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NUCLEAR FUEL MANUFACTURE

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ABSTRACT

The technologies used to manufacture nuclear fuel from uranium ore are outlined, with particular reference to the light water reactor fuel cycle. Capital and operating cost estimates for the processing stages are given, and the relevance to a developing uranium industry in Australia is discussed.

## 1. INTRODUCTION

Reactor types used in modern nuclear power stations require a variety of nuclear fuel materials and compositions. Thus gas-graphite reactors (GGRs) and heavy water-moderated reactors (HWRs) are fuelled with natural uranium metal and oxide respectively; fuel for light water reactors (LWRs) and advanced gas-cooled reactors (AGRs) is an oxide of uranium enriched in the uranium-235 isotope. Fast breeder reactors (FBRs) use mixed oxides of uranium and plutonium, and high temperature gas cooled reactors (HTGRs) operate on mixed oxides or carbides of thorium and enriched uranium. The generic term 'nuclear fuel cycle' refers to the entire program from the mining and processing of radioactive ores to the manufacture of different fuel types, reactor operation, and treatment and disposal of spent nuclear fuel and all other radioactive wastes from the cycle.

It has been predicted (OECD/NEA 1979) that LWRs will generate over 85 per cent of the Western World's nuclear power up to the year 2000 (Table 1). Accordingly this paper focuses on the technology and economics of the LWR nuclear fuel cycle and prospects for such an industry in Australia.

## 2. THE LWR NUCLEAR FUEL CYCLE

The processing stages and annual quantities of nuclear materials required to generate 1 gigawatt year (GWe-y) of electricity in an LWR (INFCE 1980a) are illustrated in Figures 1 and 2. Figure 1 depicts operations in a 'once-through' system without recycle of used fuel, and Figure 2 the reprocessing option with recycle of recovered uranium. These variants of the LWR fuel cycle involve the following operations:

- Mining and milling of uranium ores to produce a crude uranium ore concentrate known as 'yellowcake'. The uranium content of this concentrate is generally expressed in terms of the oxide  $U_3O_8$ .
- Conversion of the crude concentrate into pure uranium hexafluoride,  $UF_6$ .
- Enrichment of uranium in the uranium-235 isotope.
- Manufacture of oxide fuel (enriched  $UO_2$ ), and fabrication of fuel elements.
- Reactor operation.
- Reprocessing used fuel to recover and recycle uranium and plutonium or, alternatively, the disposal of unreprocessed spent fuel.
- Management of other radioactive wastes from the cycle.

## 2.1 Uranium Mining

Uranium is mined by three methods:

- (a) Open-cut mining, which is employed when the ore body lies close to the surface under an easily removable overburden and involves the mining, removal and stockpiling of all the material associated with the ore deposit. Overall uranium recovery efficiencies are usually about 85-90 per cent.
- (b) Underground mining is generally used for ore bodies at depths greater than 100 m, or when the ore lies under rock strata; it is more selective for ore than is open-cut mining but generally results in a lower overall uranium recovery efficiency from the deposit.
- (c) Solution mining, in which the ore is leached in situ from the underground deposit and the product solution pumped to a treatment plant; it can be employed where an ore body is horizontal, and situated on relatively impervious strata below the static water table.

Extreme care must be taken to avoid contamination of ground water. Overall recovery efficiencies of 65-70 per cent have been claimed (Frank, 1976).

Uranium can also be recovered as a by-product of other mining operations, e.g. from gold mine tailings in South Africa.

In Australia, open-cut mining techniques have recently been used at the Nabarlek deposit (Northern Territory), are in operation at Mary Kathleen (Queensland) and are planned for Jabiru and Koongarra (Northern Territory) and at Yeelirrie (Western Australia), whereas underground mining is proposed for the Jabiluka deposit (Northern Territory).

## 2.2 Milling of Uranium Ores

Uranium ores are crushed, ground and leached either by sulphuric acid or by sodium carbonate, the choice being determined mainly by the acidic or basic nature of the host rock (Merritt, 1971).

The acid leach process is suitable for the majority of uranium ores, but carbonate leaching is applicable to some uranium deposits in Western Australia, Canada and the United States.

In the acid leach process (Figure 3), the ore is heated with sulphuric acid and an oxidant. About 90 per cent of the uranium is extracted. The leach solution is decanted countercurrently from the insoluble residue (tailings) and transferred to a purification plant. The tailings residue is transferred to a retention pond, sometimes with neutralisation. The

uranium is extracted by an organic solvent or an ion-exchange resin from the bulk of the dissolved minerals, backwashed into aqueous solution and precipitated as a diuranate slurry with an alkali (e.g. ammonia). The slurry is thickened, centrifuged, dried and calcined into  $U_3O_8$  and the product pulverised and packaged into 200-litre drums.

In the carbonate leach process (Figure 4), the crushed and ground ore is heated with sodium carbonate solution containing some sodium bicarbonate with air or oxygen fed to the solution. About 90 per cent of the uranium is dissolved and the solution is decanted or filtered; undissolved solids are washed and transferred to a retention pond. Generally, the uranium carbonate solution does not require further purification; uranium may be precipitated selectively by adding sodium hydroxide, but pH must be closely controlled to retain contaminant ions in solution.

The precipitate of sodium diuranate is thickened and centrifuged. The barren solution is treated with carbon dioxide to regenerate sodium carbonate for re-use in leaching. The sodium diuranate may either be dried and packaged or treated by dissolution in sulphuric acid, and precipitation with ammonia, in which case the ammonium diuranate product is calcined.

### 2.3 Manufacture of Uranium Hexafluoride

The crude uranium ore concentrates are converted into pure uranium hexafluoride ( $UF_6$ ), a uranium compound which is readily gasified and is the feed stock for all commercial uranium enrichment plants.

Two major types of process are used for  $UF_6$  manufacture: the 'wet' processes in which the uranium is purified before conversion to  $UF_6$ , and a 'dry' hydrofluor process in which complete purification is not achieved until after the  $UF_6$  has been produced (ERDA 1976). Simplified block flow diagrams for wet and dry processes are given in Figures 5 and 6 respectively.

Both processes can achieve near complete recovery of uranium, total consumption of fluorine, and high utilisation of a number of other process chemicals such as hydrogen, hydrogen fluoride, and ammonia.

In a typical wet process, yellowcake is sampled, analysed and then dissolved in nitric acid, the solution purified by solvent extraction and either ammonium diuranate is precipitated and calcined to  $U_3O_8$  or the uranyl nitrate solution is evaporated and decomposed to uranium trioxide ( $UO_3$ ). The solid oxide is reduced with hydrogen to  $UO_2$ , reacted with hydrogen fluoride, HF, to form uranium tetrafluoride,  $UF_4$  and fluorinated to  $UF_6$  with elemental fluorine.

In the dry process, yellowcake is sampled, analysed and then conditioned for processing in a fluidised bed by crushing, pelletisation and, perhaps, removal of excessive sodium impurity. The  $U_3O_8$  is reduced to  $UO_2$  with hydrogen, reacted with hydrogen fluoride to form  $UF_4$ , fluorinated to  $UF_6$  with elemental fluorine, and fractionally distilled to separate the crude  $UF_6$  product from other volatile fluorides.

#### 2.4 Uranium Enrichment

Light water reactors require uranium enriched to 2-4 per cent in uranium-235. Commercial enrichment technologies (USAEC 1974) are based on gaseous diffusion or gas centrifugation of uranium isotopes in the form of  $UF_6$  vapour. The principles of commercial enrichment processes are shown in Figure 7.

In the gaseous diffusion process, gaseous  $UF_6$  is compressed and passed over a porous membrane. Molecules of  $UF_6$  containing the lighter isotope, uranium-235, diffuse through the membrane more rapidly than those with the heavier uranium-238 isotope; consequently, the  $UF_6$  passing the membrane has a slightly greater proportion of molecules containing uranium-235. The degree of enrichment for one membrane is minute and over a thousand successive diffusion stages are necessary to raise the proportion of uranium-235 from the naturally occurring level of 0.71 per cent to the 2-4 per cent required in the product stream, with about 0.25 per cent in a reject 'tails' stream.

Each stage requires recompression of the gaseous hexafluoride. Uranium enrichment by gaseous diffusion requires large quantities of electrical energy. About 36.5 MWe-y of electricity would be needed by a gaseous diffusion plant to enrich the uranium for the generation of 1 GWe of electricity in a LWR (USNRC 1976).

During enrichment by gas centrifugation, molecules of  $UF_6$  containing the heavier isotope uranium-238 migrate preferentially to the wall of a rapidly rotating cylinder. There is a consequent enrichment in the lighter uranium-235 isotope in the gas near the tube axis. The separation factor is greater than in the diffusion process, and the two streams removed from the tube axis and wall require only tens of stages arranged in a cascade to produce the required percentages of uranium-235 in the product and the reject tails. High centrifugal stresses limit the size of the equipment and many parallel cascades involving hundreds of thousands of centrifuges are required to achieve the separative capacity of a commercial enrichment plant.

