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ON NUCLEAR POWER AND ITS FUEL CYCLE
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UTILITIES' VIEW ON FUEL MANAGEMENT OF NUCLEAR POWER PLANTS

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1. INTRODUCTION

Electricity from nuclear energy was produced as early as in 1952 in the U.S. by ERB-1, an experimental fast breeder reactor rated at about 1.2 MW_t. This is not surprising for theoretically it was long known at that time with what fuel cycles and with what reactor types best utilisation of nuclear fuels can be achieved (Fig. 1). With this knowledge, peaceful use of nuclear energy for heat and electricity generation had aimed at high goals. However, it soon became worldwide apparent that these goals could not be realized within the initially anticipated time span. The reasons were technological. Developing these reactors and the facilities for their nuclear fuel cycles required greater efforts than presumed.

In all parts of the world, subsidiary strategies were proposed starting with reactors based on enriched and natural uranium fuel cycles respectively which in fact would by converting fertile fuel lead in a later phase to breeder reactors.

The first nuclear power plants using enriched uranium and natural uranium respectively started their operation in 1954 in the USSR (APS-1, rated at about 30 MW_t) and in 1956 in the UK (CALDER HALL, rated at about 4 x 270 MW_t).

From the competing reactor strategies which had been developed until the beginning of the sixties, especially among the nuclear weapon states but also among other industrialized countries, short-term but essential advantages of reactors based on the enriched uranium fuel cycle became evident. This was made possible by the program "Atoms for Peace" in the U.S., initiated in 1953. According to this program, enriched uranium for lease, i.e. at low prices was provided by enrichment plants which had been built for military purposes. Moreover, "Atoms for Peace" made available to the American industry the technological know-how of light water reactors originally developed for military application.

In most countries the decision for U 235 burners and against thorium and uranium converters and breeder reactors respectively was made on technological but even more on economical grounds. Only some countries have developed converter reactors, while breeder reactors are still in the prototype stage in a few countries.

In spite of the high fuel demand of uranium burners, the uranium long-term supply was secured. But also the other fuel services necessary for the nuclear fuel cycle were taken up and offered by federal and private organizations. From the utilities' viewpoint the nuclear fuel cycle of U 235 burner and uranium converter reactors was taken care of and in principle manageable.

From the beginning, the basic cost structure of electricity production by nuclear power plants has been evident. The appearance of radioactivity, its safe containment and thus more sophisticated safety relevant features in nuclear power plants as well as critical mass requirements caused about 50 % higher capital costs for nuclear than for fossil power plants. Fuel costs, however, were considerably lower for nuclear power plants, namely only about 20 % of fossil fuel costs. The closed and economic fuel cycle was the decisive factor for utilities to use nuclear energy. In the utilities' opinion, nuclear energy represented a safe and economic new source of electricity generation which could help to fulfill the utilities' task to provide at all times electricity safely and economically to the customer. In total, electricity from nuclear energy was more economic than from fossil energy (Fig. 2).

This is still true today provided that planning and construction of nuclear power plants and other installations necessary for the nuclear fuel cycle including ultimate radioactive waste disposal are not unduely delayed by other than technical reasons and provided that for all primary energy sources the same ecological standards will be applied.

Only after the successful operation of prototype nuclear power plants did utilities order nuclear reactors. The today world's total installed nuclear power plant capacity of about 80.000 MW_e splits up into about 67.000 MW_e from reactors fueld with enriched uranium and approximately 13.000 MW_e from reactors based on the natural uranium fuel cycle. The decision for nuclear energy was clearly confirmed by excellent power plant safety records as well as high plant load and operation factors. Thus for instance the cumulative load and operation factors for all 127 nuclear power stations x) lie presently at 62 % and 73 % respectively.

Since the early seventies, however, the situation has changed drastically. Industries and/or governments increased the prices for nuclear fuel and fuel services at a rate much higher than the inflation rate and also failed to build the facilities necessary to close the nuclear fuel cycle. In addition utilities are being increasingly made responsible for taking over in all areas of the nuclear fuel cycle if not the organization so at least the financing. This is true especially for fuel reprocessing, waste disposal and in part for uranium prospection, mining, and enrichment. On a competitive basis, only fuel element fabrication is available therefore at reasonable prices.

This means additional financial burdens to the utilities. Setting the total capital requirements, that is the financing of electricity generation, its transmission and distribution of a utility system which is entirely based on fossil fuels equal to 100 %, a complete transition to nuclear fuels would mean today for that utility an additional 30 to 40 % capital investment and a further 10 to 15 % for the above mentioned likely future tasks and responsibilities. Taking as an

x) Only nuclear power plants with gross electrical power more than 100 MW_e located outside the COMECON countries.

example a utility with a 20 % nuclear portion these figures will reduce to 6 to 8 % and 2 to 3 % respectively, giving a total of 8 to 11 %. This represents a considerable but manageable financial burden. Furthermore, utilities have to bear the risks of the large scale industrial realization of these new technologies. Needless to say that this situation makes the advancement of nuclear energy rather difficult in particular for countries with small nuclear energy programs.

