

THE UNIVERSITY OF MICHIGAN
INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

A TECHNICAL AND ECONOMIC ANALYSIS OF THE SEPARATION
OF PLUTONIUM AND FISSION PRODUCTS FROM
IRRADIATED NUCLEAR REACTOR FUELS

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I. ABSTRACT

It is certain that the nuclear fuels processing requirements in this country will be of increasing magnitude in the near future. This is based on the present plans of construction and operation of industrial nuclear reactors as sources of electrical power.

The technical background for the chemical processing of irradiated nuclear reactor fuels is discussed. A brief description is presented of aqueous solvent extraction methods for the separation of uranium from plutonium and fission products.

An example is presented of the application of aqueous solvent extraction methods to the processing of the fuel and blanket elements of a fast breeder power reactor operating on uranium and plutonium.

Estimated capital and operating costs are presented for an aqueous separation of plutonium and fission products from irradiated fuel elements of a fast breeder power reactor. A possible plant for the chemical processing of the irradiated reactor elements is described. This plant is integrated in location and function with the remaining parts of a nuclear reactor system.

The fast breeder power reactor of this study employs a core of enriched uranium and an encircling blanket of natural or depleted uranium. The core and blanket elements are processed separately by aqueous dissolution and organic solvent extraction. The uranium is returned to the form of metal at the conclusion of processing.

The capital cost requirements for a chemical processing plant which would be an integral part of a 500 megawatt nuclear heat power reactor are estimated to be \$6,000,000. Operating costs for the processing plant vary from \$1,200,000 to \$1,700,000 per year, depending upon the rate of reprocessing the fuel.

Costs omitted from these estimates are the cost of money and the capital requirements for general services, such as steam and electrical generation, water supply, fire protection, heavy maintenance shops, sewage disposal, cost of land, etc. For a completely self-sustaining chemical processing plant, the capital costs cited above should be increased to include general services, and operating costs should be increased to cover cost of money and any increased charges not covered by unit charges used in this estimate for service functions.

It was assumed that the U. S. Atomic Energy Commission's national laboratories in their continuing programs of development would carry the major burden of development required to achieve the operation of certain processing steps used in this chemical plant. In addition, it is believed that a private industry wishing to undertake fuels processing would have to spend a minimum of \$1,600,000 on a development and training program running concurrently with the design and construction of the chemical processing plant.

II. INTRODUCTION

A. Objectives

The use of nuclear reactors as sources of electrical power generation is fast becoming realized in this country. As can be seen in Table I, some proposed nuclear power reactors are scheduled for completion as early as 1957.

TABLE I

POWER LEVELS AND COMPLETION DATES ON SOME PROPOSED POWER REACTORS

<u>ORGANIZATION</u>	<u>ELECTRICAL POWER LEVEL (KW)</u>	<u>COMPLETION DATE</u>
Commonwealth Edison	180,000	1960
Atomic Power Development Associates	100,000	Late 1959
Consolidated Edison	250,000	December 1959
Yankee Power Group	100,000	Late 1957
Consumers Public Power District	75,000	1959
Duquesne Light Company (PWR)	60,000	1957
	<hr/> 765,000	

The realization of nuclear power brings with it associated problems that have not yet been satisfactorily solved. Two of these problems are: (1) the economical and reliable separation of the remaining fissionable material in a reactor from the fission products, and (2) the disposal and storage of the fission products after separation.

Even as early as 1960, both of these problems will be of great magnitude. It is estimated that, by 1960, fissionable material will be burned up at rate of 1500 kilograms per year, and that fission products will be produced at a rate of 1300 kilograms per year. It is also estimated that, by 1960, the amount of uranium processed will reach a rate of approximately 200 tons per year. These estimates are based on conservatively low processing rates, and they do not include reactors

owned totally by the Atomic Energy Commission nor those used for military purposes. Although thermal conversion efficiencies may vary from 20 to 40 per cent, most reactors will operate nearer the lower percentage; for these estimates, therefore, a thermal conversion efficiency percentage of 23 was used. Likewise, most reactors use partially enriched fuel at an assumed 5 per cent average enrichment, and the burn-up of uranium 235 per pass will fall between 2 and 30 per cent. For these estimates, a 20 per cent burn-up was assumed.

In the more distant future, the chemical processing of irradiated reactor fuels and the disposal and storage of fission products will become problems of increasing magnitude. The United States Atomic Energy Commission has estimated that, by 1975, 12 million kilowatts of electrical power will be generated from nuclear energy. Applying the assumptions used for the estimates of 1960, this would mean that, by 1975, uranium and thorium would have to be processed at a rate of from 2500 to 3300 tons per year, and that fission products would be produced at a rate of 20,000 kilograms per year.