However, a gas centrifuge plant uses less than one-tenth of the electrical energy required by a diffusion plant of similar capacity. The nuclear reactor could, therefore, produce at least 270 times the electrical energy required to enrich its uranium fuel by the gas centrifuge process.

Processes under development in the laboratory or at the pilot plant stage include laser separation and chemical exchange technology (Hardy 1980a). Laser enrichment involves either the selective dissociation of volatile uranium compounds or the selective ionisation of uranium atoms to an amount determined by differences in the physical properties of uranium-235 and uranium-238 isotopes. Laser enrichment might require only 10 per cent of the electricity needed for gas centrifuge processes (USNRC 1976). Chemical exchange processes utilise equilibrium differences in uranium isotopic composition between two different phases, such as two counter-current liquid solvents or a solvent and a solid ion exchange resin.

The separating capacity of enrichment plants is measured in Separative Work Units (SWU). A separative work unit is a measure of the effort expended to separate a quantity of uranium of a given assay into two components, one having a higher percentage of uranium-235 and one having a lower percentage (USAEC 1974). Separative work has units of mass and is generally expressed in kilograms, but should not be confused with quantities of uranium processed.

### 2.5 Fuel Manufacture and Fabrication

The feed material for the manufacture and fabrication of LWR fuel is uranium hexafluoride ( $UF_6$ ) enriched to about 3 per cent in uranium-235. The  $UF_6$  is converted to uranium dioxide powder ( $UO_2$ ) which is formed into pellets, sintered to achieve the desired density and ground to the required dimensions.

Enriched  $UO_2$  powder is manufactured (Figure 8) by vaporising and hydrolysing the enriched  $UF_6$  to form a solution of uranyl fluoride ( $UO_2F_2$ ). Ammonium diuranate (ADU) is precipitated with ammonia and the slurry centrifuged or filtered, the ADU is then decomposed by heating, pyrohydrolysed with steam to remove traces of fluoride, and reduced to  $UO_2$  powder with hydrogen.

In fuel fabrication operations (Figure 8)  $UO_2$  powder of desired size distribution is prepared by comminution, compaction and granulation;  $UO_2$  pellets are pressed, sintered in hydrogen gas and ground to the required size. The fuel pellets are washed, dried and loaded into tubes of Zircaloy or steel and the ends sealed with welded caps. These fuel rods

are fixed in parallel arrays forming the reactor fuel assemblies (ERDA 1976).

Reject material produced during fabrication is fed into a scrap recovery cycle in which uranium oxide is dissolved in nitric acid, the resultant uranyl nitrate is purified by solvent extraction and the uranium converted into  $UO_2$ .

## 2.6 Nuclear Power Generation

Atoms of uranium-235 undergo a nuclear fission chain reaction inside the fabricated fuel elements in the nuclear reactor. The resultant heat energy is used to produce steam and generate electricity.

Uranium-238 atoms constitute about 97 per cent of uranium in fresh fuel. This isotope is not effectively fissioned in an LWR but it contributes to heat generation by partial transformation into such elements as plutonium-239 which can undergo fission in the reactor. It is not usually recognised that about one-third of the energy generated in LWRs fuelled with uranium comes from the fission of plutonium (INFCE 1980b). Table (2) shows a mass balance per tonne of fresh and spent pressurised water reactor fuel.

## 2.7 Reprocessing Irradiated Fuel

Irradiated fuel discharged from LWRs may be reprocessed to recover plutonium and residual uranium for return to the fuel cycle. Reprocessing also enables the highly radioactive waste products from the fission reaction to be converted into a compact, stable, solid form for decay storage or ultimate disposal. Alternatively, unreprocessed spent fuel may be conditioned for disposal (USDOE 1979).

Irradiated fuel elements are stored under water at the reactor site for about 90 days to allow short-lived fission products to decay. The elements are then transported to the reprocessing plant in heavily shielded casks that are reinforced to retain the contents in the event of a transport accident, and designed for dissipation of the heat from fission product decay, which may exceed 25 kilowatts per tonne of irradiated uranium.

The fuel is stored for a total period of at least one year from reactor discharge to permit further decay of fission products before reprocessing. A simplified block diagram of reprocessing operations is shown in Figure 9. The fuel elements are chopped into short pieces to expose the irradiated fuel. After leaching the fuel in boiling nitric acid, the solution is removed for chemical treatment. The chopped Zircaloy or steel tubing 'hulls' are washed with nitric acid and water to remove adherent

solution and the washings are combined with the main product of leaching.

The product liquor is sampled and the quantity of contained uranium and plutonium determined. The solution is treated by countercurrent solvent extraction processes to separate the fission products, uranium and plutonium into three streams. The purified uranium nitrate product is converted to  $UF_6$  and transported to a plant for enrichment in the uranium-235 isotope and recycle to fuel manufacture. The purified plutonium nitrate product is stored for conversion into plutonium dioxide ( $PuO_2$ ) for use in fast breeder reactor fuel elements or in thermal reactor fuel elements in some countries.

### 2.8 Disposal of Wastes Containing Radioactivity

Wastes containing radioactivity are produced at each stage of the fuel cycle; they may occur in gaseous, liquid and solid phases and contain radioactivity in concentrations ranging from megabecquerels to hundreds of petabecquerels per cubic metre ( $\mu Ci-MCi/m^3$ ). The radioactivity in wastes arising at various steps between uranium mining and fuel fabrication occurs in nature and is associated with uranium and its decay products; radioactivity produced artificially in the nuclear reactor results from the decay of fission products, transuranic elements and the irradiation of structural components. The half-life of this radioactivity ranges from microseconds to millions of years.

One tonne of uranium in unmined ore contains about 160 GBq (4 Ci) of radioactivity; the equivalent quantity of uranium after irradiation may contain over 30 PBq (0.8 MCi) of radioactivity. More than 99.9 per cent of all the radioactivity handled in the fuel cycle is produced and retained in the spent nuclear fuel discharged from the reactor.

Radioactive waste is managed by the application of three principles: concentration and containment, dilution and dispersion, and decay storage. The appropriate combination of these principles depends on the concentration, toxicity and longevity of the radioactive species involved. Table 3 lists the principal solid effluents for disposal from the nuclear fuel cycle. Procedures for and possible consequences of the disposal of highly radioactive wastes contained in spent fuel have been discussed in Costello (1980).

### 3. CAPITAL AND OPERATING COSTS IN THE LWR NUCLEAR FUEL CYCLE

Table 4 illustrates typical capital costs of commercial fuel cycle plants, together with their interdependence in capacity and number of large nuclear reactors supported by their operation.

Table 5 presents approximate unit costs for fuel cycle services, expressed as \$ per kg U, as proportions of total fuel cycle cost, and of the

value of the electrical power generated, assuming a generating cost of 2 cents per kilowatt-hour. Light water reactor fuel cycle costs are divided into three approximately equal proportions: the costs of fresh uranium, separative work, and spent fuel reprocessing including disposal of highly radioactive wastes. The overall fuel cycle cost represents approximately one-third of the value of the electrical power generated.

### 3.1 Added Value

The export value of uranium in ore concentrates (yellowcake) can be significantly increased if it is upgraded and exported as enriched uranium hexafluoride. Consider the sale of 1000 tonnes of uranium at present world market price of \$US33/lb  $U_3O_8$ . This price is equivalent to about \$A77/kg U, and the sale of 1000 tonnes will yield \$A77 million. Consider also the conversion of 1000 tonnes of uranium to  $UF_6$  at \$A5/kg U, and its subsequent enrichment at \$A100/SWU to 3 per cent uranium-235 with a tails assay of 0.2 per cent uranium-235, requiring 5.48 kg of natural uranium feed and 4.31 SWU for every kilogram of enriched product. The quantity of product will be about 182 tonnes, and the costs of conversion and enrichment will amount to \$A5 million and \$A79 million respectively. The added value will be \$A84 million and the total sales revenue of \$161 million represents an increase of 109 per cent over the sale of yellowcake alone.

The percentage of this added value is only indicative and depends on the relative prices for yellowcake and separative work units. This percentage will rise if separative work prices increase more rapidly than those of yellowcake, and conversely.

## 4. PROSPECTS FOR A NUCLEAR FUEL CYCLE INDUSTRY IN AUSTRALIA

The prospects for Nuclear Energy in Australia are presently being studied by the National Energy Advisory Council.

### 4.1 Uranium Mining and Yellowcake Production

Australia has about 290 000 tonnes of reasonably assured uranium resources recoverable at less than \$US80/kg U, equivalent to about 18 per cent of the Western World's uranium reserves in this cost category, together with 12 000 tonnes recoverable in the cost range \$US80-130/kg U. Reasonably Assured Resources refers to uranium that occurs in known mineral deposits of such size, grade and configuration that it could be recovered within the given production costs ranges, with currently proven mining and processing technology (AAEC 1979). It is estimated that about a further 140 000 tonnes of uranium are recoverable at up to \$US130/kg U (AAEC 1979). The major reasonably assured uranium resources in Australia for which development is proceeding or planned are listed in Table 6. About 80 per cent of these

are situated in the Northern Territory of Australia and the remainder are in semi-arid areas of Queensland and Western Australia.

