International
Nuclear
Fuel
Cycle
Evaluation

XA8002400

INFCE

INFCE/DEP./WG.4/36

BASE CASE

INDUSTRIAL REPROCESSING PLANT

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P. O. Box 100
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November, 1st, 1978

Task 3

BASE CASE

INDUSTRIAL REPROCESSING PLANT

Contributed by the delegation of the Federal Republic of Germany.

BASE CASE INDUSTRIAL REPROCESSING PLANT

0. Introduction

This document deals with the general description, the design philosophies and operating conditions of a reprocessing plant for thermal reactor fuel. Based on current technology, actual operating experience and available development results the description identifies the base case of an industrial scale reprocessing plant and provides by this a means for relating and comparing the different national plans and schemes with respect to reprocessing.

To comply with this objective the description has to be generally applicable with clearly defined boundaries to the contiguous installations up- and downstream either co- or dislocated with the reprocessing plant. This includes in particular:

(a) interim storage ponds (storage required beyond reprocessing plant buffer storage)

(b) mixed oxide (MOX) fuel fabrication, including plutonium storage and conversion, fuel element fabrication and assembly plus MOX element storage prior to shipment

(c) uranium storage and conversion prior to further utilization

(d) waste conditioning facilities (HAW, MAW, LAW; excluding the in-plant waste pretreatment) and storage prior to transfer to the repository

and

(e) waste repositories

Appropriate transfer and transportation systems between the different facilities are needed.

Compared with existing plants or projects the demarcation line between the reprocessing plant and the other facilities of a nuclear fuel cycle as drawn here may appear arbitrary, nevertheless they are fixed in order to allow comparison with deviating design of national projects.

1. Definition of the Plant

1.1 Objectives

The plant described is a thermal reactor fuel reprocessing plant the objectives of which are:

(a) recovery of uranium and plutonium from irradiated oxide fuel elements; the burn-up of elements averaged over a campaign is limited to 40 GWd/t fuel,

(b) partition of uranium and plutonium and their final purification and concentration prior to transfer for further processing; products are uranyl nitrate solution and plutonium nitrate solution,

(c) pretreatment of the solid, liquid and gaseous wastes arised.

1.2 Chemical Flowsheet and Constituents of the Plant

The plant applies a Purex-type flowsheet with a chop-and-leach head end procedure. Codecontamination and partitioning of uranium and plutonium are performed in the first extraction cycle. Uranium and plutonium are subsequently purified in two separate lines consisting of two extraction cycles each.

The plant comprises ponds for reception and buffer storage of spent fuel elements, head end installations for shearing of the elements and dissolution of the fuel in nitric acid and a sequence of cycles for the extractive separation and purification of uranium and plutonium. Furthermore, there are process units for pretreatment of the various types of waste arising at different points in the course of fuel reprocessing. Interim storage capacities are foreseen for the concentrated highly active fission product concentrate (HAWC) as well as for concentrated medium active aqueous and organic liquid wastes (MAW) (see attached simplified flow diagram and plant diagram).

