel cycle facilities throughout the world, using a computerized database system, NFCIS [1]. This is complemented by a second task, establishing and developing of a nuclear fuel cycle requirements simulation system, the computer code VISTA [2].

This newly developed computer code was designed for calculating spent fuel arisings, actinide generation, plutonium separation and its utilization, as well as other information related to the back-end. VISTA is a scenario based tool which can be used to generate estimates for the closed cycle where recycle of separated fuel material is taken into account. In the course of its development, in the last few years, VISTA was used for investigating the new realities [3], nuclear power and climate change [4] and for front-end estimations of natural uranium, conversion and enrichment service requirements [5].

In order to analyze MOX fuel trends, the model estimates, for eight reactor types, average requirements corresponding to a given level of electricity generation and fuel cycle strategy. Closing the cycle is done by calculating two sets of fuel loads and unloads. One is for reactors using only uranium fuel and another is for reactors using uranium and MOX fuels. A special scenario file defines, among others, the fuel cycle strategy to be investigated, as the fraction of discharged fuel which will be reprocessed. The contents of plutonium (and other actinides) in the spent fuels is calculated using IAEA model CAIN [6]. The final step involves separating plutonium and fabricating MOX fuel which is then loaded as a part of the core of some LWRs. This method enables the simulation of a closed nuclear fuel cycle.

3. MAIN ASSUMPTIONS

VISTA estimates are based on a given scenario portraying the future of the nuclear power and its fuel cycle. For the purpose of this paper, two nuclear capacity variants coupled with three reprocessing-recycling strategies were selected. According to IAEA database, 434 nuclear power reactor units were operated in 32 countries, with a total electric generating capacity of 349 GWe worldwide as of December 1998 [7]. Future trends are based on IAEA projections as shown in Table I [8].

Table I. World Nuclear Power Capacity Variants (GWe)

	2000	2010	2020
High variant - **HV**	353	437	582
Low variant - **LV**	349	374	305

The fuel cycle strategies, shown in Table II, differ in the reprocessing ratio and number of cycles used. The S1 strategy was used in earlier investigations [2, 3, 4, 5]. It assumes that half of the spent fuel is offered for reprocessing (50% reprocessing ratio) and that plutonium extracted from UO_2 spent fuel can be recycled twice in LWRs. This strategy is used as a maximal-reference strategy. The strategies S2 and S3 assumes one cycle only, without the reprocessing of spent MOX fuel, and with end-of-period reprocessing ratio of 50% and 35% respectively. These strategies are considered to be the more probable scenarios for future reprocessing and recycling of spent fuels.

Table II. Fuel Cycle Strategies

	Reprocessing Ratio (%)	Number of Cycles
Maximal reference strategy - **S1**	50	2
High realistic strategy - **S2**	50	1
Low realistic strategy - **S3**	35	1

4. SPENT FUEL ARISINGS AND STORAGE

VISTA calculations predict worldwide spent fuel arisings. Annual spent fuel arisings were reaching a peak of about 11,300 t HM in 1990 and reduced to about 10,200 t HM in 1998. Higher burnups lead to fuel savings by decreasing the amount of fissile material in the fuel cycle and to the reduction of the amount of spent fuel to be managed [9, 10]. As can be seen in Figure 1, annual fuel discharges are reducing and are projected to increase again as the installed nuclear generating capacity will increase. This trend demonstrate the balance between increased burnup and increased nuclear capacity.

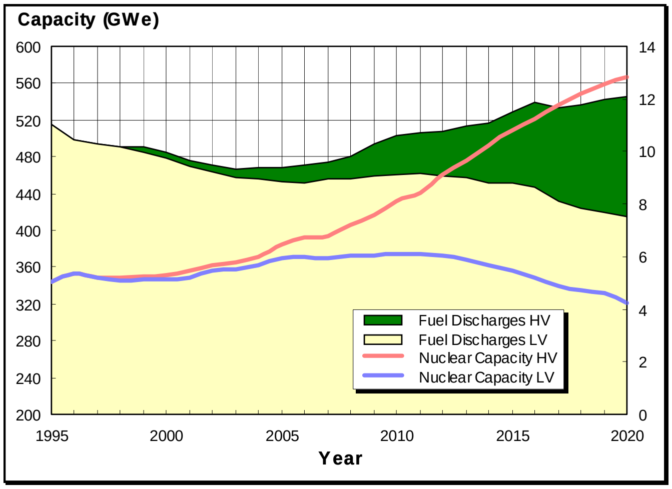

Figure. 1. Projected trends in annual fuel discharges vs. world nuclear capacity (10^3 t HM)

A comparison between amounts of spent fuel storage capacities and requirements for storage is shown in Figure 2. Storage requirements were calculated by the VISTA code using the scenarios mentioned above. The results predict that storage capacities will have about 100,000 t HM surplus over the total storage requirements until 2015.