Australia has, to date, produced only a small amount of uranium. About 3800 t U has been produced from the Mary Kathleen mine in Queensland. About 3000 t U was produced from the Rum Jungle Mines (Northern Territory) during 1954-1971, 520 t U from the El Sherana deposit (Northern Territory) during 1959-1964, 120 t U from the Rockhole mine (Northern Territory) during 1959-1962, and 720 t U from Radium Hill (South Australia) during 1954-1962 (Warner, 1976). By contrast, the potential production from reasonably assured and estimated Australian uranium resources in the cost range up to \$US130/kg U (443 000 t U) is about 50 times that of the combined past production of uranium.

The uranium mine and mill owned by Mary Kathleen Uranium Limited is operational with an output of about 800 t U/y. The Nabarlek ore body has been mined and stockpiled, and is being processed in a treatment plant of capacity 920 t U/y (Queensland Mines Limited, 1979). A treatment plant under construction for Ranger ore bodies Nos. 1 and 3 is scheduled to be operational by the end of 1981, with an initial output of 2540 t U/y expanding to 5080 t U/y when commercially practicable. The Ranger operation was the subject of a major environmental inquiry (Ranger Uranium Environmental Inquiry, 1976, 1977).

Environmental impact studies have been made of the proposed development of the Jabiluka ore body (proposed output 2540 t/y expanding to 7630 t U/y in the fifth year of production - Pancontinental Mining Ltd 1979) and the Koongarra No. 1 ore body (output 850 t U/y - Noranda Australia Ltd 1978), but these have not yet received government approval. Developments of the major Australian uranium resources have been reviewed by Hardy (1980 b).

A pilot treatment plant for the Yeelirrie ore body is under construction and a full scale plant of output 3000 t U/y is planned. (Western Mining Corporation 1978.)

A total Australian uranium production capability of 5500 tonnes uranium per year in the late 1980s was listed (NEA 1979) for producers approved by December 1979, together with estimates of maximum attainable production capability of 20 000 tonnes uranium per year by 1990. The reduction in forecasts of the growth of nuclear power, together with the estimates of future uranium production capacity in other uranium resource countries could present some difficulties in market entry for new producers in Australia. The long delay in Australia's entry has

encouraged North American and African producers to expand and commit new projects.

A recent survey of price forecasts (EPRI 1978) suggests that prices of uranium may decrease to \$US30/lb  $U_3O_8$  (\$A70/kg U) over the longer term, and this trend is evidenced by current (1980) spot market prices of \$US30-33/lb  $U_3O_8$  (\$A70-77/kg U). The lower figure corresponds to a sales revenue of \$A700 million for export of 10 000 tonnes of uranium as yellowcake.

#### 4.2 Prospects for a Uranium Conversion Industry in Australia

The minimum economic capacity for a hexafluoride conversion plant is thought to be about 5000 t U per annum, costing about \$A70 million and providing employment for 130-150 people. This level of output from Australian mines seems likely in the mid to late 1980s. Siting requirements could be met in many industrial locations in Australia.

Estimates of the profitability of a 5000 tonne U per year conversion plant indicate an internal rate of return of about 6 per cent (constant dollar values), and a return of invested capital in about nine years of full scale operation. This rate of return is similar to that from conventional chemical plant operations.

The competitiveness of manufacturing natural uranium hexafluoride for export could be offset substantially by additional freight charges. Hexafluoride is transported in returnable steel pressure vessels, whereas yellowcake is shipped in non-returnable drums. An additional transport cost of up to 50¢/kg U for hexafluoride relative to yellowcake export seems probable, and absorption of this in the competitive (delivered) conversion price of about \$5/kg U would sharply decrease profitability.

Hexafluoride conversion in Australia would be essential for the operation of a uranium enrichment plant in this country. This would largely isolate the plant from transport problems since only the enriched fraction (about 20 per cent of the converted uranium) would be exported, and the freight costs would be a very small part of the total enrichment charge. In this event, an Australian conversion plant could be operational by the early 1990s consistent with possible dates for operation of an Australian enrichment plant. Depending on the market for enriched uranium, capacity for uranium hexafluoride production could be expected to increase from 5000 t U/y to over 10 000 t U/y by the mid 1990s.

#### 4.3 Prospects for an Australian Enrichment Industry

The majority of uranium exported from Australia will be used to fuel LWRs, and will therefore require enrichment services. Upgrading of yellowcake to enriched uranium hexafluoride could more than double uranium sales

revenue (Chapter 3).

The factors requiring consideration before proceeding to construction and operation of an enrichment plant in Australia were identified by Hardy (1977) as:

- When will there be a market for Australian enriched uranium?
- What will be the size and growth rate of this market?
- What technology should be used?
- How could the venture be organised and financed?

Projections by the AAEC (1979) of supply and demand for enrichment services by the Western World suggest 1992 as the earliest date for a market in the Western World for enriched uranium from new plant; this market might grow at about 2 to 3 million SWU per year, reaching about 20 million SWU from new plant by the year 2000 (Fig. 10). The proportion that Australia might reasonably expect to supply is difficult to assess and depends on such factors as regional balances of supply and requirements, contract conditions, price, political and national influence and security of supply of both separative work and uranium. However, as an example, if all of an annual production of 10 000 tonnes of uranium were to be enriched it could support an enrichment plant capacity of about 5-8 million SWU/year, the actual capacity depending on the value chosen for the U-235 content in the tails stream. The capacities quoted refer to tails containing 0.2 and 0.3 per cent U-235 respectively.

The present competing commercial enrichment technologies are gaseous diffusion and gas centrifugation. Gaseous diffusion technology has been highly successful for more than twenty five years, but it is economic only in plants having a capacity in the range 6 to 10 million SWU/year. Such plants cost 3 to 4 billion dollars (Australian) and also are large consumers of electrical power, a 10 million SWU/year plant needing a power input of about 2500 MWe.

By contrast it is estimated that centrifuge technology is economic at plant capacities as low as 1 million SWU/year, requiring a substantial but appreciably lower capital investment of about \$A400 million and a power input of about 25 MWe. Modular construction of banks of centrifuges could permit plant capacity to be expanded to suit a growing market for separative work. The technology is being demonstrated in European plants operated by URENCO-CENTEC, an organisation set up under a tripartite agreement by the UK, the Federal Republic of Germany and the Netherlands. US Centrifuge technology is understood to involve a smaller number of larger centrifuges for a given output than required by European technology and has been adopted for construction of new enrichment plant in the USA.

The Commonwealth Government announced in January 1979, that it was proceeding to study the feasibility of establishing a commercial uranium enrichment industry in Australia. BHP, CSR, Peko-Wallsend and Western Mining Corporation have set up a joint venture, called the Uranium Enrichment Group of Australia (UEGA) to undertake a feasibility study of the possibility of establishing an Australian commercial uranium enrichment industry. Discussions have been held with URENCO-CENTEC and with the Governments of France, Japan and the US on the possibility of enrichment technology being made available to Australia. A favourable report by UEGA should lead to detailed investigation of the many factors involved, including choice of technology, siting, profitability and modes of financing plant construction and operation. A 10 year lead time is not unlikely for the several stages of design, environmental impact assessment, construction, licensing and commissioning of a plant hence, if the market prospects in the early 1990s are to be realised, a decision in the early 1980s will be necessary.

#### 4.4 Prospects for the Fuel Fabrication Industry in Australia

Relative to the other sectors of the fuel cycle industry, fuel fabrication requires low capital investment and can provide an added value of about 25 per cent of that of the equivalent unenriched yellowcake (Table 5). Australia is not likely to have a significant nuclear power program in the near future, therefore any local fuel fabrication industry would, in the main, be export-oriented. Confidence in the product, however, must be established, and potential customers would require the fuel to undergo long-term irradiation testing in a reactor, so the absence of domestic reactors operating with the fuel would be a severe problem. A completely independent testing and demonstration program is impracticable, as it could involve costs of millions of dollars.

The commercial feasibility of an export-oriented plant in Australia probably depends on a financial and technological commitment by a major overseas reactor manufacturer, and such a plant would be in competition with established fabrication plants associated with reactor manufacturers overseas. In view of this, import restrictions or other economic barriers to trade might be involved. Consequently, a fuel fabrication industry in Australia seems more likely to be a long-term proposition with fuelling of domestic nuclear power reactors as the main aim.

#### 4.5 Prospects for Fuel Reprocessing and High Level Waste Solidification in Australia

Australia has no program for the installation of nuclear power stations. Spent fuel from the two Australian research reactors is too small

in quantity to justify reprocessing economically other than in existing facilities overseas; moreover, such fuel would not be an acceptable feed for a plant designed for reprocessing LWR fuel.

Australia's total installed electrical generating capacity is about 24 000 MWe. Stocks and Faulkner (1980) have predicted a need for about 20 000 MWe of new capacity between the years 1990 and 2000. These capacities may be compared with the trend towards the construction of large reprocessing plants, each capable of supporting between 30 000 to 50 000 MWe of LWR power. Should the decision be made to commit a major part of Australia's growth in generating capacity after 1990 to nuclear power but not to dispose of unprocessed spent fuel, construction of a reprocessing and high level waste solidification plant for domestic needs would not be economically feasible until well into the next century.