The objectives of this paper, then, are threefold: (1) to present a detailed method of nuclear fuels processing, (2) to outline a unique method of fission-product disposal and storage, and (3) to present cost data for the facilities and operations necessary to accomplish nuclear fuels processing and fission-product disposal and storage.

The processes discussed here were developed at the Oak Ridge, Argonne, and Brookhaven National Laboratories.

B. Position of Fuels Processing in Nuclear Operations

The majority of the presently proposed power reactors contain fissionable material in the form of metallic fuel elements. The fissionable material is usually alloyed with some other metal such as aluminum, zirconium, or chromium, but it can also be placed as an oxide in a matrix of sintered stainless steel. This "meat" material is "sandwiched" in thin-plate or -rod form between protective coatings of metal cladding. The cladding can be aluminum, zirconium, stainless steel or other normally refractory-nonreactive materials. The whole plate or rod is kept as thin or small as possible to permit high heat transfer out of the plate with relatively small temperature gradients through the plate itself. A number of these "sandwiches" are put together to form an assembly called the fuel element. The reactor core proper is composed of a number of these fuel elements arranged so that critical conditions are satisfied and a coolant can be passed through the core.

Periodically during reactor operation, the fuel elements must be removed from the core. As fission occurs, fission products accumulate inside the fuel elements, and, if this accumulation is allowed to continue, the reactor eventually becomes "poisoned" and must shut down. Usually, even before poisoning occurs, sufficient physical changes take place in the fuel elements to necessitate their removal from the core. These physical changes are warping, elongation or shrinkage in one or more directions, bending, and the forming of surface protrusions. Also, the cladding material occasionally ruptures, causing long-lived radioactivity to diffuse into the reactor coolant, again necessitating the removal of fuel elements from the core. Although fuel elements may be removed from the reactor core for any of these reasons, structural considerations usually limit the "burn-up" or life of the fuel elements in the reactor core.

At the time of discharge, the irradiated fuel element may contain

anywhere from 99 to 60% of its original charge of fissionable material. This material represents too high a capital investment to discard, and so the fissionable material must be separated from the fission products and re-fabricated into a fresh fuel element. Those reactors serving more than one purpose, such as breeding, converting and power producing would require additional processing to separate the manufactured fissionable material plutonium-239 or uranium-233 from the inert uranium-238 or thorium-232, and to separate the fissionable material from fission products. This additional processing would have to be done on both the core and blanket elements.

This example study is limited to dual purpose reactor fuel, since this type appears to be the most promising economically for long range application.

C. Ground Rules

Certain technical and economic ground rules have governed the preparation of this example study of a plant for the aqueous processing of irradiated nuclear fuels. A complete understanding of these ground rules is essential to the proper interpretation of the technical design decisions and the cost estimates made. The most important of these ground rules are discussed below.

For the past three years, a program has been under way to obtain an economic estimate for the steady state operation of a completely integrated fast breeder power reactor system as conceived by the Atomic Power Development Associates. This reactor system will include the facilities necessary for making the nuclear power plant self-sufficient, and will incorporate those operations necessary to prepare the reactor feed material and to reprocess the fuel after use.

Because of the scarcity of economic information pertaining to the design, construction, and operation of a reprocessing chemical plant as associated with a fast breeder power reactor, Atomic Power Development Associates initiated this program, the conclusions of which are reported in this example study.

For this study a fuel separation system employing aqueous chemical technology was selected. Other processing schemes are currently being developed, but the aqueous chemical technology was selected as a part of a program to obtain a background of technical and economic information by which optimum means of processing the fuels from a fast breeder reactor might be achieved.

The following particular requirements adhered to in this study were:

1. Core fuel and blanket elements were to be processed with two separate sets of equipment, thus avoiding isotopic contamination.
2. Decontaminated uranium metal and cold plutonium salt were to be produced.

Important technical assumptions embodied in this study were:

1. Two cycles of decontamination by solvent extraction operations are adequate.
2. Under certain conditions, fuel can be processed aqueously after relatively short cooling periods.
3. Metallic salts may be reduced remotely.

Maintenance for the hot cell area is to be conducted directly and service lives of equipment are to be specified which will permit scheduled shutdowns on sufficiently long-time intervals to permit profitable operation. When equipment life cannot be predicted accurately, the equipment is located so that maintenance can be performed by remote means.

Economic assumptions employed in estimating the cost of a separations plant were:

1. Cost of money was not considered.
2. Various capital and operating costs were not included in this estimate because they would be prorated to the processing plant as a part of a reactor-fabrication-processing complex. These costs are such items as capital requirements for steam generation, water supply, electrical generation, and the respective distribution networks external to the processing plant; fences,

guards, roads, railroads, land, fire protection, and a central air exhaust handling unit. Consequently, the cost estimates given in the conclusions of this paper are lower than estimates would be for a fully independent and isolated fuels separation plant.