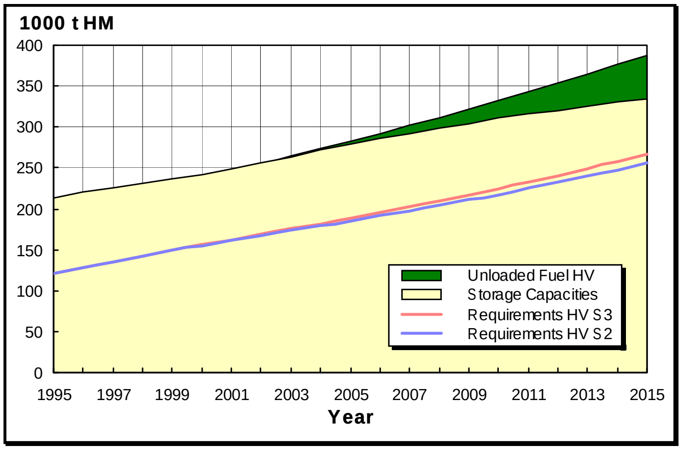

Figure 2. Comparison between spent fuel storage requirements and capacities worldwide (10^3 t HM)

This comparison demonstrates in a clear way, that the increased amounts of spent fuel must be taken seriously in consideration, by increasing worldwide storage capacities or by continuing reprocessing of spent fuels. The worldwide storage capacity which is shown here, may be sufficient if reprocessing continues during the time period until 2015, but the same trend is also showing that continuous effort on spent fuel management is required. It should be noted that the situation regarding storage capacity can be radically different in different countries; some countries, for example those in Western Europe, have enough capacity, while others do not.

5. REPROCESSING

Spent fuel reprocessing is a proven technology and reprocessing services are now available on a commercial basis to reactor operators. Table III, lists the status of the current and projected reprocessing capacities worldwide [1]. At present France is successfully operating the reprocessing plants in La Hague for LWR spent fuels with a capacity of 1,600 t HM/a and has already reprocessed 12,000 t HM of LWR spent fuel. The United Kingdom operates now two main plants with a total capacity of 2,700 t HM/a. In Japan, construction work on the Rokkasho-mura reprocessing plant with 800 t HM/a continues, but delays will cause it to be several years behind schedule. The Russian Federation planned in the 1980s to commission a second large scale reprocessing plant (RT-2 at Krasnoyarsk) at the beginning of the next century, 2005, but it has been cancelled for financial reasons. India is commissioning the Kalpakkam plant with a capacity of 100 t HM/a for PHWR and the Chinese government is planning to build a large scale plant by the year 2020.

Table III. Current and Projected Reprocessing Capacities (t HM/a)

	Fuel type	1998	1999	2000	2005	2010	2015	2020
China	LWR				25	25	25	825
France	LWR	1600	1600	1600	1600	1600	1600	1600
India	PHWR	60	160	160	460	460	460	460
	Research reactor	50	50	50	50	50	50	50
Japan	LWR	100	100	100	620	900	900	900
Russia	LWR	400	400	400	400	400	400	400
UK	FBR	10	10	10	10			
	GCR/Magnox	1500	1500	1500	1500	1500		
	LWR/AGR	1200	1200	1200	1200	1200	1200	1200
Total		4920	5020	5020	5865	6135	4635	5435

The total projected reprocessing capacity worldwide increases over the period 1998-2010 due to the deployment of new plants in Japan and India, but after 2010 it will probably change due to likely closure of the Sellafield (B205) plant and introducing of a second plant in China. Figure 3 shows a comparison between worldwide reprocessing capacities and the projected reprocessing requirements calculated by the VISTA code.