Crook (1977) and latterly Ringwood (1980) have proposed that fuel elements containing Australian uranium be leased to overseas countries with the condition that the spent fuel be returned to Australia for reprocessing and disposal of immobilised wastes by deep geologic burial. This course of action was regarded as a supporting measure against possible proliferation of nuclear weapons from Australian uranium.

Government policy is that, although Australia as a major exporter of uranium will closely monitor any international studies concerned with reprocessing and the nuclear fuel cycle, there is no intention of storing other countries' radioactive wastes in Australia (Fraser 1977).

#### 4.6 Prospects for Disposal of High Level Waste or Unprocessed Spent Fuel in Australia

INFCE (1980a) concluded that the disposal of high level radioactive wastes by deep geologic burial can be carried out with a high degree of safety and without undue risk to man or the environment. However, the small quantities of research reactor fuel used in Australia, coupled with the lack of any commitments for the installation of Australian nuclear power stations, have not warranted any investigation of the suitability of Australian geology for high level waste disposal. As noted earlier, there is no intention of storing other countries' radioactive wastes in Australia (Fraser 1977).

#### 4.7 Overview of Nuclear Fuel Cycle Prospects in Australia

Uranium mining and milling is an established and expanding Australian industrial activity. The prospect of upgrading uranium exports from yellowcake to enriched uranium hexafluoride is the subject of an existing study by Australian industry and might mature with conversion and enrichment facilities operational by the early 1990s.

Fuel cycle services such as fuel fabrication, reprocessing and disposal

of high level waste or unprocessed spent fuel are distant prospects, being contingent on the establishment of a substantial nuclear power program in Australia.

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TABLE 1

REACTOR DISTRIBUTION - LOW POWER GROWTH ESTIMATE\*

Year	Total Nuclear Power GWe	LWR %	HWR %	AGR %	GGR %	HTR %	FBR %
1980	144	87.2	5.3	2.0	4.9	0.2	0.3
1990	432	89.5	6.0	1.8	1.0	0.4	1.2
2000	832	86.2	8.7	2.0	0.0	0.4	2.6

\* From OECD/NEA (1979)

Legend:

LWR Light Water Reactor  
HWR Heavy Water Reactor  
AGR Advanced Gas Cooled Reactor  
GGR Gas-graphite Reactor  
HTR High Temperature Reactor  
FBR Fast Breeder Reactor

TABLE 2

MASS BALANCE PER t U IN PWR FUEL

Constituent	Fresh Fuel		Spent Fuel	
	kg		kg	
Uranium	235U	33	234U	0.002
			235U	8.0
	238U	967	236U	4.0
			238U	943.0
Transuranic Elements	-	-	237-239Np	0.76
			236-242Pu	9.0
			241-243Am	0.1
			242-244Cm	0.04
Fission Products	-	-	3H	35.1
			to 161Dy	
			<hr/> 1000 <hr/>	<hr/> 1000.00 <hr/>

TABLE 3

SOLID WASTES FOR DISPOSAL /GWe y<sup>(1)</sup>

Stage	Nature	Volume M <sup>3</sup>	Activity	
			TBq	(Ci)
Mining	Waste rock <sup>(2)</sup>	8000 to 140 000	-	-
Milling	Tailings	41 300	20	550
Hexafluoride	Chemicals	68	0.04	1.2
Enrichment				
Fuel Fabrication				
Nuclear Reactor	Control rods	480	7.4 x 10 <sup>3</sup>	2 x 10 <sup>5</sup>
Operation	Sludges, resins	460	260	7 x 10 <sup>3</sup>
Fuel Reprocessing				
• High level	Vitrified solid	5.4	4.3 x 10 <sup>5</sup>	11.7 x 10 <sup>6</sup>
• Medium	Cladding hulls	22.0	6.3 x 10 <sup>4</sup>	1.7 x 10 <sup>6</sup>
• Low level	Chemicals	55.5	220	6.0 x 10 <sup>3</sup>

NOTES: (1) Basis: Reprocessing with uranium recycle

(2) Depends on mining methods

TABLE 4URANIUM FUEL CYCLE CAPITAL COST AND MANPOWER REQUIREMENTS

	Capacity t U/y	Capital Cost \$A(1979)	Operational Manpower	Equivalent Reactors Supported (x 1000 MWe)
Uranium Mine and Mill	2500	$325 \times 10^6$	250	15
Hexafluoride Plant	5000	$70 \times 10^6$	130 - 150	30
Enrichment Plant				
• Gas Centrifuge	$1 \times 10^6$ SWU/y [1500 t U/y]	$400 \times 10^6$	200 - 300	9
• Gaseous Diffusion	$10 \times 10^6$ SWU/y [15 000 t U/y]	$4 \times 10^9$	1200	90
Fuel Fabrication Plant	500 t (enriched U)	$50 \times 10^6$	500	170
Reprocessing and Vitrification Plant	1500 t (spent fuel)	$1 \times 10^9$	400	50

TABLE 5

FUEL CYCLE OPERATING COSTS

	Unit Cost \$A(1979)	Cost Per Unit Power ¢/kWh	% of Fuel Cycle Cost	% of Value of Power Generated
U <sub>3</sub> O <sub>8</sub>	\$ 77/kg U	0.21	30.8	10.4
Conversion UF <sub>6</sub>	\$5/kg U	0.01	1.5	0.5
Enrichment	\$100/SWU	0.20	29.4	10.0
Fuel Fabrication	\$100/kg U	0.05	7.4	2.5
SPENT FUEL -				
Storage	\$6/kg U	0.003	0.4	0.14
Shipping	\$16/kg U	0.008	1.2	0.4
Reprocessing	\$300/kg U	0.15	22.0	7.5
Waste Disposal	\$100/kg U	0.05	7.3	2.5
TOTAL =		0.68	100.0	34.0

NOTE: A 1000-MWe nuclear reactor operating at 70% load factor generates each year about  $6 \times 10^9$  kWh, valued at about \$122 million, assuming a generation cost of 2¢/kWh.

TABLE 6

MAJOR AUSTRALIAN URANIUM DEPOSITS

Deposit and Company	Resources* (tonnes U) and Ore Grade (% U)	Planned Initial Production (tonnes U per year)	Status at 1 February 1980
Jabiluka, NT Pancontinental Mining Ltd	176 000 0.33%	2500 <sup>+</sup>	Final EIS submitted
Ranger, NT Ranger Uranium Mines Pty Ltd	85 000 0.2%	2500 <sup>#</sup>	Construction started June 1979. Mill startup planned for October 1982
Yeelirrie, WA Western Mining Corporation	40 000 0.12%	2200	Pilot plant under con- struction. Production mill startup by late 1984
Koongarra, NT Noranda Aust Ltd	11 000	900	Draft EIS submitted
Nabarlek, NT Queensland Mines Ltd	8000	900	Construction started May 1979. Yellowcake prod- uction by mid-1980
Mary Kathleen, Q Mary Kathleen Uranium Ltd	5000	600	Mill recommissioned in 1975