3. No significant reductions in capital costs can be achieved by building a processing plant under the conditions of this study to process less than 300,000 pounds per year of source and fissionable material. However, this production rate is four times as great as is required for the reactor operations studied.

Design criteria for this study were drawn from two general sources. In areas where industrial experience was available, common industrial practices as to structures, vessels, and materials were employed. In areas where radioactive materials were handled, the experience of the U. S. Atomic Energy Commission and its contractors was interpreted in setting up design criteria formulated on the premise that sufficient data are currently available to make feasible the design of a nuclear fuels recovery plant which can be successfully operated under a profit system. In the specific areas where no industrial precedent exists, designs presented are contingent upon development programs. Service life of equipment used in the process hot cell must be assessed through extensive testing prior to plant construction in order that designs and materials of construction may be specified.

Further boundary conditions of this study were: the integrations of the location of required facilities, the application of specific safety and performance requirements, and the postulate that the entire effort of development and construction would be undertaken on a suitable time schedule.

D. Procedures Followed

Designs and cost estimates were generally based upon the criteria described in the preceding section.

The authors have assumed that the development of chemical methods and

equipment designs not previously described would be a large, but straightforward effort. A good share of this effort could be assumed by the U. S. Atomic Energy Commission National Laboratories in their continuing programs of development. An additional effort would be required by a private industry undertaking a fuels separation enterprise for the solution of problems peculiar to that industry's effort.

Wherever applicable, previously described chemical methods have been employed in the purification and separation of source and fissionable materials. In some cases, chemical methods similar to those now known could probably be developed for closely related purposes. Because of the requirement of processing fuels cooled for a relatively short period of time, remotely operated equipment placed behind heavy shielding was considered for the conversion of source and fissionable salts to metals. Such a process of remote metals reduction is relatively undeveloped, but is necessitated by the radioactivity of uranium-237 and of neptunium-239 present in short-cooled fuels. The use of fuels cooled for 90 to 120 days after removal from the reactor would permit the use of directly operated and maintained metal reduction facilities.

III. BACKGROUND AND THEORY OF AQUEOUS PROCESSING

The discussion to follow covers liquid-liquid extraction processes that have been recently developed at several of the U. S. Atomic Energy Commission sites. The reasons for the steps will not be apparent unless some background and theory on such processes is presented. Although the fuel elements currently being processed are different from the breeder reactor elements both in configuration and materials of construction, it is apparent that the processing steps are identical except for the dissolution and feed adjustment steps.

This is indicative of the flexibility that can be allowed in fuel element materials and still be compatible with aqueous processing by liquid-liquid extraction.

A. Basis for Process

Uranyl salts of the halides and nitrates are quite soluble in polar organic liquids. In the fission product spectrum extending from zinc on the low atomic number end to gadolinium on the upper end, only the fission product cerium (Ce-144) is extractable from aqueous solution to an organic phase to any appreciable degree. The distribution ratios of cerium and of $\text{UO}_2(\text{NO}_3)_2$ between aqueous and organic phases are sufficiently different that a complete separation would be achieved.

Plutonium in the plus 5 and 6 oxidation states is extracted into organic phases in a manner similar to uranium, but it is easier to reduce and oxidize than uranium. Plutonium in the plus 3 and 4 states is not extracted by polar organic solvents. A combination of these phenomena then furnish a basis for a process that will separate uranium and plutonium from fission products and at the same time furnish a means of separating the uranium and plutonium.

Distribution ratios (organic/aqueous) are functions of the concentration of the extractable component, the concentrations of common ion (i.e., such as HNO_3 , $\text{Al}(\text{NO}_3)_3$, with $\text{UO}_2(\text{NO}_3)_2$ in the aqueous phase), and the organic solvent being used.