2. GENERAL ASPECTS OF NUCLEAR AND FOSSIL FUEL MANAGEMENT

All three areas of the nuclear fuel cycle - fuel procurement, fuel utilization, and waste disposal - although in principle similar to that of fossil fuels, represent quite difficult tasks for the utilities (Fig. 3).

Generally, utilities were experienced in the management of fuels for conventional power plants. As usually fossil fuels are delivered directly to the power plants, utilities' fossil fuel management consisted mostly of providing fossil fuel storage facilities with respect to the maintenance of sufficient fuel supplies. In case of the nuclear fuel cycle utilities are closely and directly involved in all steps of fuel management.

The nuclear fuel cycle is characterized by the essential aspect that the government exercises considerable influence on practically all steps of the nuclear fuel management. This starts already during utilities' fuel procurement when export and transfer permits for fissile material are being granted by the governments, not to speak of the enrichment plants which are government property. As far as fuel utilization and waste disposal is concerned, federal agencies define the safety regulations for the operation of nuclear power stations, reprocessing plants, and also for ultimate waste disposal installations. By this they considerably affect construction times as well as costs of such facilities. In some countries ultimate waste disposal is taken care of by governmental organizations which are to be reimbursed.

At this point it is appropriate to remark that safeguard activities at utilities' nuclear power stations do not represent problems, since they are not sensitive installations. Item accounting should suffice to perform efficient safeguarding.

Due to economic, safety, and ecological reasons the most important steps of the nuclear fuel cycle are carried out in plants with big capacities. The nowadays usual unit size of a nuclear power station lies in the range from 1000 to 1300 MW_e. Enrichtment plants, reprocessing plants and waste disposal facilities are even designed to provide 50 nuclear power plants.

For some countries already the large power plant unit size makes it difficult to take advantage of nuclear energy. The reasons are well known. Countries whose nuclear power programs have not planned for 20 to 50 nuclear power stations, will not be able to produce energy by means of nuclear power stations at an economic optimum. Moreover, these countries will for practically all steps of the nuclear fuel cycle also be dependent on other countries.

Fuel Procurement

Prospection, mining, and extraction of both fossil and nuclear fuels can be considered as routine technololy. Preparation for use of nuclear fuels including conversion, enrichment, and fabrication of fuel elements is much more complicated than equivalent steps for fossil fuels and requires new technologies. Transport problems are quite different for both types of fuel. Fossil fuel is transported in big quantities by means of large oil tankers, pipelines, and railways. For the transportation of the small quantities of nuclear fuel by trucks, ships, and railway only small special transport devices (like flasks, drums, etc.) are required. Naturally this difference has a considerable impact on the transportation sector.

Fuel Utilization

Energy originating from nuclear fuel needs sophisticated in-core fuel management in order to arrive at minimum release of radioactivity at maximum energy output by the nuclear power plant. This is achieved by competent engineering and staff support in managing all fuel operations. More details will be given later in Chapter 4.

While the energy content of fossil fuels is extracted in a single combustion process, maximum utilization of nuclear fuels will result by multiple recycling of the original and converted fuels. This, of course, necessitates special facilities for reprocessing and refabricating nuclear fuels.

Waste Disposal

Wastes are generated during all steps of any fuel cycle. Increasing environmental standards have led to the consideration but in general not to the introduction of new waste technologies for fossil fuels. The existence and nature of fossil wastes are less well known but accepted by the public.

Wastes from the nuclear fuel cycle essentially handled at the reprocessing plants and at different storage facilities represent new technologies for industry and utility and cause mistrust and fear to the public.

Utilities are bound to and need international agreements and obligations for their nuclear fuel management in general and for their waste disposal in particular.

The nuclear controversy is more and more concentrating on problems in connection with the nuclear fuel cycle. Thereby no distinction is made whether a specific problem has technically and technologically been resolved or not.

3. NUCLEAR FUEL MANAGEMENT ACTIVITIES AND RESPONSIBILITIES

The nuclear fuel cycle centrally embedded in any nuclear energy program is to be carefully organized with respect to all fuel management activities in order to fulfill the earlier mentioned objectives of cheap and safe electricity production. Besides technical and economic factors affecting nuclear fuel management activities political aspects have increasingly begun to influence the organization of nuclear fuel management activities, let alone the responsibilities resulting from such activities.

Obviously, the scope of nuclear fuel management activities varies from country to country although the overall situation has been historically and still is strongly characterized by the big nuclear weapon states.

In Figure 4 it has been attempted to show in a schematic fashion how and to what degree utility, industry, and government of a country are involved in the various areas of nuclear fuel management with respect to financial engagement and responsibility. This structure of activities with all its interdependencies represents only a gross classification indicating general responsibilities which of course is subject to changes if a specific country's situation is considered. Needless to say that the indicated coarse structure of fuel management activities should be fixed in advance of the realization of nuclear power plant construction programs although a certain evolution may simultaneously take place.