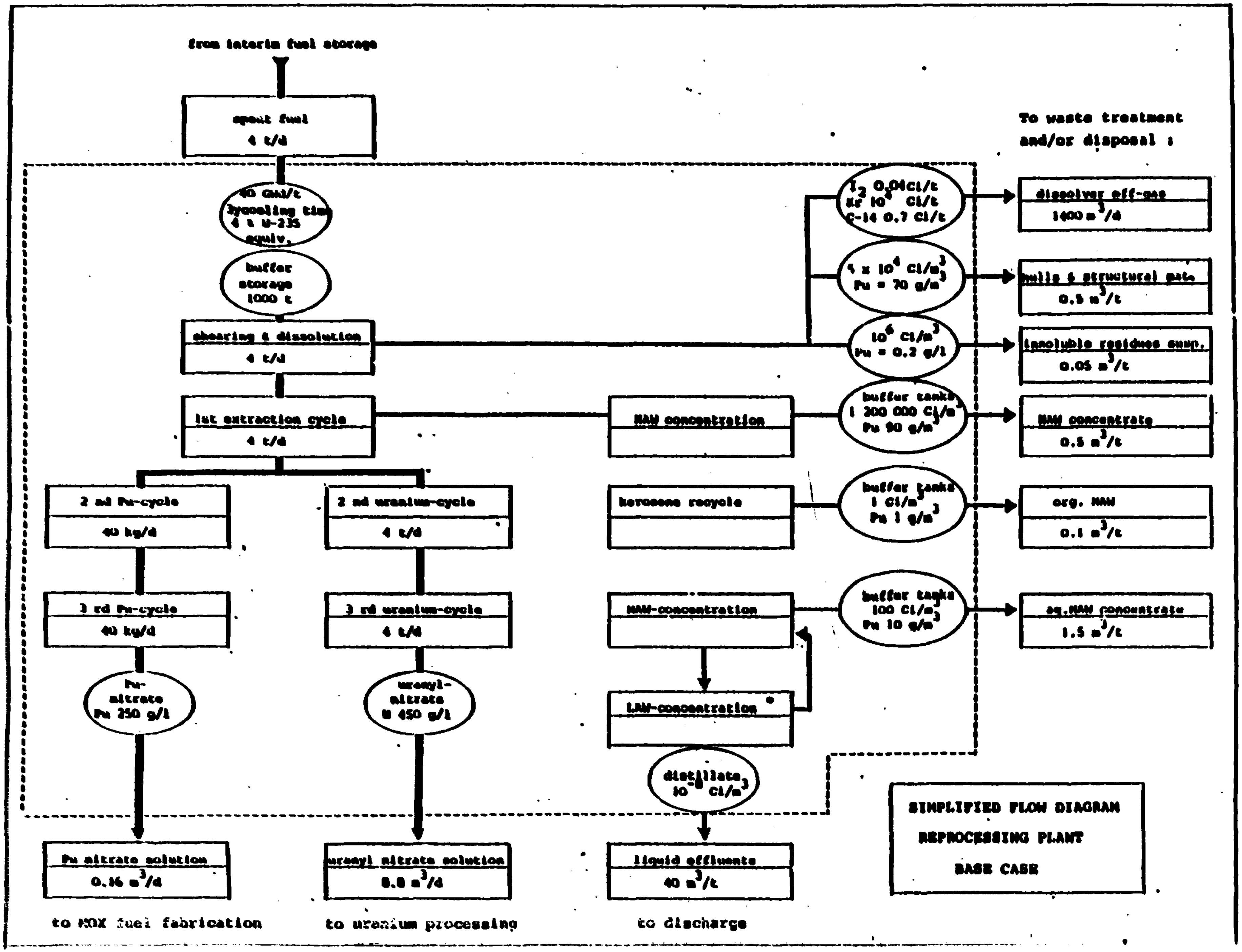
1.3 Plant Characteristics and Design Principles

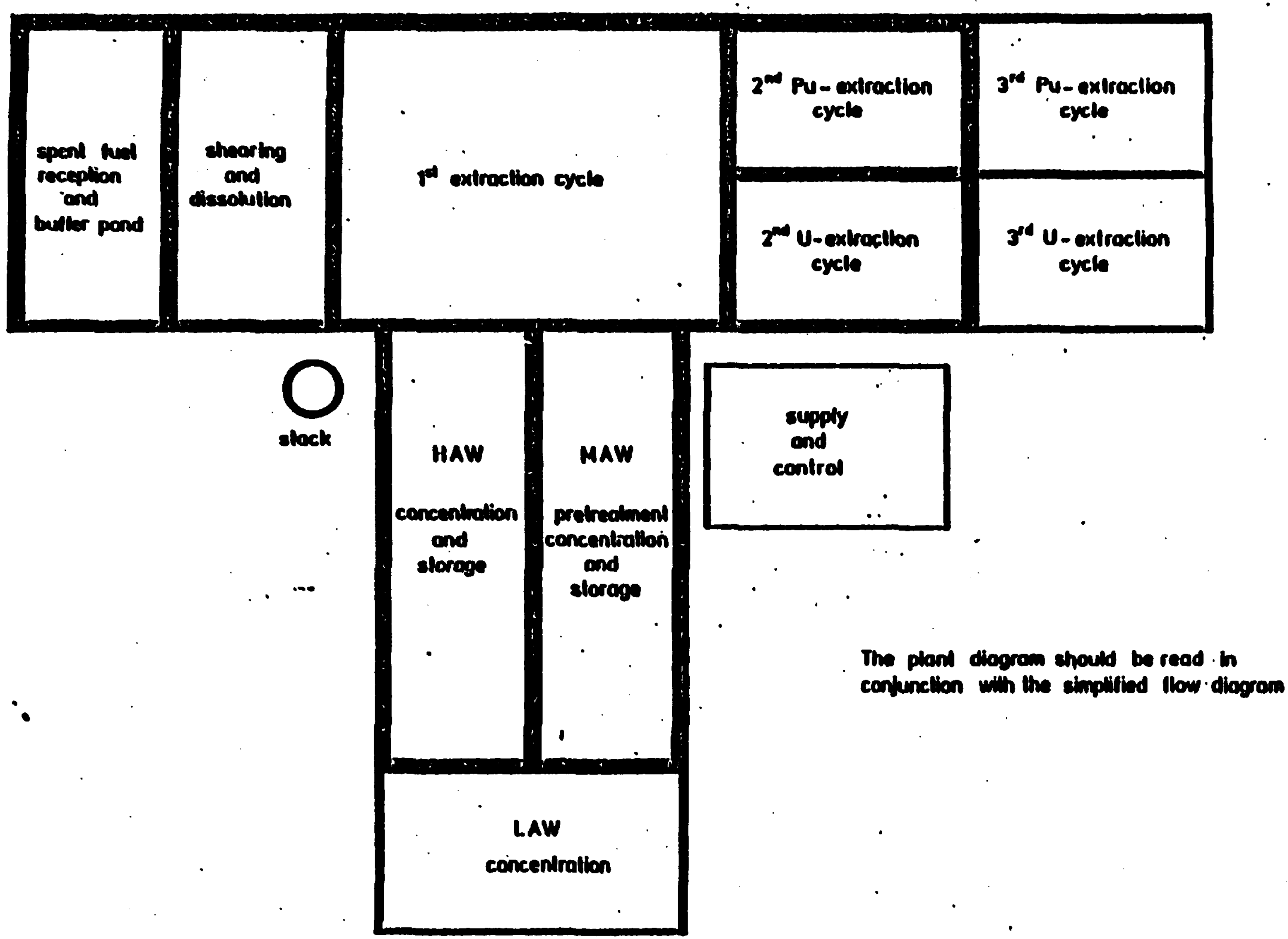
The Plant is characterized as follows:

- design capacity — 4 t U/d
- availability — between 175 d/y (very conservative) and 300 d/y.

Commercial operation within these parameters will yield a yearly throughput of 1000 t U/y.

- burn up of fuel elements (averaged over a campaign) — up to 40 GWd/t.
- cooling time of fuel elements — about 3 years
- mode of operation — continous operation on shift


from interim fuel storage
spent fuel
4 t/d
40 GWd/t
3y cooling time
4 % U-235
equiv.
buffer
storage
1000 t
shearing & dissolution
4 t/d
1st extraction cycle
4 t/d
2 nd Pu-cycle
40 kg/d
2 nd uranium-cycle
4 t/d
3 rd Pu-cycle
40 kg/d
3 rd uranium-cycle
4 t/d
Pu-
nitrate
Pu 250 g/l
uranyl-
nitrate
U 450 g/l
Pu nitrate solution
0.16 m3/d
uranyl nitrate solution
8.8 m3/d
to MOX fuel fabrication
to uranium processing
HAW concentration
kerosene recycle
MAW-concentration
LAW-concentration
distillate
10-8 Ci/m3
liquid effluents
40 m3/t
to discharge
I2 0.04 Ci/t
Kr 10? Ci/t
C-14 0.7 Ci/t
4 x 10^4 Ci/m3
Pu = 70 g/m3
10^6 Ci/m3
Pu = 0.2 g/l
buffer tanks
1 200 000 Ci/m3
Pu 90 g/m3
buffer tanks
1 Ci/m3
Pu 1 g/m3
buffer tanks
100 Ci/m3
Pu 10 g/m3
To waste treatment
and/or disposal :
dissolver off-gas
1400 m3/d
hulls & structural mat.
0.5 m3/t
insoluble residues susp.
0.05 m3/t
HAW concentrate
0.5 m3/t
org. MAW
0.1 m3/t
aq.MAW concentrate
1.5 m3/t
SIMPLIFIED FLOW DIAGRAM
REPROCESSING PLANT
BASE CASE



Plant Diagram (schematic)

- Due to the close neighbourhood to the other fuel cycle facilities at the same site, generally, storage capabilities in the plant can be reduced to those capacities, which are indispensable to maintain plant operability. This holds specially for the buffer storage pond of spent fuel elements and the uranium- and plutonium product streams. As far as the concentrated highly active fission product concentrate (HAWC) and the concentrated intermediate active aqueous and the organic liquid wastes are concerned capacities for intermediate storage are provided.

- spent fuel reception and buffer storage for plant operation only	1000 t U
- Uranylnitrate buffer storage (450 gU/l)	100 m^3
- Plutoniumnitrate buffer storage (250 g Pu/l)	1 m^3

<u>Liquid waste</u>

(Definition of waste specification according to IAEA-classification)[a]

- highly active waste concentrate (HAWC) (> 10^4 Ci/m^3)	initially available capacity 1000 to 2000 m^3
- medium level aqueous waste concentrate (MAW) (10^{-1} to 10^4 Ci/m^3)	minimum storage capacity 1500 m^3 according to one year operation; prudent management practice may require up to 10 000 m^3.

- organic liquid waste	200 m^3 prior to processing and recycling
- low active liquid waste (LAW) ($<10^{-1}$ Ci/m^3)	residue after evaporation is added to the MAW

Solid wastes

Arisings of solid waste consist essentially of the following categories:

- cladding and structural material of fuel elements, residue of feed clarification	0,6 m^3 / t
- ion exchange resins and iodine absorber material	10 m^3 / year
- off-gas and exhaust air filters	500 m^3 / year
- Pu-contaminated waste, decontamination material and engineering wastes	1,5 m^3 / t

The solids are stored intermediately in solid waste silos or uncompacted in drums before they are transferred to the central waste treatment facility.