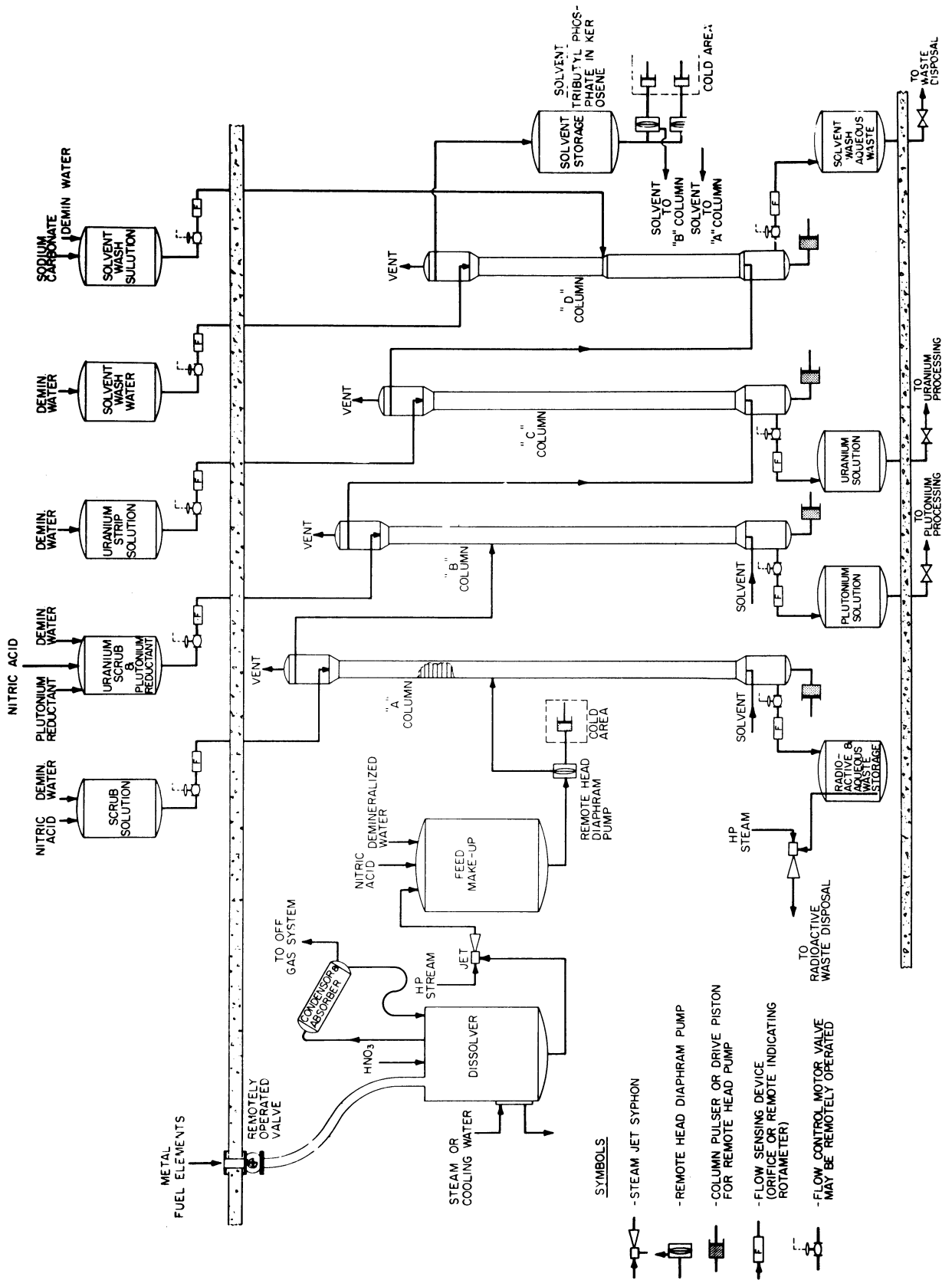
Two processes have been worked out using solvent extraction separation methods. These are the "Redox" and "Purex" processes, which differ only in the nature of the organic solvent and the salting agents employed. The Redox process uses methyl isobutyl ketone (MIBK) as the solvent and $\text{Al}(\text{NO}_3)_3$ as the salting agent in the aqueous phase, while Purex uses tributyl phosphate (TBP) dissolved in kerosene as the organic solvent and HNO_3 as the salting agent.

It has been found that some fission products, upon dissolution of the irradiated fuel elements, give species that display characteristics similar to colloids. Ruthenium (Ru-106) is the most troublesome element in this respect. For decontamination from ruthenium, therefore, it is necessary to run a series of extraction-stripping operations on the process feed material before the product meets "cold" specifications. Processing plants built in the past have usually employed three cycles of extraction-stripping between the feed material and the final product solution. Decontaminations achieved in these cycles run approximately 10^4 , 10^2 , and 10 for the first, second, and third cycles, respectively. Since daughter products from uranium decay have been removed in the extraction steps, the uranium product from these plants is usually less radioactive than natural uranium for long cooled feed material. Where short cooled fuels are processed, as discussed in this paper, the product will still be radioactive due to the presence of U-237.

B. Process Example

Figure 1 illustrates the requirements for one cycle of a solvent extraction process. This figure pictures pulse columns as the liquid-to-liquid contactors; however, mixer settler, packed columns, or other types of contactors could be used. This particular flowsheet assumes an aluminum-uranium type of fuel element similar to the fuel element of the Materials Testing Reactor. These elements are assumed to have been removed from a breeder or converter reactor so that plutonium is present,

FIG. 1
TYPICAL PROCESSING FLOWSHEET FOR SEPARATING PLUTONIUM, URANIUM, AND FISSION PRODUCTS BY SOLVENT EXTRACTION



the elements have been cooled sufficiently, and fission product decay heat has been largely dissipated. A Purex type flowsheet is illustrated, but the Redox flowsheet would be quite similar.