It has been tried to describe the present situation as well as to indicate already apparent future trends. Question marks characterize at the moment unforeseeable developments. In general, as can be seen in Figure 4, those areas of the nuclear fuel cycle are now and very likely in the future adequately taken care of which either have originated from military developments or which are characterized by relatively small capital investments and risks. On the other hand, it also becomes evident that utilities' financial engagement in practically all fuel utilization and waste disposal activities is bound to grow. The same of course is true for the responsibility of utilities' increased fuel management activities. This development has been named "fuel management according to the principle of the causer".

Some brief remarks shall suffice to describe the actual situation with respect to fuel procurement, fuel utilization, and waste disposal.

All sectors belonging to fuel procurement are industrially well established, enabling the utilities to take care of and organize the individual steps of their nuclear fuel procurement. They do this usually by signing contracts with qualified partners. Nevertheless, lately the utility has been asked for increased financial contributions to several areas of fuel procurement (for example, prospection, enrichment). It is argued that this would give the utilities better control of fuel resources and would help to cover the investments necessary for the development and the introduction of new technologies.

Uranium enrichment is still as it has been historically strongly controlled by governmental institutions, the reasons being political. Industry's future engagement in this area is at the moment hard to predict.

As to fuel fabrication and fuel transportation it should be remarked that these activities are fully and competitively developed and fall into the industry's responsibilities.

Turning to the various steps listed under fuel utilization it can clearly be said that the utility has expectedly to a very great extent assumed the responsibilities of reactor operation. As these responsibilities will further increase in the future, in-core fuel management activities necessary for safe and economic reactor operation will be discussed in some detail in the next chapter.

Originally the storage of spent fuel from operating power stations has been envisaged to be limited to a couple of years. Misjudgement of the development of and inactivity of industry and government on the reprocessing sector have led to a bottleneck of spent fuel storage. The result of this is that utilities are spending large amounts of money to enlargen already existing or to create new storage capacities for irradiated fuel. As not very many fuel storage facilities have been built so far, utilities have also to bear involuntarily the research and development costs for these facilities. The advantage of large spent fuel pools is the higher flexibility in scheduling reprocessing campaigns with respect to both the minimization of radiation hazards and the optimum strategy for uranium and plutonium recycling.

Reprocessing of spent nuclear fuel originating from light water reactors is a prerequisite in order to be able to utilize the energy potential still contained in the irradiated fuel. The nuclear controversy has particularly focused the public's attention to reprocessing.

This is due especially to the political significance of technologically large scale reprocessing facilities representing so-called "sensitive plants" subject to safeguarding of all fissile materials. They require high capital costs for economically operable plant sizes. In addition, other factors such as the lack of licensing standards and of allocation of accepted sites for reprocessing facilities characterize the present situation.

At present no technological nor economic reasons do exist which necessitate spent fuel reprocessing immediately after fuel unloading from the reactor. Moreover, because of high capital and research and development costs, industry so far was quite reluctant to engage in fuel reprocessing. However, some governmental companies have started to fill the reprocessing backlog. Future developments are not easy to predict.

Presently it seems as though due to political pressures granting construction and operation permits to utilities for scheduled nuclear power stations will be strongly linked to a well working and established reprocessing technology. Thus it is no prophesy to deduce utilities' increased financial engagement in all reprocessing activities together with higher responsibilities in this area.

On an international scale the organizational structure of fuel reprocessing is not yet established. In this respect, cooperation within

"Regional Fuel Cycle Centers" as initiated and presented by IAEA at this conference could advantageously contribute to a favourable development, especially in countries with limited or slow nuclear energy programs.

Utilities' view and decision on the recycle of reprocessed uranium and plutonium which is the property of and for which the utility is responsible will strongly depend on the price and availability of natural uranium, on economically operating reprocessing plants, and last but not least on the transition to fast breeder reactors. However, the political decision to recycle uranium and plutonium has to come from a country's government. Unfortunately, fast decisions on recycling are not expected in the near future.

Financial engagement in ultimate radioactive waste disposal and responsibilities for this fuel management activity is seen by utilities as follows. All radioactive wastes originating from fuel procurement activities are financially taken care of by the industry as fuel prices do contain waste management activities. Radioactive wastes from reactor operation are clearly a matter of the utilities according to the causer principle. As to the radioactive wastes from reprocessing plants the situation is not clearly transparent. However, at the moment at most utilities the assumption prevails that hight level radioactive wastes from reprocessing have to be taken care of by the utility.

In Figure 5 an attempt has been made to synthesize from the foregoing analysis utilities' view on the fuel management of nuclear power plants with perhaps a cautious glimpse into the future.

Doing this, a flow diagram has been chosen to describe in a logistic manner how nuclear fuel management activities may evolve passing from the present, first to the likely near term and later to utilities' desired fuel management strategy. The essential partners, that is utility, industry, and government, which are to cooperate in establishing that hopefully for all partners desired configuration of nuclear fuel management must share together all financial engagement and responsibilities on an international scale.

Besides the uncertainties of the decisions indicated in Figure 5 which in fact touch on as fundamental questions as going nuclear or not, there remains the time ambiguity, that is the time span whithin which decisions will be taken by governments, industries, and utilities and within which large scale technologies for fuel reprocessing, waste disposal, and fast breeder reactors can be established.