\* *In situ* resources based on company announcements

+ Expansion to 7600 tonnes per year planned after five years

# Expansion to 5000 tonnes per year envisaged

NT Northern Territory

WA Western Australia

Q Queensland

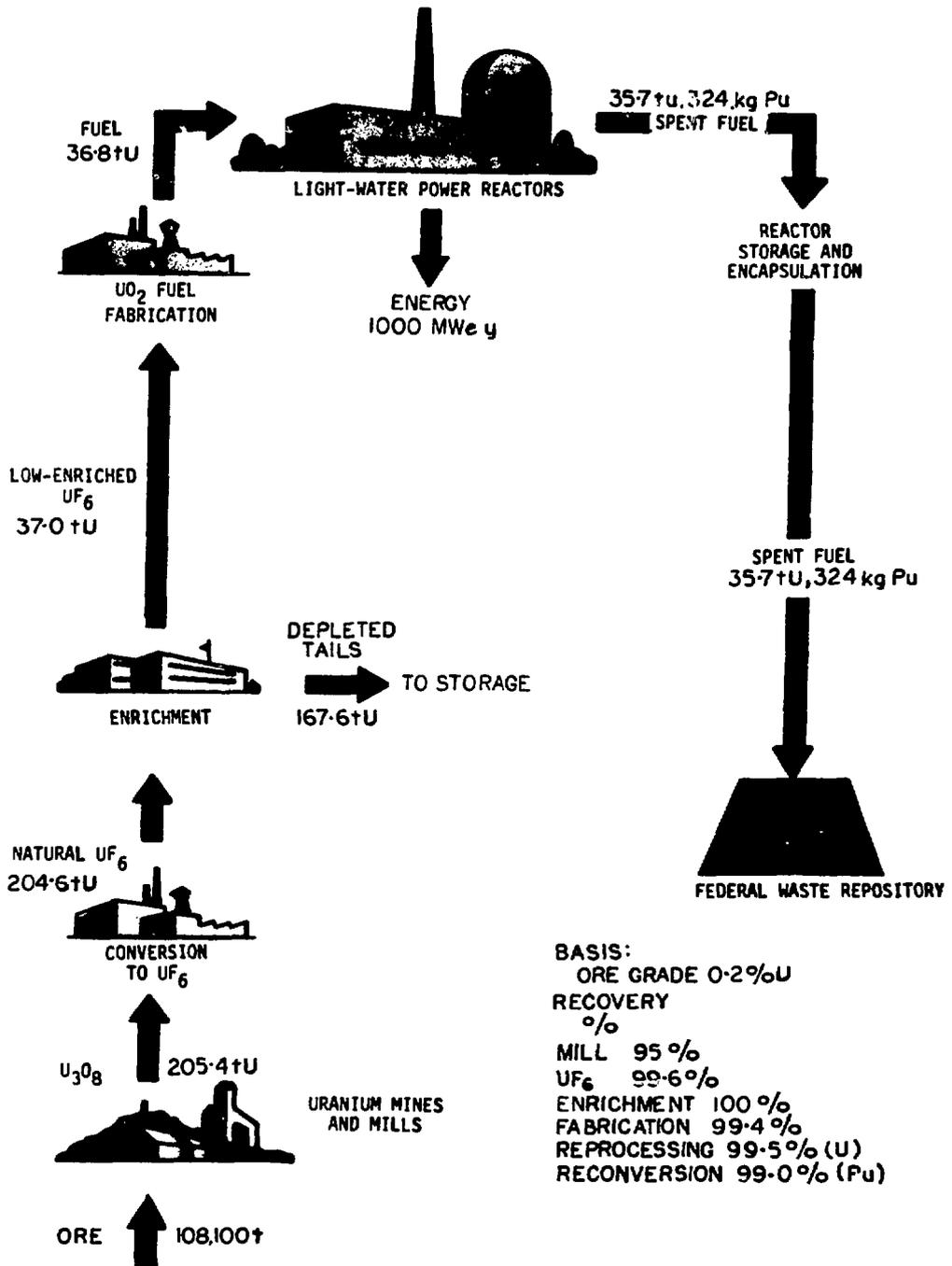


Figure 1. "ONCE THROUGH" LWR FUEL CYCLE

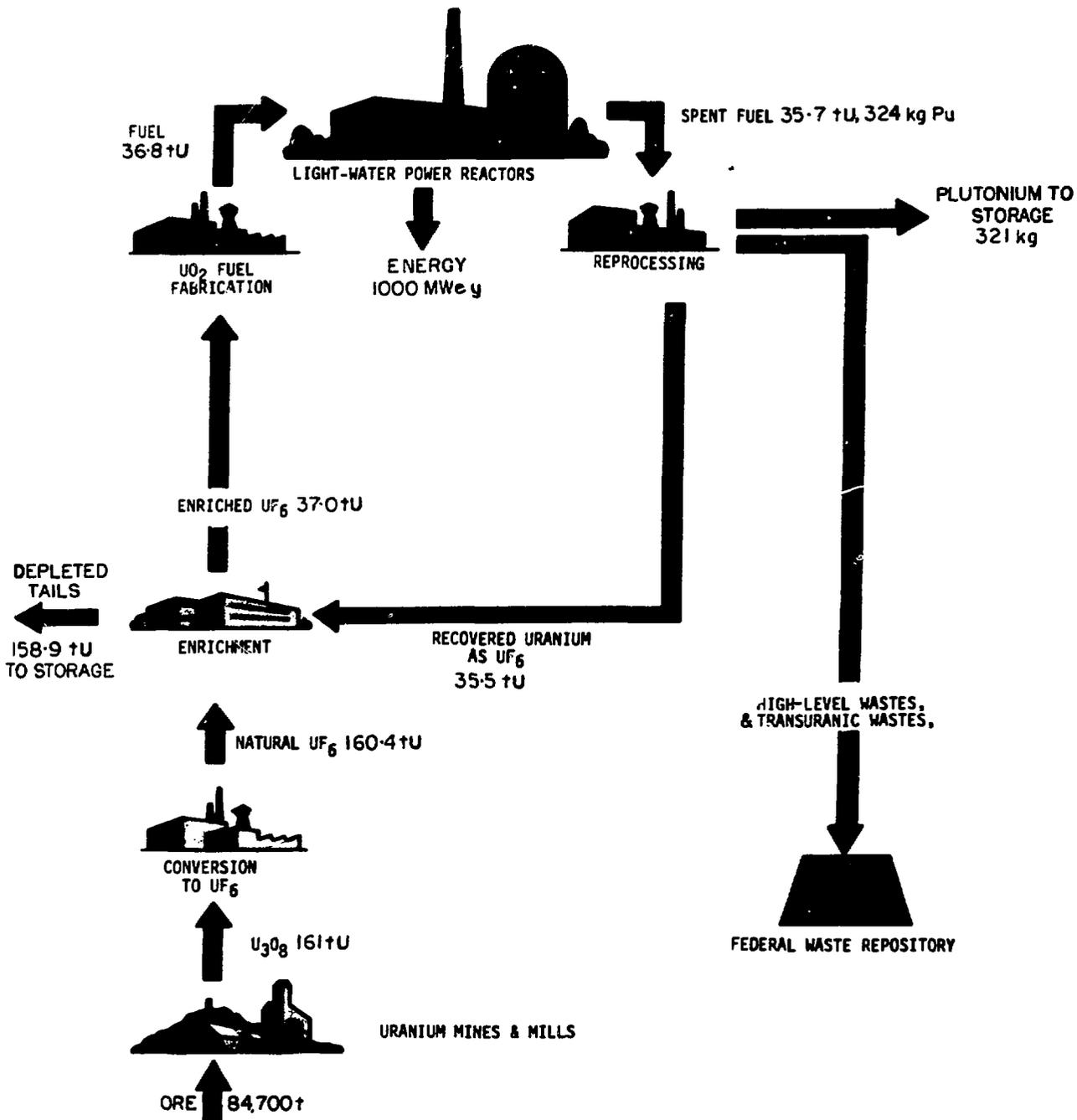
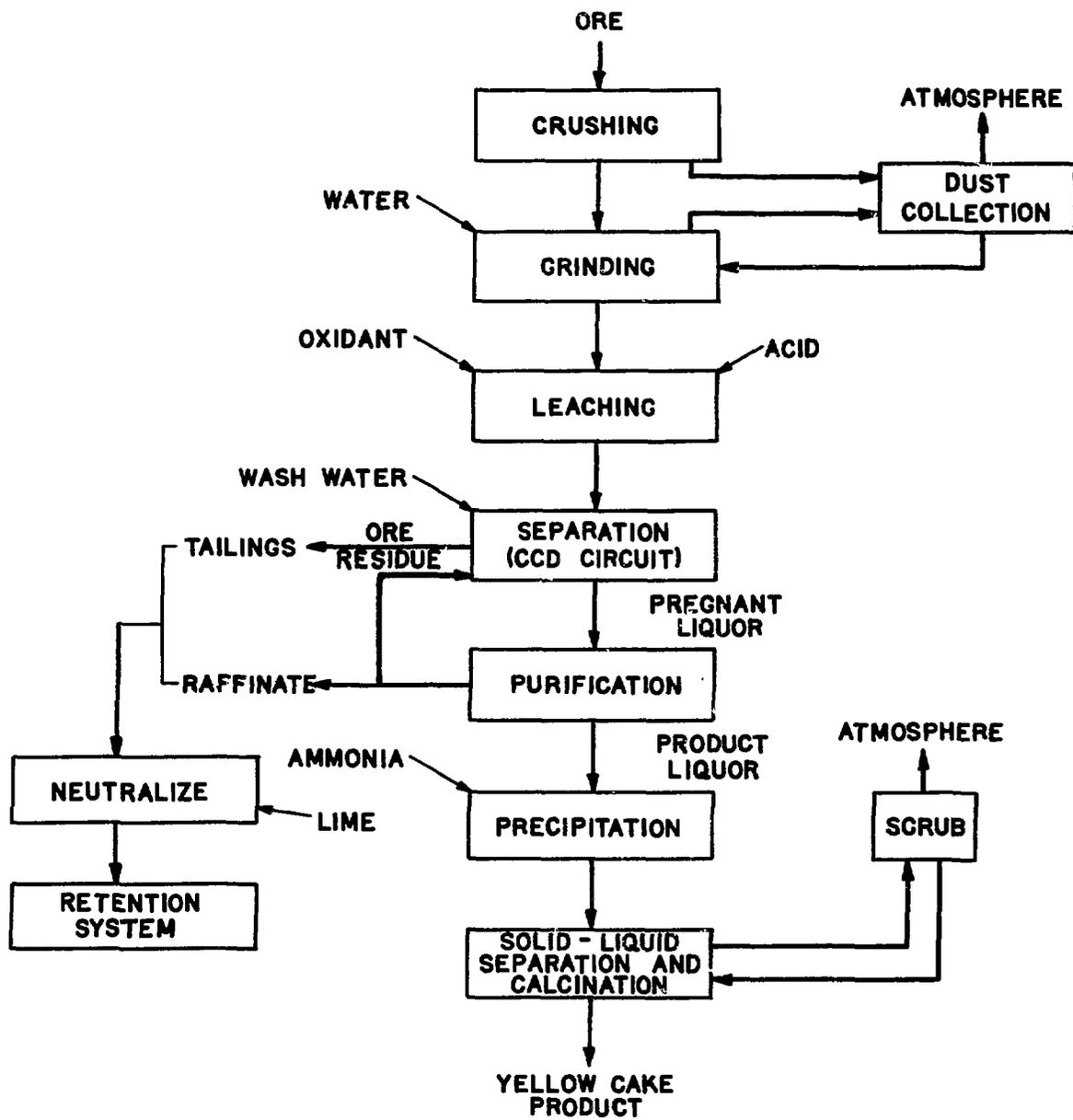
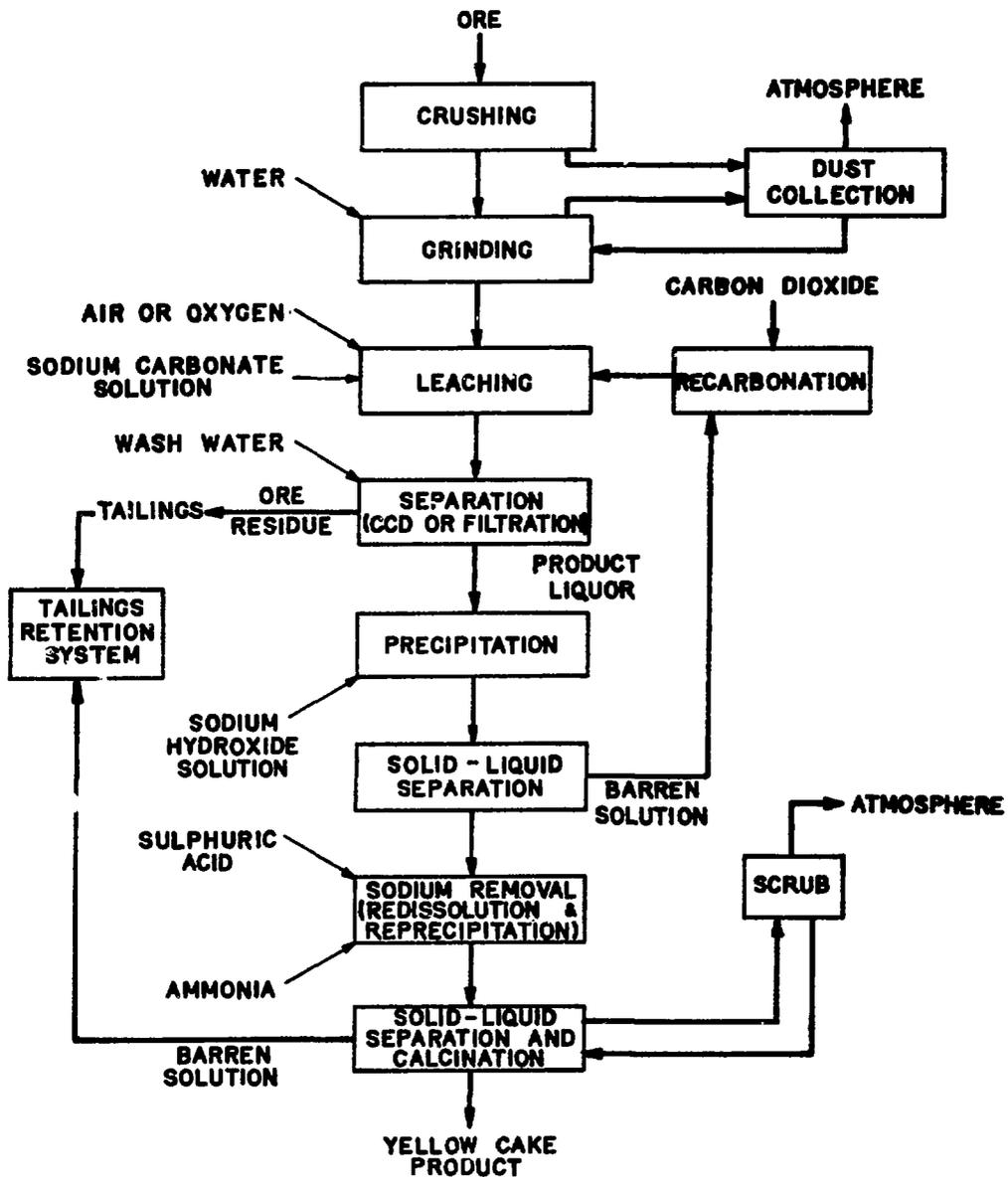