Fuel elements are charged from a shielded carrier through a remotely operated valve and slug chute into the dissolver. Nitric acid is added and dissolution of the fuel element takes place, with liberation of oxides of nitrogen and fission product gases. Oxides of nitrogen are re-absorbed into the overhead condensate and returned to the dissolver, while fission product gases are removed in an off-gas processing system or, in remote areas, discharged into the atmosphere through a high stack.

When dissolution is complete, the dissolver solution is transferred by a steam jet into the feed make-up tank, where concentrations of uranium and nitrate ion are adjusted to give suitable extraction feed.

Feed solution is pumped by a metering pump to the feed inlet point of Column A. Organic solvent, tributyl phosphate in kerosene, is passed counter-current to the combined feed and scrub solution in Column A, and it extracts the uranium and plutonium from the aqueous phase. The solvent then passes through the scrub section of the column (that part of the column above the feed point), where traces of fission products are removed from the rising organic phase.

Fission products, cladding materials, and impurities leave the system in the aqueous waste stream from the base of the column. This stream is usually concentrated and stored in large underground storage tanks. However, an alternative method is given in subsequent pages.

Uranium and plutonium in the solvent leave the settling zone of Column A and enter the feed point of Column B. The scrub stream in this column contains a reductant which reduces the plutonium valence state to the +3 or +4, at which point it becomes non-extractable and enters the aqueous phase. Uranium is not affected by the reductant and remains in the organic phase. Plutonium leaves

Column B in the aqueous bottom stream while uranium leaves in organic phase from the top settling section. Solvent entering the bottom of Column B scrubs all uranium out of the plutonium bottom stream while the aqueous reductant stream entering the top of Column B scrubs all the plutonium out of the uranium stream leaving the top of the column. The plutonium stream is routed to another solvent extraction-stripping cycle where it is further purified.

Uranium in the organic phase leaving Column B cascades into the bottom of Column C. Here the metal in solution is stripped from the organic stream by a water stream entering the top of the column. The aqueous phase in this column contains no salting agent so the uranium distribution ratio favors the aqueous phase. Aqueous solution from the bottom of Column C is routed to a subsequent solvent extraction-stripping cycle for further decontamination. Solvent from Column C is scrubbed and purified by carbonate-water streams in Column D. After this scrubbing, the solvent is suitable for re-use in Columns A and B.

Pulse columns are also illustrated in Figure 1. The contents of these columns are pulsed 40 to 120 times per minute by a reciprocating plunger. Operation of these columns has been described in detail by Burns, Groot, and Slansky (1) and by Sege and Woodfield (2).

C. Design and Types of Liquid-to-Liquid Contactors

Contactors correlations and stage requirements have been done by graphical step-by-step calculations, similar to McCabe-Thiele distillation calculations, as well as by the height of a transfer unit concept. In regard to time, it is much easier to use the step-by-step procedure since determination of transfer units requires a graphical integration.

In processes like Redox and Purex, the solvent phase is usually pre-saturated with water, and solvent solubility in the aqueous phase is low. It is usually assumed that the operating lines are straight. Distribution ratios vary with salting agent and metal concentration, so that equilibrium lines are straight

only over the dilute ends of the system. The Redox process in particular has a very curved equilibrium line in the more concentrated end of the system.

If equilibrium and operating lines are substantially straight, the stage requirements can be computed using the equation by Barson and Beyer (3).

N = number of theoretical stages.

x_f = concentration of extractable component in aqueous feed.

x_w = concentration of extractable component in aqueous waste stream.

Y_2 = extractable component in organic extractant feed (usually zero).

m = y^*/x^* or distribution ratio org./aq. of extractable component.

$\frac{O}{A}$ = flow ratio of organic-to-aqueous phases (i.e., slope of the operating line).

$$N = \frac{\log \left[1 - \frac{(x_f - x_w) \left(\frac{O}{A} - m \right)}{m x_w - Y_2} \right]}{\log \left(\frac{m O}{A} \right)}$$

Stage requirements can be computed using this equation with no column reflux or with x_f evaluated at reflux conditions for both the column scrub and extraction section. Stages required in the scrub section are based upon extractable fission product distribution coefficients.

The stripping columns must be calculated by graphical means, since the equilibrium lines are highly curved. In many cases, two or more components are being transferred in this column.

The number of transfer units can be calculated by Weigand's (5) approximation and are accurate enough for design purposes.