Utilities' future major emphasis must lie on some areas of fuel utilization (reprocessing and recycling) and waste disposal as these fuel management activities bear the most uncertainties coming either from industry or government.

Apparently the political decisions which have to be made by a country's government represent the greatest uncertainties in this model. This is not surprising as the factors which lead to political decisions are numerous and obey rules which go beyond the scope of this analysis.

It is clear that only if reprocessing is established, uranium and plutonium recycling can be considered. On the other hand if reprocessing on a technologically large scale is established fuel recycling is likely, especially since mixed oxide fuel fabrication has already industrially been established. That leaves the essential decision to introduce breeder reactors or not. This decision, however, cannot be expected in the near future.

4. IN-CORE FUEL MANAGEMENT

When nuclear power reactors are operated, highest priority must be attributed to the radiological optimization of the fuel. To the utility, this means besides all legal requirements of radiation dose limits to the public the minimization of radiation exposure to its own personnel during operation, refueling, and repair works.

All activities during reactor operation to achieve these goals can be subsumed as in-core fuel management. In-core fuel management is part of nuclear fuel management.

Figure 6 shows schematically the different areas of in-core fuel management.

For all these areas it is an important prerequisite to have available sufficiently sophisticated computational tools. Moreover, most of the in-core fuel management areas are interdependently related to each other. This interrelationship together with a program system for optimization of in-core fuel management is shown in Figure 7.

Initially in-core fuel management activities are not necessarily performed by the power utility but it is our belief that a higher responsibility of the utility in these sectors leads to better fuel cycle economy, to safer and better in-reactor performance of fuel, and to prompt and responsive remedies when inevitable main component outages or perturbances to planned operations occur.

The International Atomic Energy Agency has repeatedly been asked by some member states about information concerning openly or commercially available computer codes or computer code systems for in-core fuel management calculations of nuclear power reactors.

The IAEA has executed a project "Computer Codes for In-Core Fuel Management of Power Reactors", giving a survey of the presently tested and used computer codes applicable to the in-core fuel management of light and heavy water reactors.

FIGURE CAPTIONS

Figure 1 Fuel utilization for electricity production by nuclear and fossil power plants

Figure 2 Cost of electricity production for nuclear and fossil power plants

Figure 3 Differences in the management of nuclear and fossil fuels

Figure 4 Financial engagements and responsibilities of utility, industry, and government in nuclear fuel management

Figure 5 Utility's nuclear fuel management: Tansition from present to desired situation

Figure 6 Areas of in-core fuel management

Figure 7 In-core fuel management: Program system for optimization of in-core fuel management.

Figure 1

		N U C L E A R					F O S S I L
FUEL USAGE		BURNER	CONVERTER			BREEDER	BURNER
STEAM SUPPLY SYSTEM		PWR, BWR	HWR	HTR		LMFBR	BOILER
FUEL		U, Pu	U, Pu	U, Pu	U, Th	U, Pu	Oil, Coal
FUEL UTILIZATION FOR ELECTRICITY PRODUCTION (%)	no recycle	0,2	0,2 - 0,3	0,2 - 0,3	0,3	NA	34 - 36
	full recycle	0,2 - 0,3	0,4	0,4	0,5	24 - 28	NA

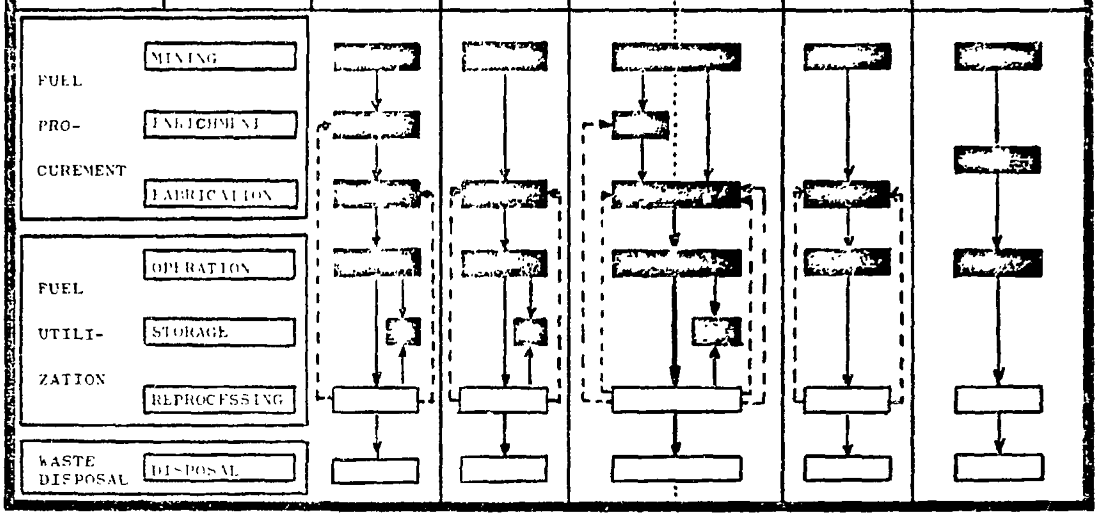


Figure 2

COSTS	1970 1)		1975 2)	
	FOSSIL (oil)	NUCLEAR (PWR, BWR)	FOSSIL (oil)	NUCLEAR (PWR, BWR)
	600 MWe	600 MWe	650 MWe	1300 MWe
	6000 h/a	6000 h/a	7000 h/a	7000 h/a
CAPITAL (%)	37	57	18	56
OPERATION (%)	6	33	6	15
FUEL (%)	57	10	76	29
TOTAL (Pf/kWh)	3,0	2,4	6,4	4,3