Gaseous waste

The aerial effluents of the plant will comprise air from the operating areas, the cells and the vessel ventilation system. The vessel ventilation air from the earlier parts of the process (shearing and dissolution) will contain iodine-129 and kryton-85 and is therefore segregated for further treatment. The plant will be fitted with an absorption and retention system for iodine whilst the kryton-85 will be discharged with the filtered air. Whereas removal of krypton-85 was not important in the past, presently methods are under development for retention of krypton. The plant will be designed to segregate the krypton-85 bearing stream and direct it to a krypton concentration and storage plant when available.

Plant availability

Although the reprocessing plant is principially assumed to run on a single line process, some provision for redundancy has to be made. As the need for redundancy besides the maintenance philosophy applied (see chapter 2) depends on

- engineering standards and capabilities available in the country in question
- commercial risks, the operator is prepared to take,

no generally valid decision or recommendation can be made.

2. Maintenance Philosophy

The base case utilises the latest technology for maintenance of radiochemical plants and this comprises three different systems each with its own application to the appropriate section of the plant. These are:

(a) remote maintenance by installed mechanical devices,

(b) modular replacement employing decontamination, removal and replacement of components e.g. evaporator calandria,

(c) contact maintenance which involves complete decontamination, entry to the cells, and repair or replacement of plant equipment by normal engineering interventions.

Remote maintenance will be employed for mechanical items in the highly active parts of the plant such as in the shear cell which will be equipped with in-cell hoists, manipulators and specially designed tools.

The modular replacements will be applied chiefly to items the life of which is expected to be less than that of the whole plant. These items will be designed for partial decontamination and removal by means of hoist and replacement utilising remote joints or welding.

Contact maintenance will be applied to the highly active and medium active solvent extraction plant and similar areas. Its use presupposes a stand-by line of similar equipment in a separate cell if maximum use is to be made of the commercial potential of the plant.

It should be noted that from a non-proliferation point of view the acceptance of this philosophy means that those areas of the plant containing fissile material in a form suitable for diversion, e.g. dissolver solution onwards, are in contact maintenance areas which require lengthy decontamination before access for plant modification can be made, whereas the use of remote maintenance techniques which require very little time for a plant modification or repair to be done is confined to the shear cells and similar head end operations where the fuel is not in a readily divertible form.

Plant items will, as far as possible, be fabricated from all-welded corrosion-resistant stainless steel and the use of moving parts inside process cells will be minimized, e.g. by employing air lifts or steam ejectors for liquor transfers. Equipment for the supply of services or inactive chemicals, will in general, be located outside the biological shielding and will be maintained directly. Remote maintenance techniques will be rehearsed on full-scale mock-ups, thus providing highly-trained personnel to carry out the in-plant operations.

3. Safety philosophy

Once a general lay-out of the reprocessing plant has been identified detailed analysis can be performed to determine the specific safety requirements. Items of general importance are e.g. radiation protection, the enclosure of radioactive materials (containment) and measures of criticality control.

3.1 Radiation protection

The facility is assumed to use currently available technology for radiation protection measures. It is built according to internationally accepted standards of shielding and operated within the guidelines of environmental radiological safety recommended by the International Commission on Radiological Protection (ICRP).

3.2 Containment

Handling of radioactive and fissile material is a typical feature of a reprocessing plant. Because of the special properties of the material a multiple containment system is applied in those sections of the plant where fissile and radiating material is handled. This kind of enclosure meets as well in-plant and environmental protection requirements as proper protection against unauthorized action.

To achieve these objectives special design criteria are observed, including:

(a) the multiple barrier principle according to which radioactive materials are treated or stored in housings consisting of several independent enclosures, e.g. :
- stainless steel process vessels,
- heavily shielded process cells
- in the essential areas of the plant inner or outer building structures must be an impact-resistant barrier.

(b) strict observation of quality assuring standards for the activity enclosures and the corresponding safety equipment.

(c) to reduce potentially harmful events to a minimum, partly inherent safety precautions are foreseen, as for example:

- avoidance or reduction of nuclear materials' transfers between installations,
- avoidance of high pressure and elevated temperatures in the process,
- precautions against interaction of process equipment in the case of an incident.

Based on postulated modes of failure, including incidents due to external hazards, such as earthquake, flood, storm and fire, calculations must prove that the effects of the damage remain within predetermined limits with regard to:

- activity release,
- interaction between different components,
- radiation exposure to the operating people and the public.

3.3 Criticality Control

During fuel processing the fissile material may exist as a solid or - mainly - in form of aqueous or organic nitrate solutions. Measures have to be taken to prevent critical excursions. The aim of all methods is to assure subcritical conditions under all circumstances.

Important parameters effecting criticality are the following:

Initial enrichment of the fuel, burn-up, mass, concentration, moderation, presence of neutron poisons, geometry, reflection and interaction.