N_{ox} = number of transfer units required based on the organic phase.

y = extractable component concentration along operating line.

y^* = equilibrium concentration of extractable component.

y_1, y_2 = limits of component concentration contactor is operating between.

$$N_{ox} = \int_{y_1}^{y_2} \frac{1 dy}{y^* - y} + \frac{1}{2} \ln \frac{1 + y_2}{1 + y_1}$$

Packed columns, pulse columns, and mixer settlers have been used in processing irradiated fuels. The throughputs of such equipment have been given in references (1), (2) and (4). Pulse columns were selected for use in this study since some solids may be carried over from the feed preparation steps and equipment of this type handles small quantities of solids readily; in addition, columns are easier to make "critically safe" for the uranium concentrations encountered, and stage heights are reasonably low. Packed columns and mixer settlers have many advantages when these considerations are not factors.

D. Fuel Element Compositions Processable by Aqueous Solvent Extraction Means

In general, any fuel element that can be dissolved in an aqueous medium can be processed by aqueous means. Compositions containing aluminum-uranium, zirconium-uranium, and stainless steel-uranium have all been successfully processed. In this paper, an element of chromium-steel and uranium is discussed and means of processing by aqueous solvent extraction is outlined.

IV. DESCRIPTION OF FUEL ELEMENT AND BLANKET MATERIALS AND FUEL AND BLANKET HANDLING EQUIPMENT OF A POWER BREEDER REACTOR.

The fast power breeder being developed by the Atomic Power Development Associates, Inc., is a nuclear power plant which includes the reactor, associated fuel element handling equipment, heat removal and utilization equipment, site and major buildings.

The reactor assembly consists of core fuel elements which are surrounded by uranium elements as blanket material.

The reactor core is an assembly of partially enriched uranium alloy rods. Some plutonium is produced in the core fuel elements. The blanket elements surrounding the core are fabricated elements using depleted uranium, (U-238), or natural uranium, and in which most of the plutonium is produced. At periodic intervals, a number of core fuel elements are removed from the reactor. Upon a predetermined schedule, a number of blanket elements are also removed.

Upon removal of core and blanket fuel elements, the units are stored in molten sodium or NaK for cooling.

Two types of core fuel elements are projected: The pin-type elements, Figure 2, and the plate-type element, Figure 3. (6).

In geometrical assembly and fabrication technology, blanket elements are considerably different from core fuel elements. A group of cylindrical pins containing initially depleted uranium-238 or natural uranium are assembled into a blanket element with a hexagonal cross section. The overall length of a blanket element is 8' - 4½". A drawing of the proposed blanket element is shown in Figure 6.