1) Reference: Yearbook of Atomwirtschaft 1970

2) Reference: Reaktortagung 1976, Michaelis, H., Status der Wettbewerbsfähigkeit der Kernenergie, p. 319

Figure 3

FUEL CYCLE		FOSSIL	NUCLEAR
FUEL PROCUREMENT	PROSPECTION	ESTABLISHED	ESTABLISHED
	MINING EXTRACTION	ESTABLISHED	ESTABLISHED
	PREPARATION FOR USE	ESTABLISHED	ESTABLISHED
	TRANSPORT	BIG QUANTITIES	SMALL QUANTITIES
FUEL UTILIZATION	PLANT OPERATION	ESTABLISHED	ESTABLISHED
	FUEL STORAGE	BIG QUANTITIES	SMALL QUANTITIES
	REPROCESSING	NA	NECESSARY
	RECYCLING	NA	NECESSARY
WASTE DISPOSAL from	FUEL PROCUREMENT	ESTABLISHED	ESTABLISHED
	PLANT OPERATION	NEW	NEW
	REPROCESSING	NA	NEW
	PLANT DECOMMISSIONING	ESTABLISHED	NEW ASPECTS
ENGINEERING STAFF REQUIREMENTS		LOW	HIGH
SAFEGUARD ASPECTS		NA	IMPORTANT
PUBLIC CONTROVERSY		MINOR	MAJOR
FUEL COSTS		HIGH	LOW
CAPITAL INVESTMENT FOR FUEL CYCLE		HIGH	LOW