The control of criticality is exercised by the following measures:

- administrative measures, such as mass limitation or concentration limitation, checked by analysis and/or on-line monitoring e.g. with neutron monitors,
- application of soluble or heterogeneous neutron poisons,
- geometrical limitations of the equipment in connection with precautions against neutron interaction.

No criticality control measures are required in process areas where fissile material is absent or is present merely in traces. The transition from nuclearly favorable to non-controlled equipment will be protected by the use of on-line instrumentation, analytical control and, where necessary, physical devices.

4. Safeguards and physical protection

The objective is the detection and prevention of diversion of significant quantities of nuclear materials from peaceful nuclear activities.
To obtain this objective

- material accountancy
- containment design and operational measures
- surveillance
- physical protection

will all be applied.

4.1 Material accountancy

Accountancy means the determination of the quantity of fissile materials within the plant and its change over a period of time. It is accomplished by:

- definition of the material balances areas
- selection and definition of the key measuring points for determining the nuclear material flow
- selection and definition of the key measuring points for determining the physical inventory
- selection of analytical and measuring methods for fissile material which are the basis for accounting and operating records, accounting reports and special reports
- frequency and procedure for evaluating the physical inventory

4.2 Containment design and operational measures

The construction of the reprocessing plant to meet the protection measures described in 3.) provides a very substantial protection against unauthorized access to fissile material. It will be part of the design to provide that these protective systems are integrated to ensure the highest degree of resistance against diversionary activities.

The design of such penetrations of the protective shielding as are necessary e.g. for sample and instrument devices, will be such that they are protected by strong structural features, interlocked operating devices and surveillance instrumentation.
Waste streams containing fissile material will be batched, analized and the batch later recorded. The concentration of the plutonium in the waste streams is in the range of 1 to 2 percent (see flow sheet). This material is strongly diluted and not freely accessible due to containment measures and the high radioactivity.

4.3 Surveillance

The plant is designed in such a way to facilitate an efficient surveillance by the inspectors of international authorities, who are entitled to carry out controls in the plant within the context of procedures described above.
In performance of their duties the inspectors will have all appropriate access to the plant.
National authorities and the plant management will support the international inspectors.
In addition, to safeguard the flow of fissile material, cameras (film or television) may be applied to observe the movements and/or handling of such material at strategic points.

4.4 Physical protection

Over and above that protection given by the radiation and contamination barriers inherent in the design, the physical protection of the plant will be further reinforced by the use of modern methods to prevent illegal and forced exit or entry.
These measures will comprise resistant barriers in the building shell, a limited number of ingress and egress points, surveillance and detective devices and in depth segregation of the reprocessing site.

5. Specification and Selection of Major Equipment

The extensive experience in design and construction of reprocessing plants has shown that the following methods will lead to successfull implementation:

All production and safety relevant equipment of the plant has to meet specific requirements. These parts are to be designed, manufactured and checked according to quality assurance standards. The standards specify materials and fabrication methods as well as preliminary and final acceptance tests. They are submitted to experts' approval and the technical data sheets of the equipment are submitted for clearance.

Before any safety relevant equipment is installed certificates on preliminary tests, construction inspections and final work-tests have to be presented to and checked by the licensing authorities.

After installation, all safety relevant functions will be proven according to performance check-lists and a final acceptance certificate will be issued.

The selection of major equipment is based on numerous criteria, some of which are of paramount importance:

- reliability of performance
- safe operation
- simplicity of operation, repair and replacement
- proven and with the handling of radioactivity compatible design.

Some major equipment being selected for the reference design and possible alternatives are given below:

process step	reference design	alternative
shearing	element bundle shear	single pin chopping with disassembly of the fuel element in advance chemical decladding
first extraction cycle	pulsed columns	mixer settlers centrifugal contactors
second and third uranium extraction cycle	mixer settlers	pulsed columns
second and third plutonium extraction cycle	pulsed columns	-

A multiplicity of suitable equipment for the different process units and further details are published in the open literature.

6. Ventilation philosophy

The ventilation system is designed

- for adequate supply of fresh air to all buildings
- to maintain specified room temperatures
- for removal of contaminated room air as well as of noxious gases and vapours
- for filtering and controlled release of the exhaust air via a stack

The aerial effluents of the plant will comprise filtered air from the operating areas, the cells and the vessel ventilation system.
The filters will be designed to reduce the entrained activity to acceptable levels and will contain all foreseeable incidents in the plant.

According to their radioactive material release potential the rooms of the buildings are connected to different graded negative pressure zones to prevent the spreading of contamination inside the buildings.
The pressure gradient ensures a directional flow from rooms with a lower contamination potential to those with a higher radioactivity inventory. Thus, various pressure zones are installed in each building. The lowest pressure is maintained in the cell block.

Prior to the discharge to the environment by a stack all exhaust air which is or might be contaminated is passed through high efficiency particulate and aerosol filters.

7. Utilities and services required

7.1 Cooling water, Electricity supply, Steam

Cooling water and electricity supply are of particular interest with respect to the reliable cooling of self-heating highly radioactive wastes. For emergencies, sufficient water is available from a cooling pond and power supply is provided by diesel generators.