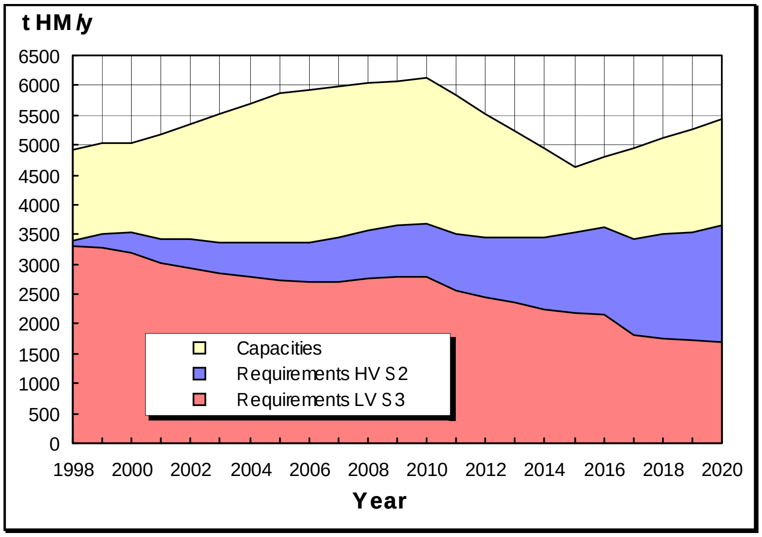

Figure 3. Comparison between worldwide reprocessing capacities and anticipated reprocessing requirements calculated by the VISTA code (t HM/a)

The worldwide reprocessing requirements shown here are actually a sum of LWR and non-LWR reprocessing requirements. In the scenarios mentioned above, LWR nuclear generating capacity is increasing during the time frame of this work. As reprocessing requirements follows the trend of annual spent fuel discharges, VISTA estimations predict that reprocessing requirements for LWR fuels will be around 2,000 t HM in 2000, reduced to around 1,700 t HM in 2005 and will increase back to 2,000 t HM in 2015. This estimate is complimented with the reprocessing of non-LWR fuels. VISTA projects a constant reduction in reprocessing requirements of these fuels, especially due to the end of the GCR Magnox program in the United kingdom sometime within the next 10 to 15 years. It should be noted here that reprocessing requirements are very sensitive to political decisions in different countries and may change sharply in the coming years.

6. PLUTONIUM UTILIZATION

Plutonium is generated (and is partly burned) during the operation of uranium-fuelled nuclear reactors and forms part of their spent fuels. The IAEA estimates that in 1998, about 76 tonnes of plutonium were contained in discharged spent fuels worldwide. It is foreseen that the annual plutonium production, as presumed from spent fuel arisings in Figure 1, will remain more or less the same until 2015. The cumulative amount of plutonium in spent fuels from power reactors worldwide is predicted to reach 2,000 tonnes in 2015. Some of the plutonium contained in reactor spent fuel has been separated and a part of it (approximately one third) has, up to now, been used to manufacture MOX fuel for LWRs and experimental and prototype FBRs, but the major part of the separated plutonium is currently stored, mainly at the British, French and Russian reprocessing sites.

As one of the main expectation of this work was to estimate MOX fuel trends, VISTA was used to investigate the using of separated plutonium to fabricate MOX fuel to be used in LWRs. In 1995, about 8 tonnes of plutonium were used in LWRs and in breeder reactor development programs. VISTA estimates that annual amounts of up to 25 tonnes of plutonium will be used for fabricating MOX fuel towards 2010, assuming that MOX fuel will have a share of 30% in the core of LWRs worldwide [11].

MOX fuel fabrication is becoming a mature industry activity, particularly in Belgium, France and the United Kingdom. Fabrication plants for MOX fuel are being operated in Belgium, France, the United Kingdom, Japan and India. Table IV, lists the status of the current and projected MOX fuel fabrication capacities worldwide [1, 11, 12].

Table IV. Current and Projected MOX Fuel Fabrication Capacities (t HM/a)

Country	Plant	1998	2000	2005	2010
Belgium	Dessel P0	35	40	40	40
France	Cadarache, CFCa	35	40	40	40
	Marcoule, MELOX	120	160	160	160
India	Tarapur	5	10	10	10
Japan	JNC Tokai	15	15	5	5
	Rokkasho-mura			100	100
UK	Sellafield MDF	8	8	8	8
	Sellafield SMP		120	120	120
Russian Federation	Mayak			10	50
Total		218	393	493	533

VISTA calculations are based on the assumption that the plutonium separated by reprocessing of LWR spent fuel, is used to fabricate MOX fuel which will be loaded in LWRs. The procedure used to calculate these estimates involves using of the separated plutonium for the required MOX fabrication. This means, that using of plutonium from stockpiles for fabricating of MOX fuel is not taken into consideration.

It is assumed that the share of MOX assemblies in the core of LWRs using this type of fuel is 30%. The S1 strategy assumes that the plutonium extracted from UO_2 spent fuel can be recycled twice in LWRs. A comparison of MOX fuel production capacities and predicted MOX fuel requirements to 2010 is given in Figure 4.