Figure 4

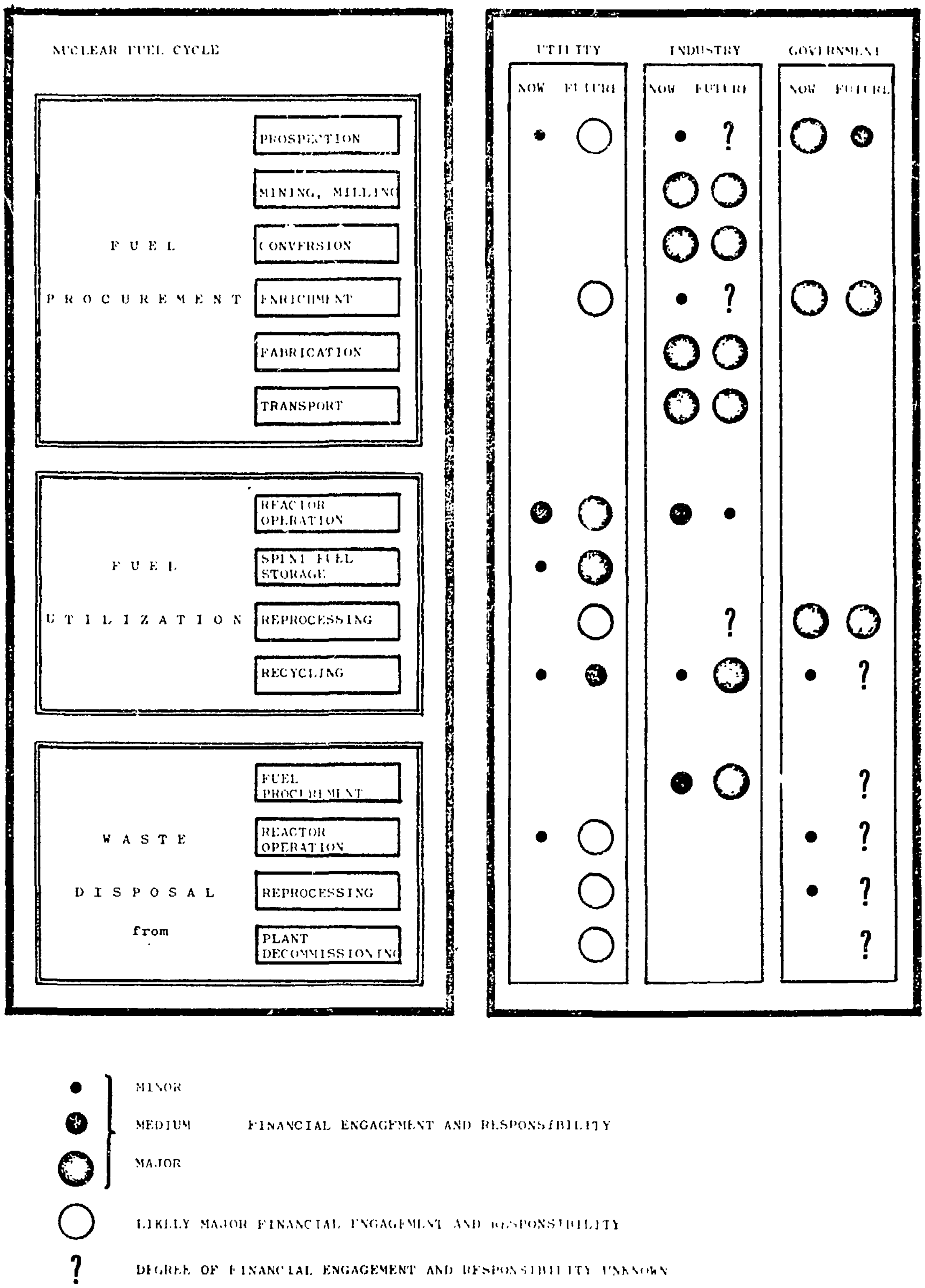

NUCLEAR FUEL CYCLE
FUEL PROCUREMENT
PROSPECTION
MINING, MILLING
CONVERSION
ENRICHMENT
FABRICATION
TRANSPORT
FUEL UTILIZATION
REACTOR OPERATION
SPENT FUEL STORAGE
REPROCESSING
RECYCLING
WASTE DISPOSAL from
FUEL PROCUREMENT
REACTOR OPERATION
REPROCESSING
PLANT DECOMMISSIONING
UTILITY
INDUSTRY
GOVERNMENT
NOW
FUTURE
MINOR
MEDIUM
MAJOR
FINANCIAL ENGAGEMENT AND RESPONSIBILITY
LIKELY MAJOR FINANCIAL ENGAGEMENT AND RESPONSIBILITY
DEGREE OF FINANCIAL ENGAGEMENT AND RESPONSIBILITY UNKNOWN