The annual consumption of cooling water, electricity and steam is approximately as follows:

- cooling water	2,000,000 m^3 / y
- electricity	100,000,000 kwh / y
- steam	500,000 t / y

7.2 Transport connections

The site is situated such that heavy loads have access at all times by rail and/or road.

7.3 Effluents

A local sewage system is able to cope with the accruing sanitary water and the possibility of disposing of industrial effluents exists.

7.4 Other services

In view of the employment of highly qualified personnel the site is situated such that the necessary infrastructure is provided for.
The site is also within the range or larger industrial enterprises which can supply technical services and from which specialists can be drawn in cases of major repairs.

8. Research and Development required to support plant construction

Research and Development within this context may have amongst others the prime objectives

- generation of data for system layout
- optimization of the process
- improvement of plant availability
- demonstration of system performance with respect to licensing.

The R+D Programmes may be related to

- basic research and development
- testing of components and pilot scale systems in cold and hot runs
- construction and operation of appropriately scaled pilot plants to qualify e.g. chemical flow sheets, remote techniques, training of personnel
- proving of components of actual size before implementation into the plant

Amount and type of research and development work required depend on the individual needs of the country in question.

9. Construction schedule

The attached Time-Schedule covers an estimated period of 11 years from start of planning to final tests and gives some indication of the interlinked activities between Licensing Authorities and Licensee:

Planning starts with Conceptual Study and Safety Analysis Report, both of which are required before filing the Application for approval.

Henceforth, basic and detailed engineering can be started, but will be continuously influenced by the conditions and requirements - especially on safety - which will be laid down in the licensing procedure during the whole course of the project.

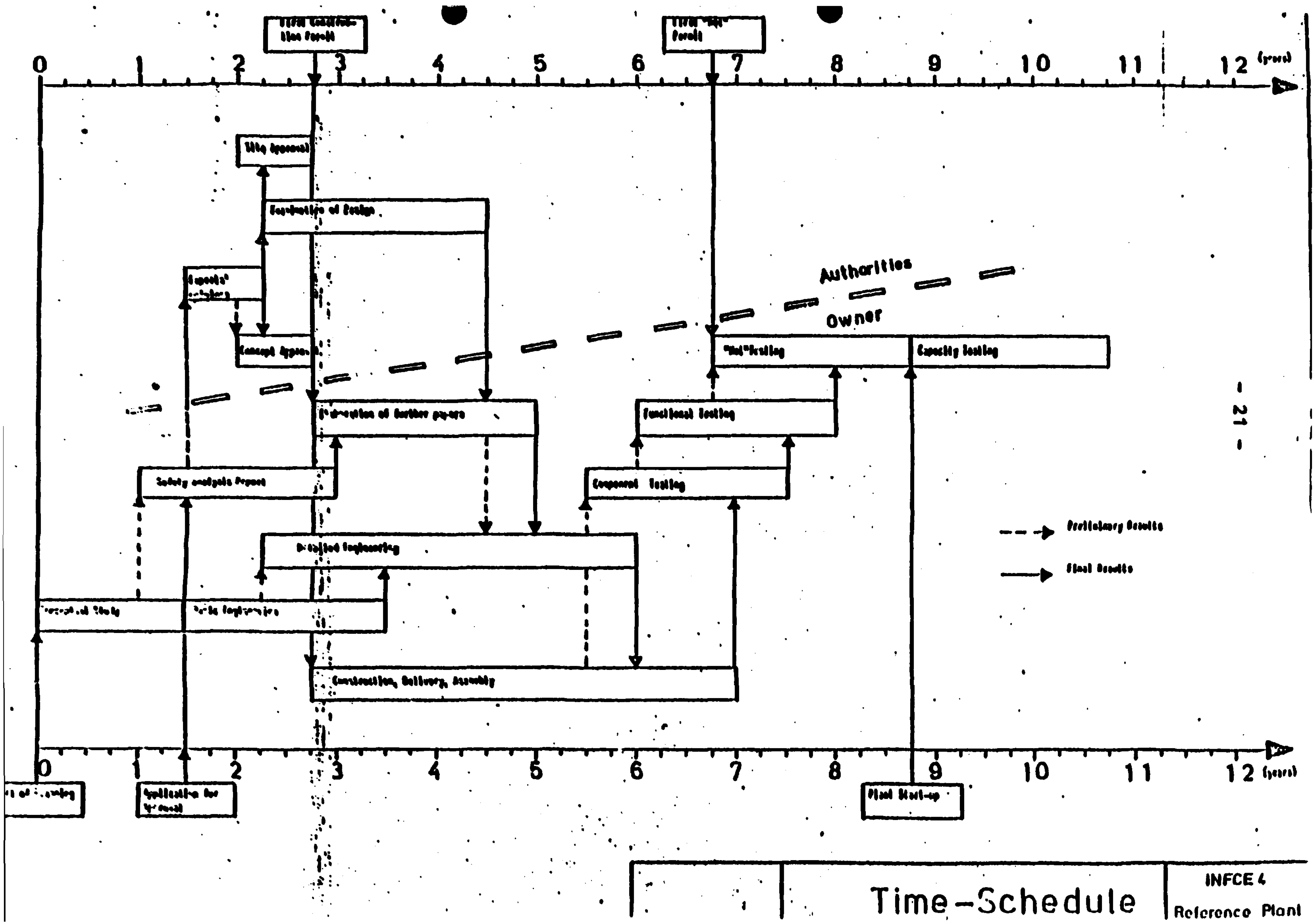
Meanwhile - supported by independent experts and advisors - the licensing authority works out rules and regulations for approval of site and concept and eventually issues the First Construction Permit, which enables the licensee to start construction-work on site.