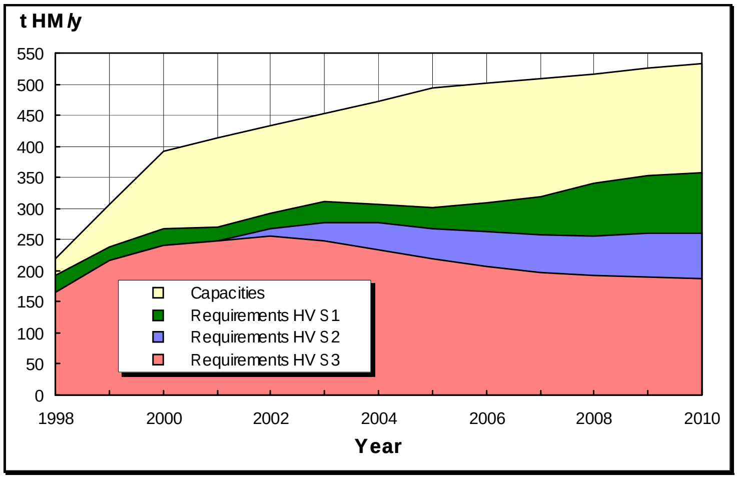

Figure 4. Comparison between worldwide MOX fuel production capacities and anticipated annual MOX fuel requirements calculated by the VISTA code (t HM/a)

At present, MOX fuel requirements are near the full production capacities. The results obtained from VISTA show a trend of increased requirements for MOX fuel in the short-term, with some reduction later. The reason for this phenomenon is linked directly to the annual reduction in spent fuel discharges, therefore reduction in the spent fuel which is sent to reprocessing plants. Together with a parallel reduction in fresh fuel requirements, the result will be reduction in the requirements for MOX fuel. However, this trend may change as it depends on the continuation of reprocessing or using of stockpiles of separated plutonium, currently in storage. The trend may also change if the share of MOX fuel in the core will increase over the 30% value used in this investigation. As can be seen in Figure 4, in all scenarios calculated, the supply will be in excess of demand up to 2010 because of commissioning of the Sellafield SMP, expansion of the MELOX plant capacity and deployment of the Rokkasho plant in Japan.

The imbalance between separation and use of plutonium resulted in an estimated inventory of separated civil plutonium of about 190 t at the end of 1998. This corresponds to earlier projections and published data [3, 13, 14]. Estimated future trends relating to worldwide inventories of separated civil plutonium, based on the assumptions mentioned above, were calculated using VISTA and are presented in Figure 5.

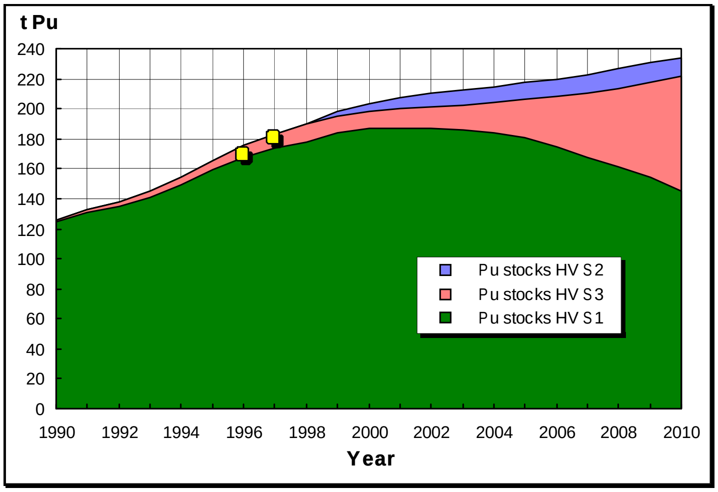

Figure 5. Estimated separated civil plutonium inventories worldwide (t Pu)

Future separated plutonium inventory forecasts have significant associated uncertainties and are quite sensitive to MOX fuel fabrication and spent fuel reprocessing assumptions. The situation regarding plutonium stocks, and plans which are underway to use them, differ from country to country. In some countries MOX programmes are actively implemented, in others, though, recycling of separated plutonium is not expected to take place in the short term. In addition, limited quantities of military stocks of weapon plutonium may soon be transferred into the civilian sector.

On the basis of the assumptions mentioned above, VISTA predicts that the stockpiles of separated civil plutonium will continue to rise. This trend may change if multiple recycling of plutonium will take place, as is demonstrated using the S1 reprocessing and multiple recycling strategy, or in the case of using plutonium from stocks to fabricate MOX fuel.

The results of calculations for the multiple recycling strategy S1, demonstrate a trend of reducing separated civil plutonium inventories. VISTA estimates that in this strategy, fabricating MOX to feed 30% of LWR cores, will require additional plutonium, more than the quantities which will be available from reprocessing of spent fuels. This additional quantities may come from the plutonium stored as stockpiles and the consequence of such operations will lead directly to reduction in separated civil plutonium inventories.

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