Figure 5

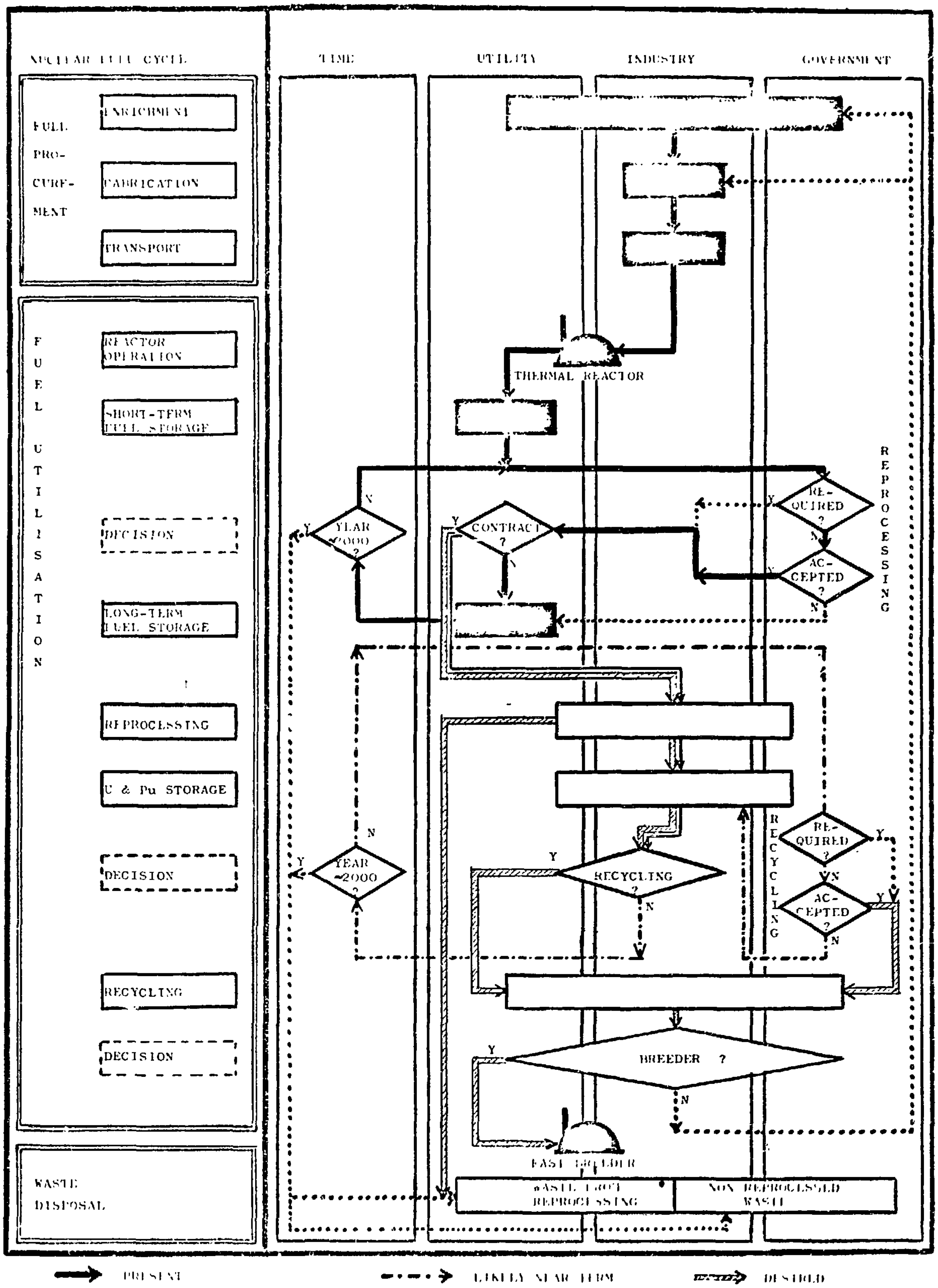

NUCLEAR FUEL CYCLE
TIME
UTILITY
INDUSTRY
GOVERNMENT
FUEL PRO-CURE-MENT
ENRICHMENT
FABRICATION
TRANSPORT
FUEL UTILISATION
REACTOR OPERATION
SHORT-TERM FUEL STORAGE
DECISION
LONG-TERM FUEL STORAGE
REPROCESSING
U & Pu STORAGE
DECISION
RECYCLING
DECISION
WASTE DISPOSAL
THERMAL REACTOR
YEAR ~2000 ?
CONTRACT ?
RE-QUIRED ?
AC-CEPTED ?
REPROCESSING
YEAR ~2000 ?
RECYCLING ?
RE-QUIRED ?
AC-CEPTED ?
RECYCLING
BREEDER ?
FAST BREEDER
WASTE FROM REPROCESSING
NON REPROCESSED WASTE
Y
N
PRESENT
LIKELY NEAR TERM
DESIRED