Further construction permits will follow, laying down detailed requirements for the following steps of construction.

After construction and assembly of major portions of machinery and equipment, "cold" component testing will start followed by functional testing of sections of the plant.

Having examined the test-results and being satisfied, the licensing authority will issue, in accordance with the licensing procedure, a limited preliminary operation permit which allows the licensee to start the first operational test of a plant section with radioactive material.

Other preliminary operation permits for further sections will be issued, and after having tested all sections of the plant, reprocessing of spent fuel will commence with small batches at first. The plant will reach design capacity within approximately two years.


Authorities
Owner
Time-Schedule
INFCE 4
Reference Plant
0 1 2 3 4 5 6 7 8 9 10 11 12 (years)

10. Safety and Environmental Evaluation

Th- shearing and dissolving of fuel elements and the extraction and separation of uranyl- and plutoniumnitrate solutions from the highly radioactive fission products are the characteristic features of the Reprocessing Plant.

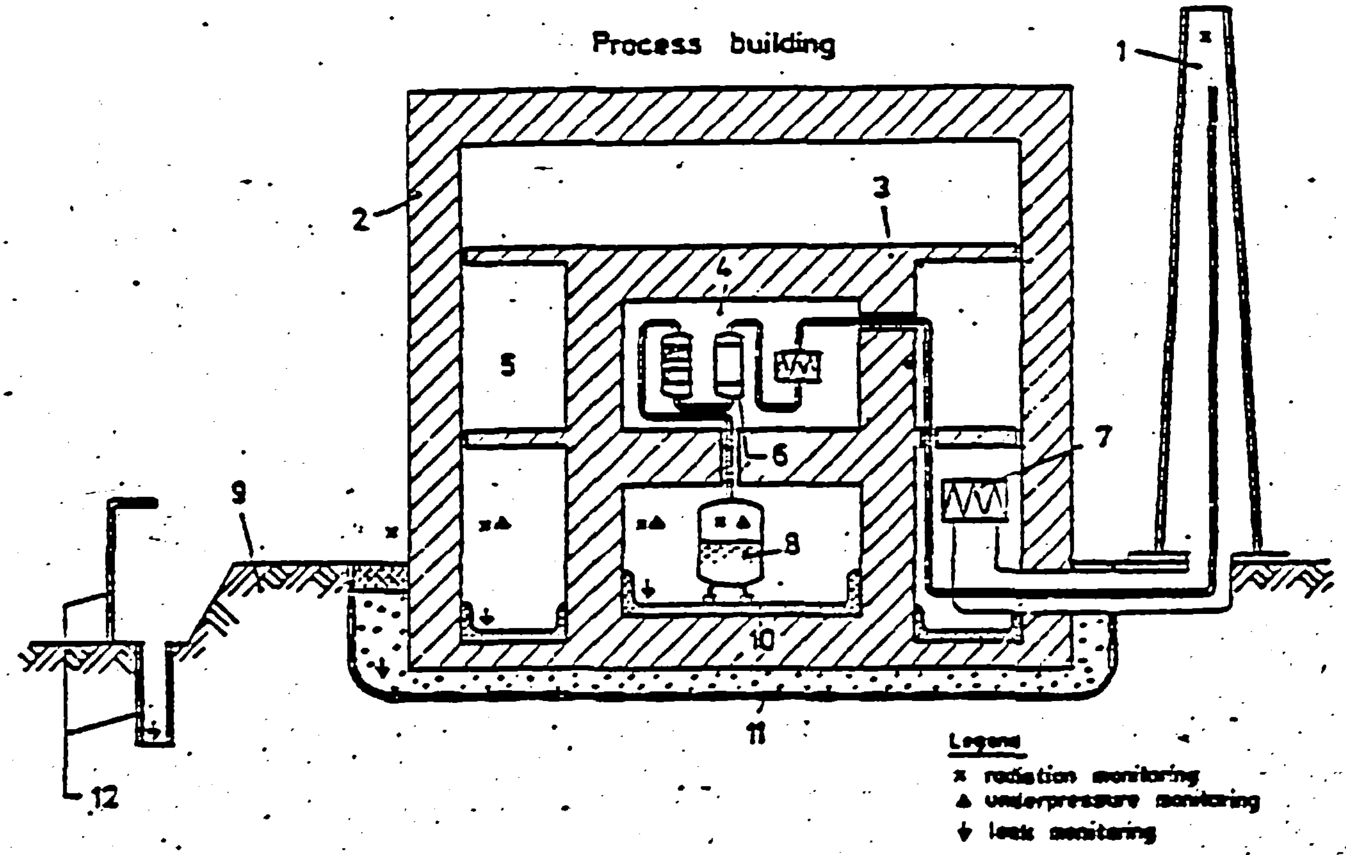
The handling of open radioactive material requires the containment system of multiple barriers as schematically shown in the attached drawing. The radioactive material is enclosed in a leak-tight system of stainless steel equipment, vessels and interconnecting piping. Any connection with the environment is equipped with highly effective devices to prevent spread of radioactivity; for instance, the ventilation system is equipped with filters designed to reduce the entrained activity to acceptable levels and to contain even all foreseeable incidents in the plant. All equipment and piping holding radioactive material is enclosed in "hot cells", which consist of heavy concrete walls in order to shield the personnel against radiation. The "hot cells" and the surrounding auxiliary rooms, intervention passages etc. are enclosed again by the outer concrete walls of the building. The essential areas of the plant are protected by an impact resistant barrier formed by the inner or outer building structures.