Figure 2. LWR FUEL CYCLE WITH REPROCESSING AND URANIUM RECYCLE

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**FIGURE 3. URANIUM MILL - ACID LEACH PROCESS SIMPLIFIED  
BLOCK FLOW DIAGRAM (USAEC 1974 )**



**FIGURE 4. URANIUM MILL - CARBONATE LEACH PROCESS  
SIMPLIFIED BLOCK FLOW DIAGRAM  
(after Merritt 1971)**

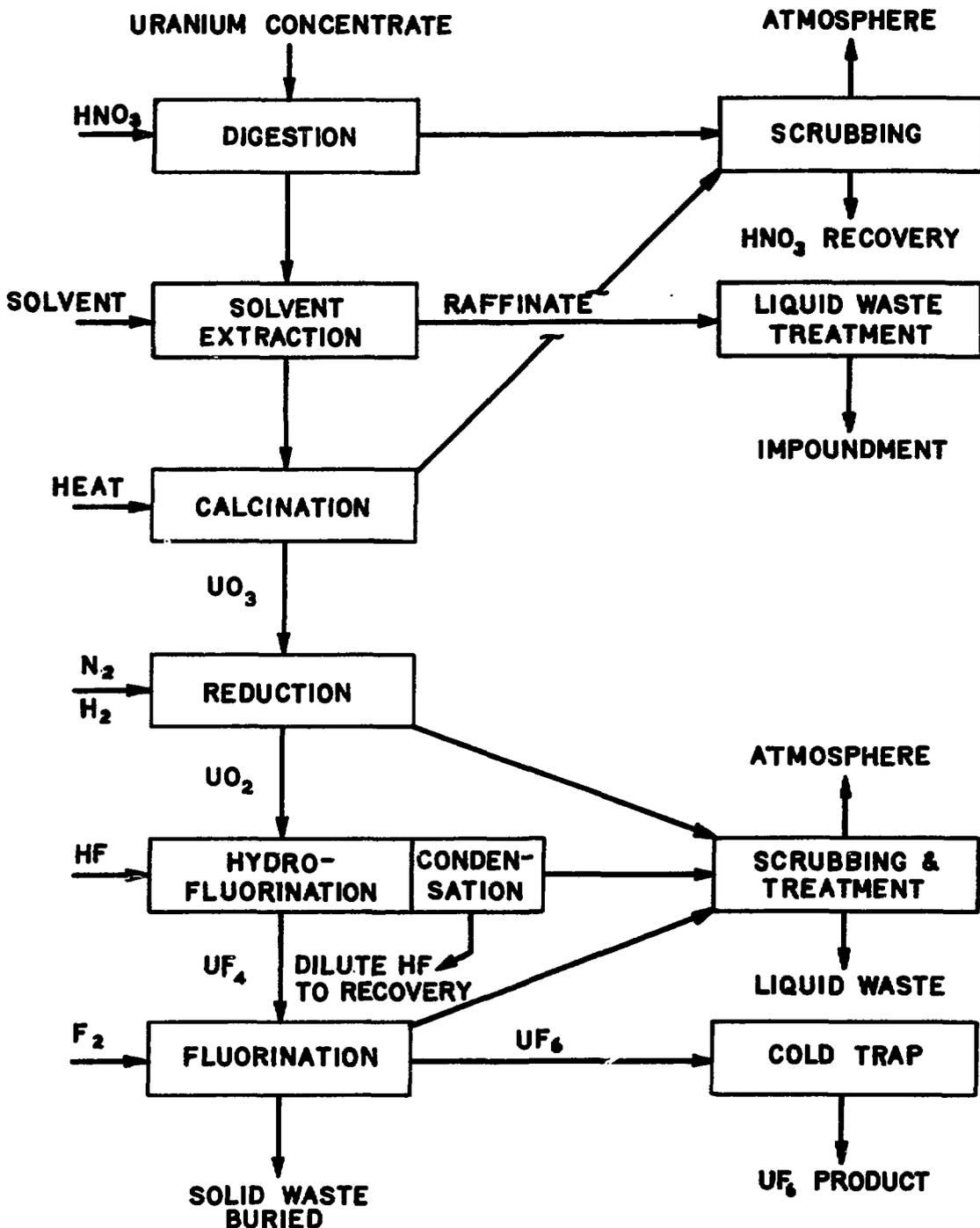
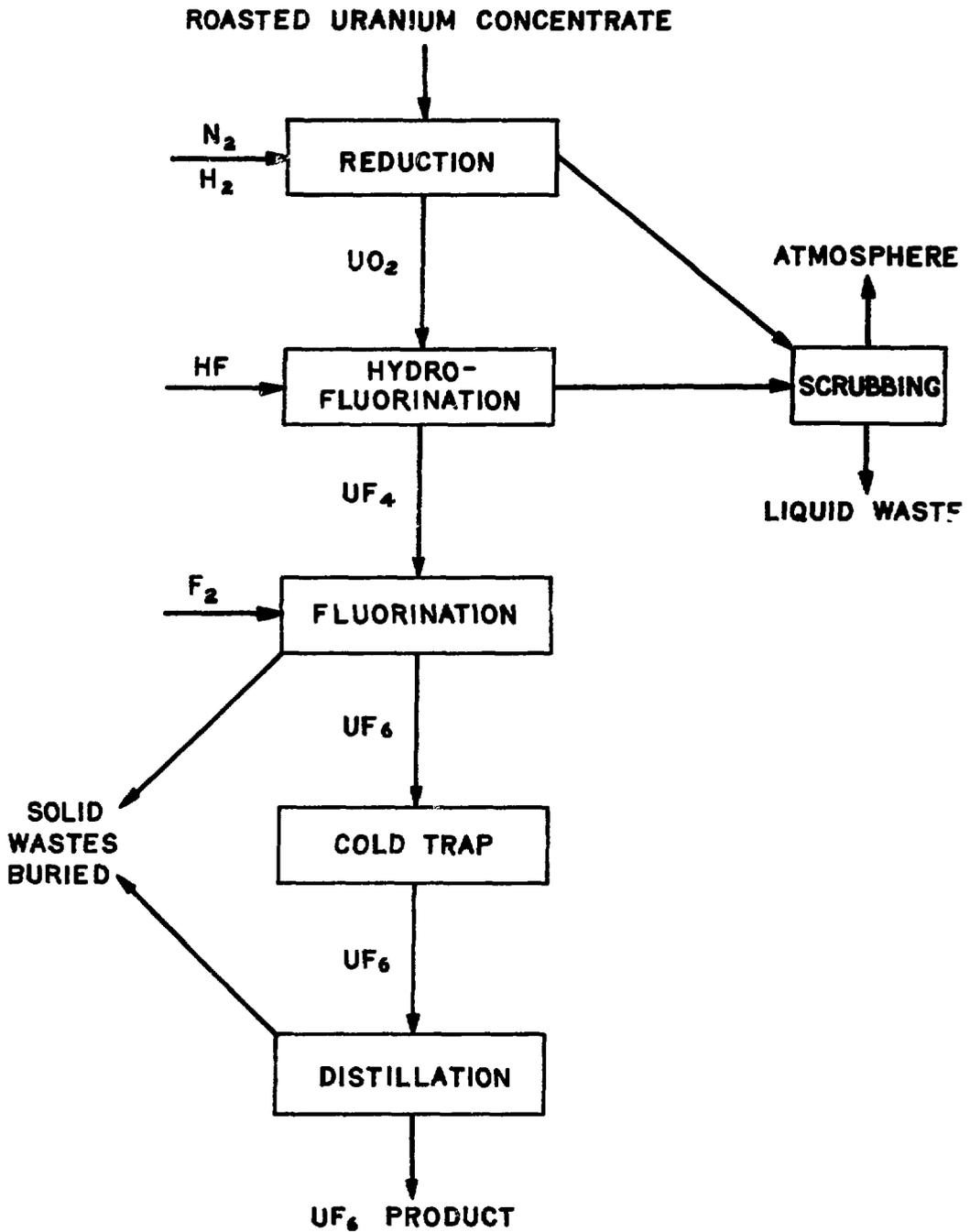
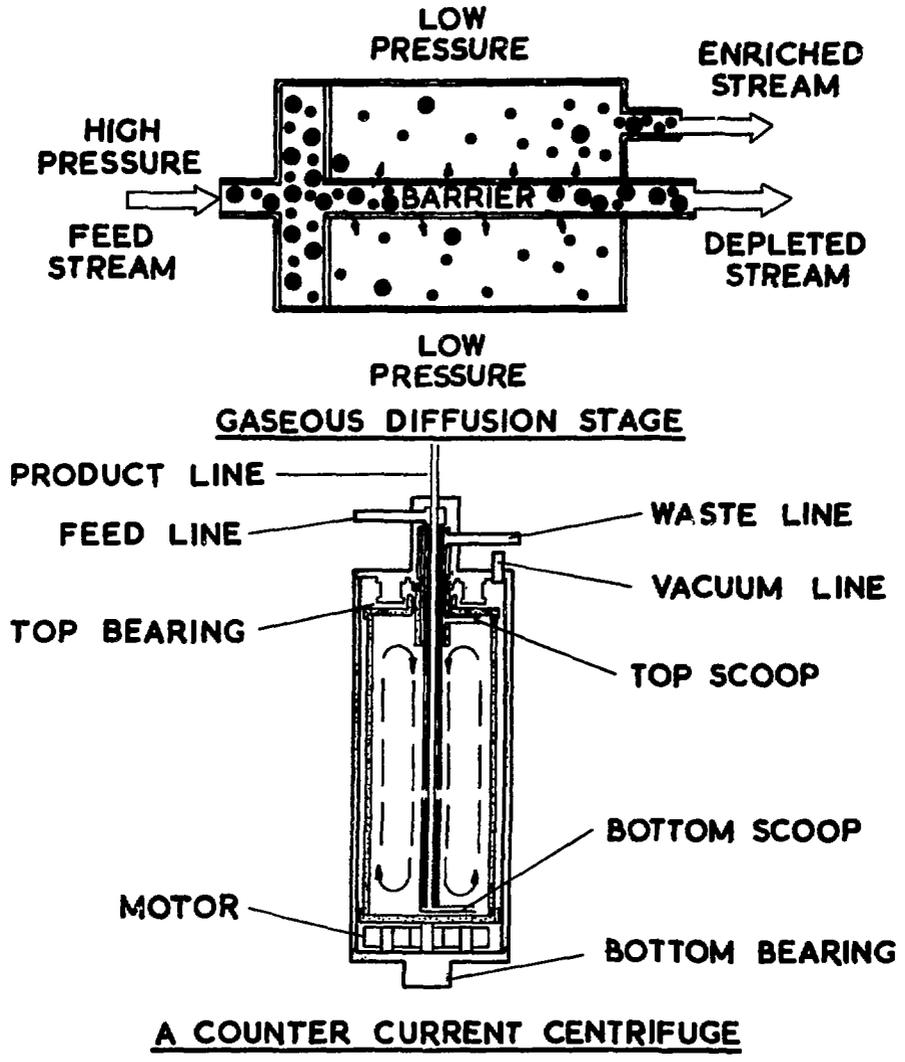


FIGURE 5.  $UF_6$  PRODUCTION - WET SOLVENT EXTRACTION  
SIMPLIFIED BLOCK FLOW DIAGRAM (USAEC 1974 )