Figure 6

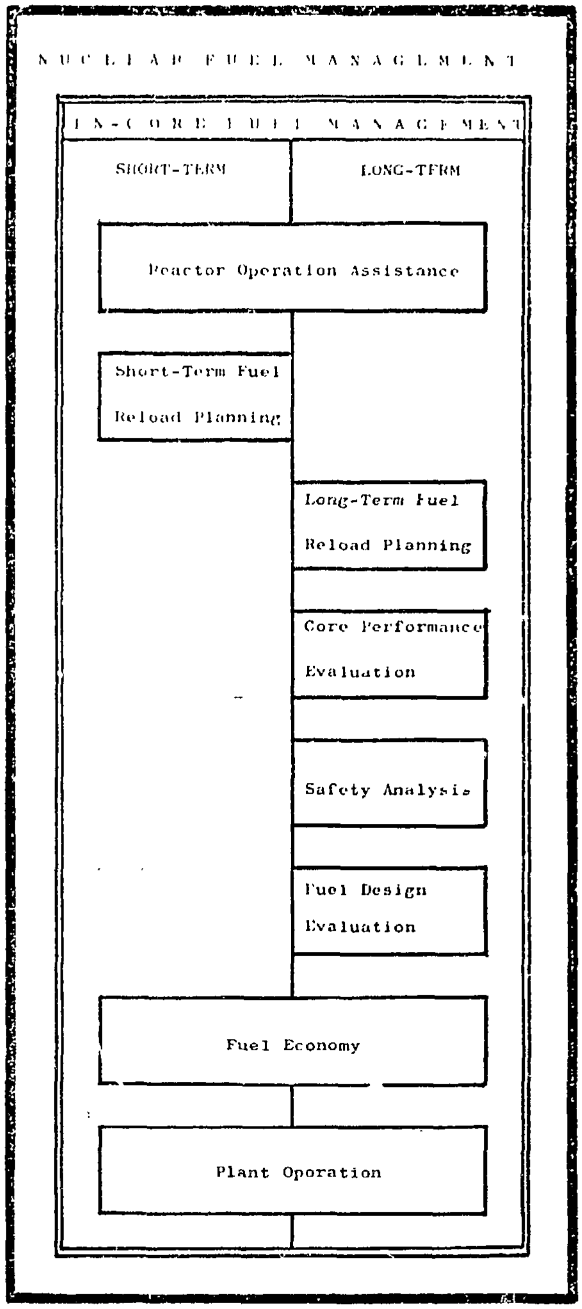
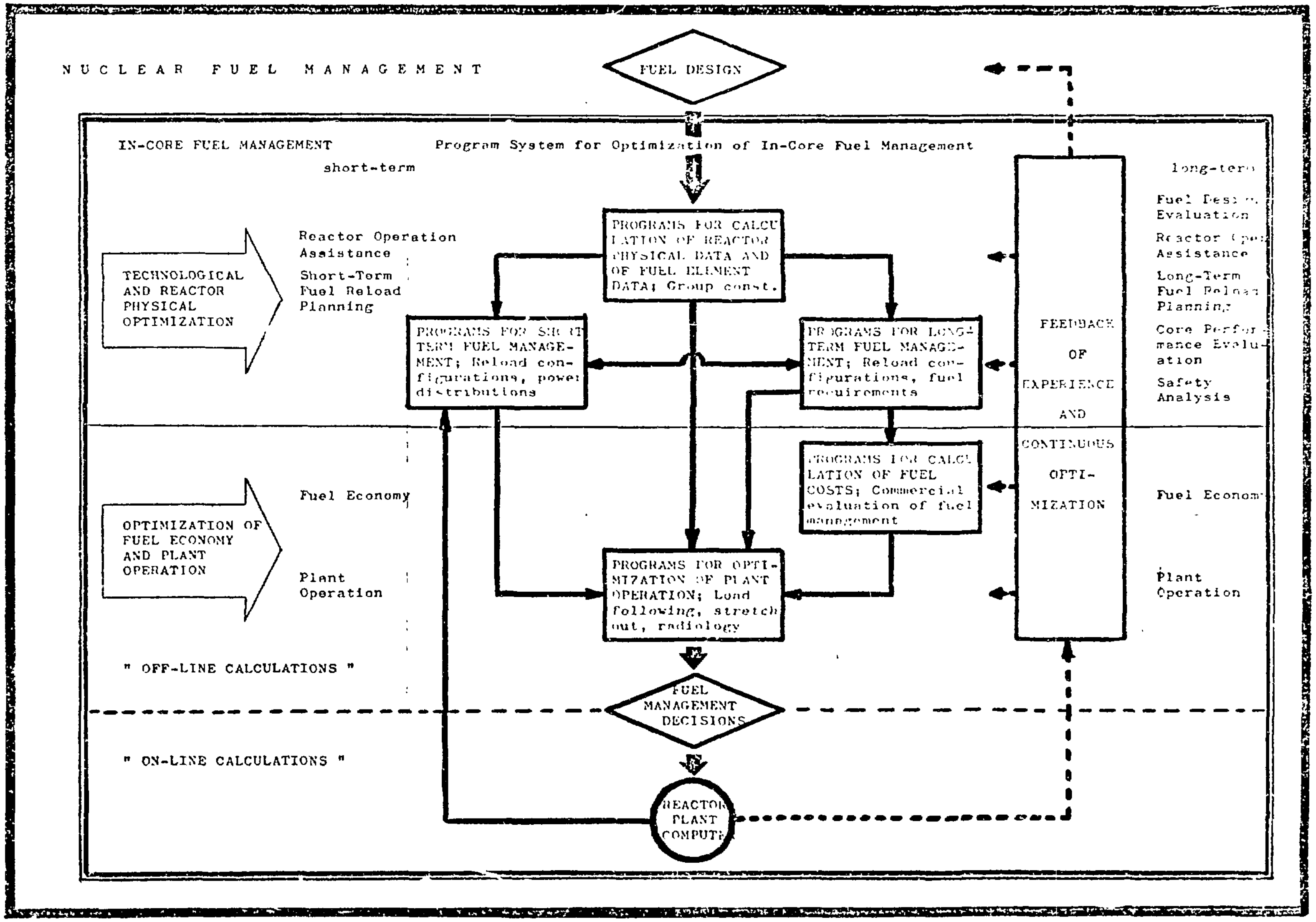

NUCLEAR FUEL MANAGEMENT
IN-CORE FUEL MANAGEMENT
SHORT-TERM
LONG-TERM
Reactor Operation Assistance
Short-Term Fuel Reload Planning
Long-Term Fuel Reload Planning
Core Performance Evaluation
Safety Analysis
Fuel Design Evaluation
Fuel Economy
Plant Operation

Figure 7


NUCLEAR FUEL MANAGEMENT
FUEL DESIGN
IN-CORE FUEL MANAGEMENT
Program System for Optimization of In-Core Fuel Management
short-term
long-term
TECHNOLOGICAL AND REACTOR PHYSICAL OPTIMIZATION
Reactor Operation Assistance
Short-Term Fuel Reload Planning
PROGRAMS FOR CALCULATION OF REACTOR PHYSICAL DATA AND OF FUEL ELEMENT DATA; Group const.
PROGRAMS FOR SHORT TERM FUEL MANAGEMENT; Reload configurations, power distributions
PROGRAMS FOR LONG-TERM FUEL MANAGEMENT; Reload configurations, fuel requirements
PROGRAMS FOR CALCULATION OF FUEL COSTS; Commercial evaluation of fuel management
PROGRAMS FOR OPTIMIZATION OF PLANT OPERATION; Load following, stretch out, radiology
FEEDBACK OF EXPERIENCE AND CONTINUOUS OPTIMIZATION
Fuel Design Evaluation
Reactor Oper. Assistance
Long-Term Fuel Reload Planning
Core Performance Evaluation
Safety Analysis
OPTIMIZATION OF FUEL ECONOMY AND PLANT OPERATION
Fuel Economy
Plant Operation
" OFF-LINE CALCULATIONS "
FUEL MANAGEMENT DECISIONS
" ON-LINE CALCULATIONS "
REACTOR PLANT COMPUTER