Further precautions are taken to avoid any inadmissible release of radioactivity during normal operation as well as during pre-supposed incidents, i.e. failure-events, which have been assumed and determined in the safety analysis report and are part of the licensing procedure. Such precautions are for example:

- High quality control standards for design and fabrication
- Redundant systems for the safe removal of decay heat
- Redundant systems for safe plant control
- Operational procedures laid down with and approved by the licensing authority

Comprehensive measures are to limit the release of radioactive offgas and effluents even in case of failure events significantly below internationally agreed minimum values which have been laid down by ICRP-regulations, and will protect the plant personnel as well as the inhabitants of surrounding region.

A permanent control system inside and outside the fence is prepared to supervise continuously the strict observation of the permitted operation limits.



1 stack
2 outer protective shell
3 shielding structure
4 concrete cells
5 working area
6 vessel off-gas purification
7 double filter
8 process vessel
9 earth embankment
10 drip - tray
11 groundwater sealing
12 environmental monitoring (of air and groundwater)

	Containment system of a reprocessing plant

11. Cost Estimates

Due to deferring economic data in countries intending to get involved in reprocessing of spent nuclear fuel on a full industrial scale, it is necessary to quote data being estimated on an international basis.

In 1976 IAEA, Vienna, has published a study titled "Regional Nuclear Fuel Cycle Centres". Assuming that IAEA has considered all relevant data obtainable in concerning countries this study seems to be an adequate basis to give an idea of the cost structure.

Estimate of investment costs for irradiated fuel reprocessing facilities [1]

Components of costs \ Annual throughput capacity (t/a)	Costs (US$ X 10⁶) 300	750	1500	3000
1. Design and construction	465	650	915	1555
Conversion of Pu products	35	50	85	145
2. Recruitment, training and cold startup	35	55	75	100
Total investment costs (Items 1 & 2)	535	755	1075	1800
Unit investment costs (US$ X 10^6/(t/a))	1.78	1.01	0.72	0.60
3. Annual operating costs (US$ X 10^6)	20	30	40	50
Unit operating costs (US$ X 10^6/t)	0.067	0.040	0.027	0.017

1) See: Regional Nuclear Fuel Cycle Centres, Vol. I, 1977 Report of the IAEA Study Project, IAEA, Vienna, Table 17 - III.

The table summarizes the estimate of investment and annual operating costs anticipated for the various plant sizes considered. The investment costs are assumed to consist of two main components: (1) the design and constuction costs: and (2) staff recruitment and training costs, and cold-startup costs. All costs are given in 1976 US dollars. The economy of scale for the reprocessing plant is reflected in the unit investment and unit operating costs given in Table.

12. Economic evaluation

It is doubtful whether in the near future the credits for recycling of reprocessed uranium and plutonium will be equal to or higher than the reprocessing cost.

However, in the long term range there is a natural trend to higher uranium prices due to limited uranium reserves. At higher uranium prices the calculated credits for reprocessed uranium and plutonium will increase accordingly.

Furthermore, from an economic point of view it has to be taken into consideration that reprocessing of nuclear fuel from thermal reactors paves the way for the by 60 times more efficient use of uranium in fast breeder reactors.

The difference between the total costs for reprocessing of spent fuel including ultimate waste disposal and the credits for recycling of uranium and plutonium will be less than 5 % of the total nuclear power generating cost and cannot seriously effect the competitiveness of nuclear power.