**FIGURE 6.  $UF_6$  PRODUCTION - DRY HYDROFLUOR PROCESS  
SIMPLIFIED BLOCK FLOW DIAGRAM (USAEC 1974 )**



**FIGURE 7. ENRICHMENT PROCESSES**

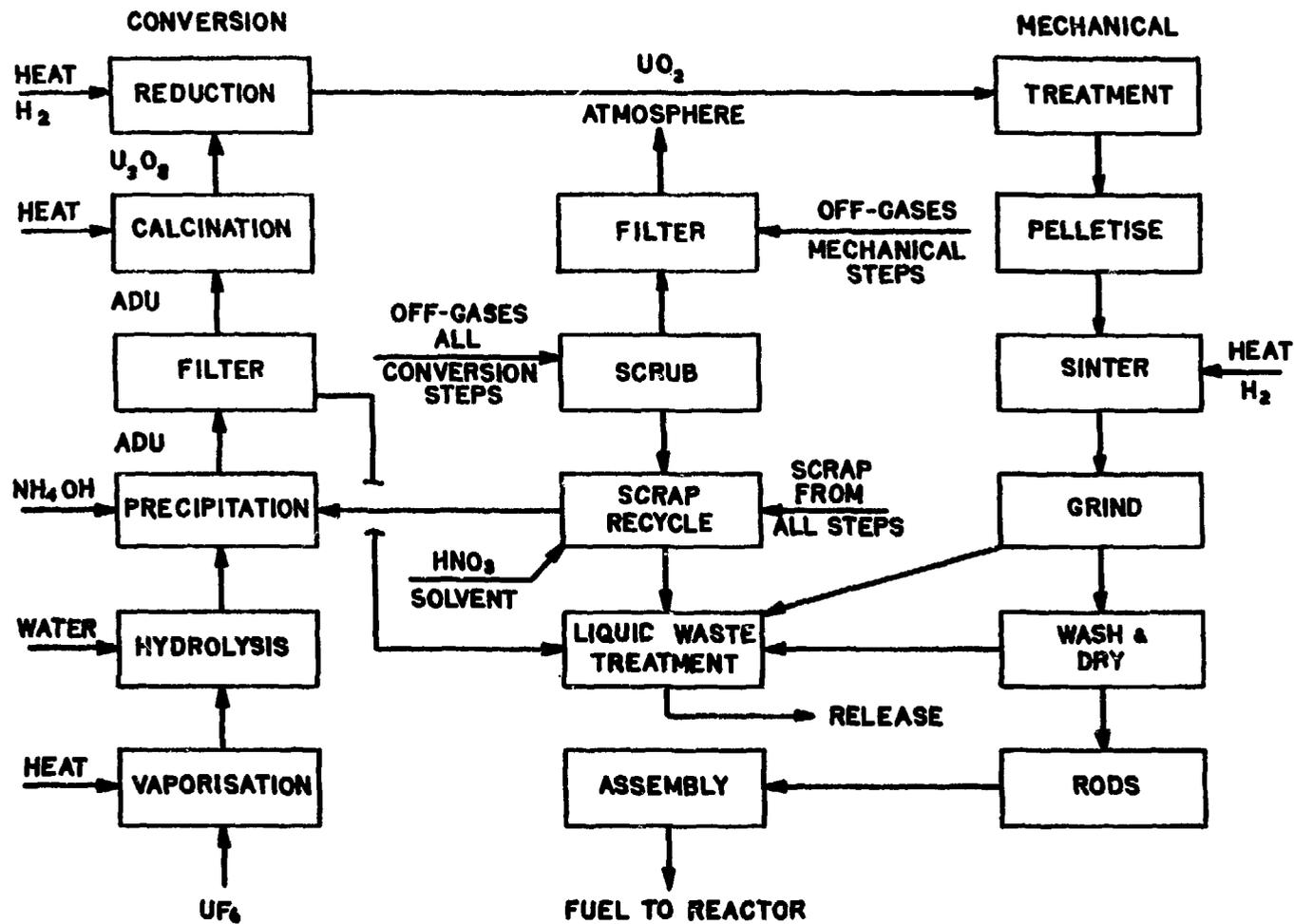
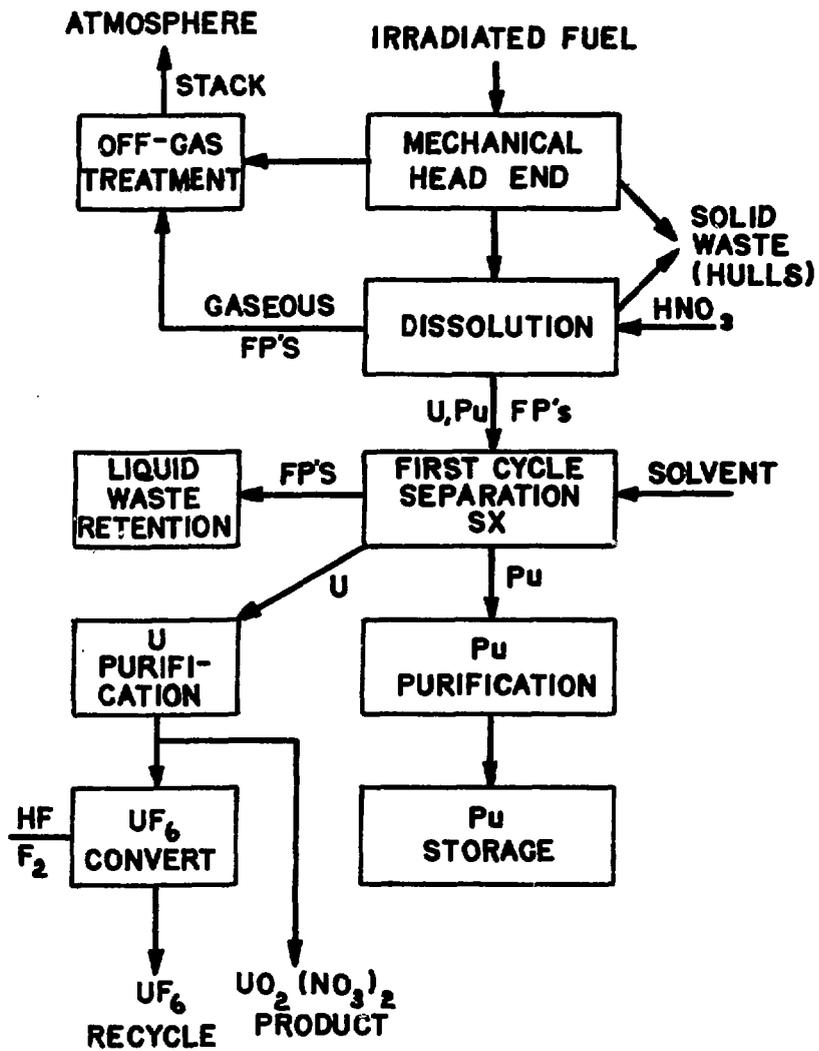


FIGURE 8. FUEL FABRICATION - ADU PROCESS SIMPLIFIED BLOCK FLOW DIAGRAM (USAEC 1974 )



**FIGURE 9. FUEL REPROCESSING SIMPLIFIED BLOCK FLOW DIAGRAM (USAEC 1974a)**

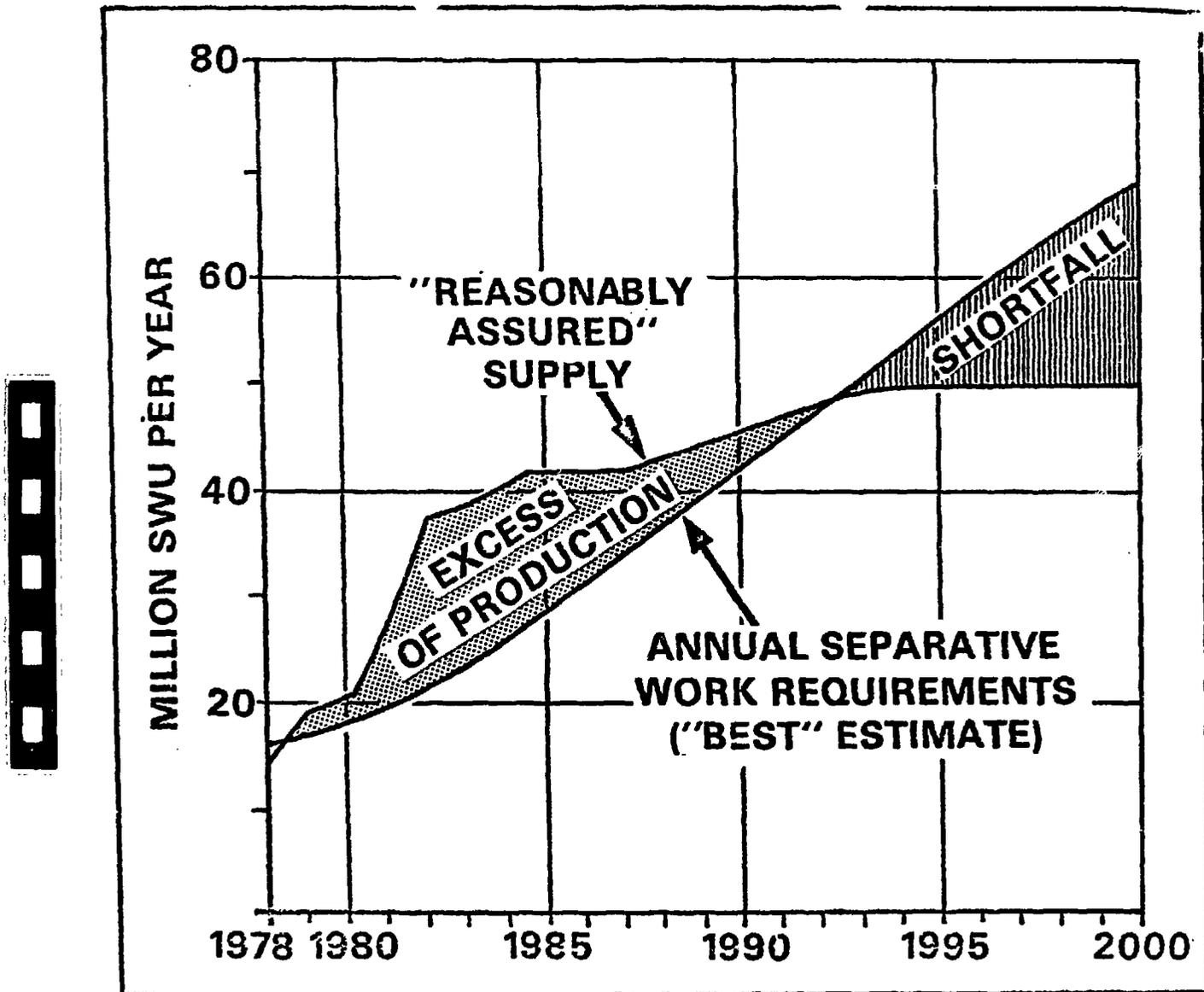


FIGURE 10. WESTERN WORLD ENRICHMENT: COMPARISON OF SUPPLY AND REQUIREMENTS