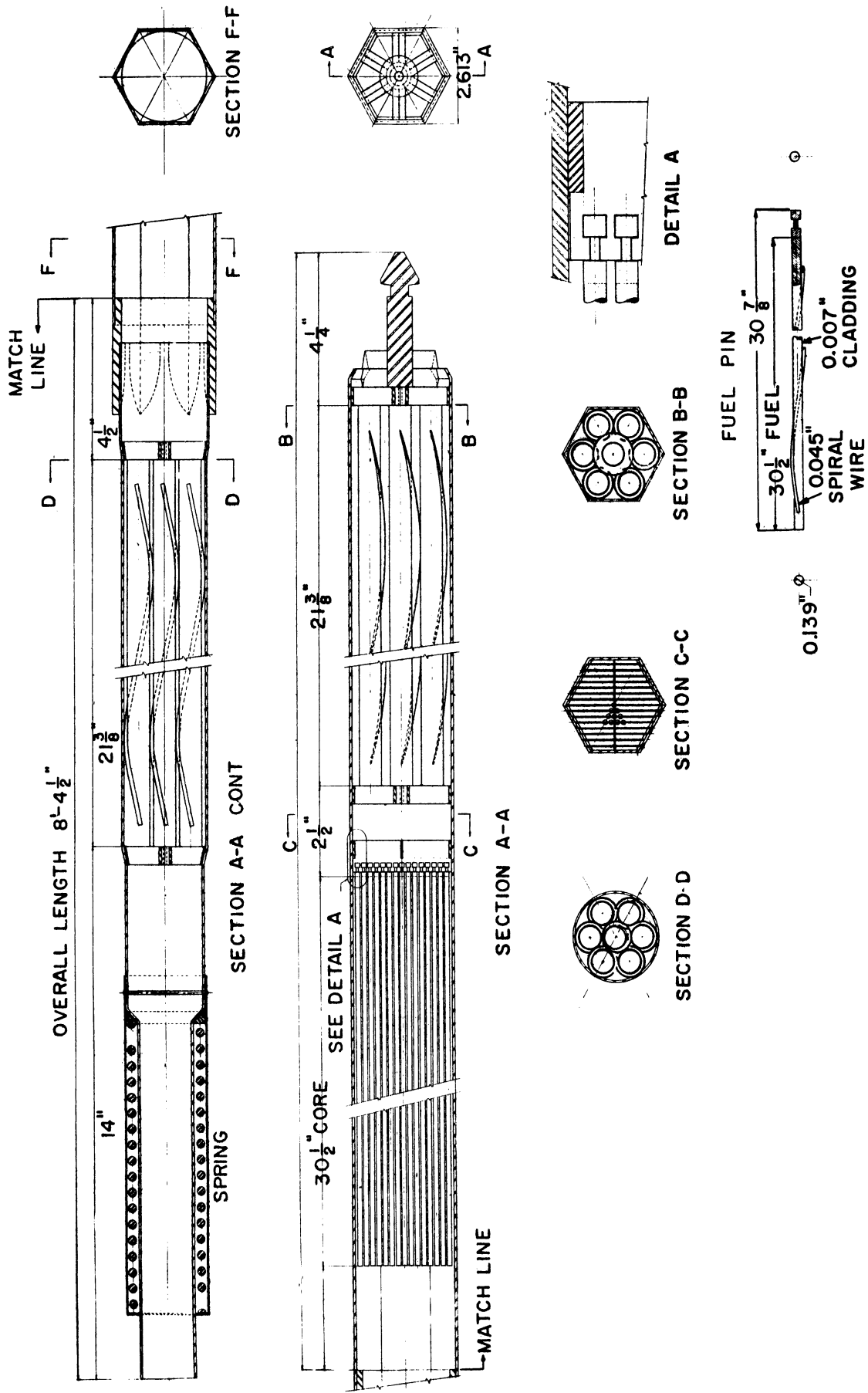


FIG. 2 PIN-TYPE FUEL ELEMENT

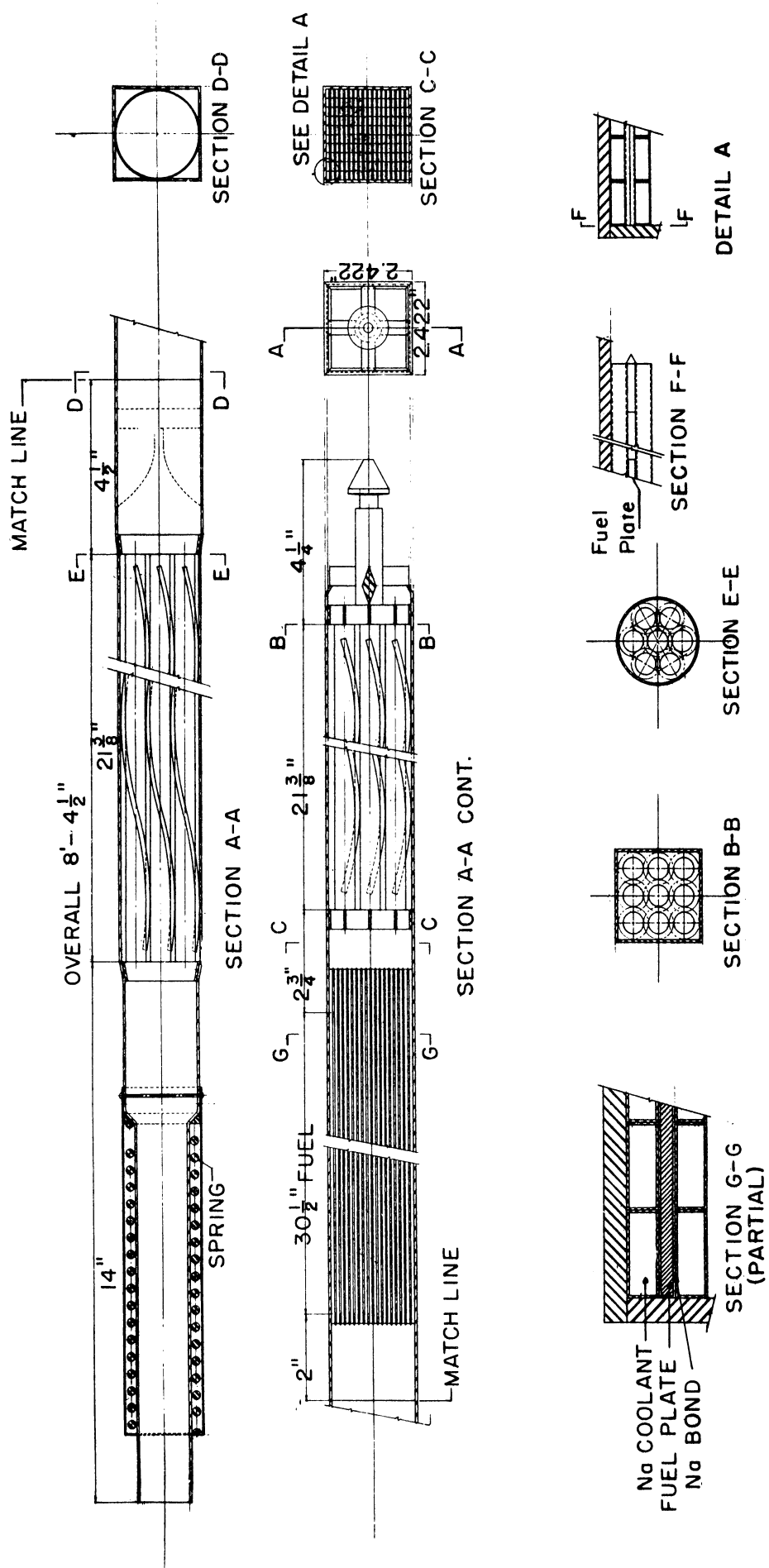


FIG. 3 FLAT-PLATE-TYPE FUEL ELEMENT

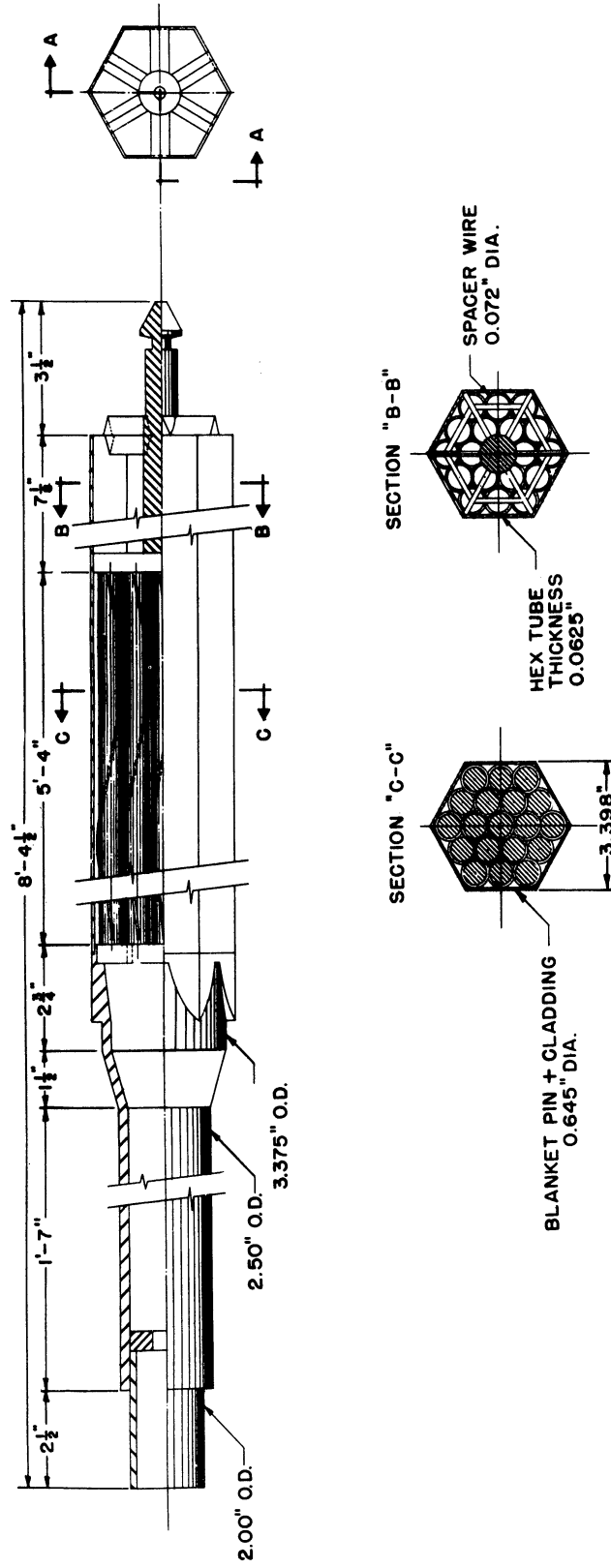


FIG. 4 RADIAL BLANKET SUB-ASSEMBLY

Element handling mechanisms are provided for removal of fuel and blanket elements from the reactor and for insertion of new or recycled elements. Equipment and facilities for transferring irradiated elements from the reactor to storage and cooling areas are considered part of the reactor facilities. When irradiated elements are removed from the reactor, it is necessary to store the materials in molten sodium or NaK until such time as fission nuclide decay permits their removal from the molten metal coolant.

After an adequate period for decay, fuel and blanket elements can be disassembled, inspected, and transferred from the reactor building.

V. DESCRIPTION OF PROCESS STUDIED IN THIS PAPER

A. General

Several processes were considered for the chemical separation of fuel and the blanket elements from a power breeder reactor. One of them was an aqueous method of solvent extraction of uranium and plutonium from the other parts of the fuel as previously described. In this process, the uranium is converted to the metal, but the plutonium is shipped as an aqueous solution decontaminated of fission products.

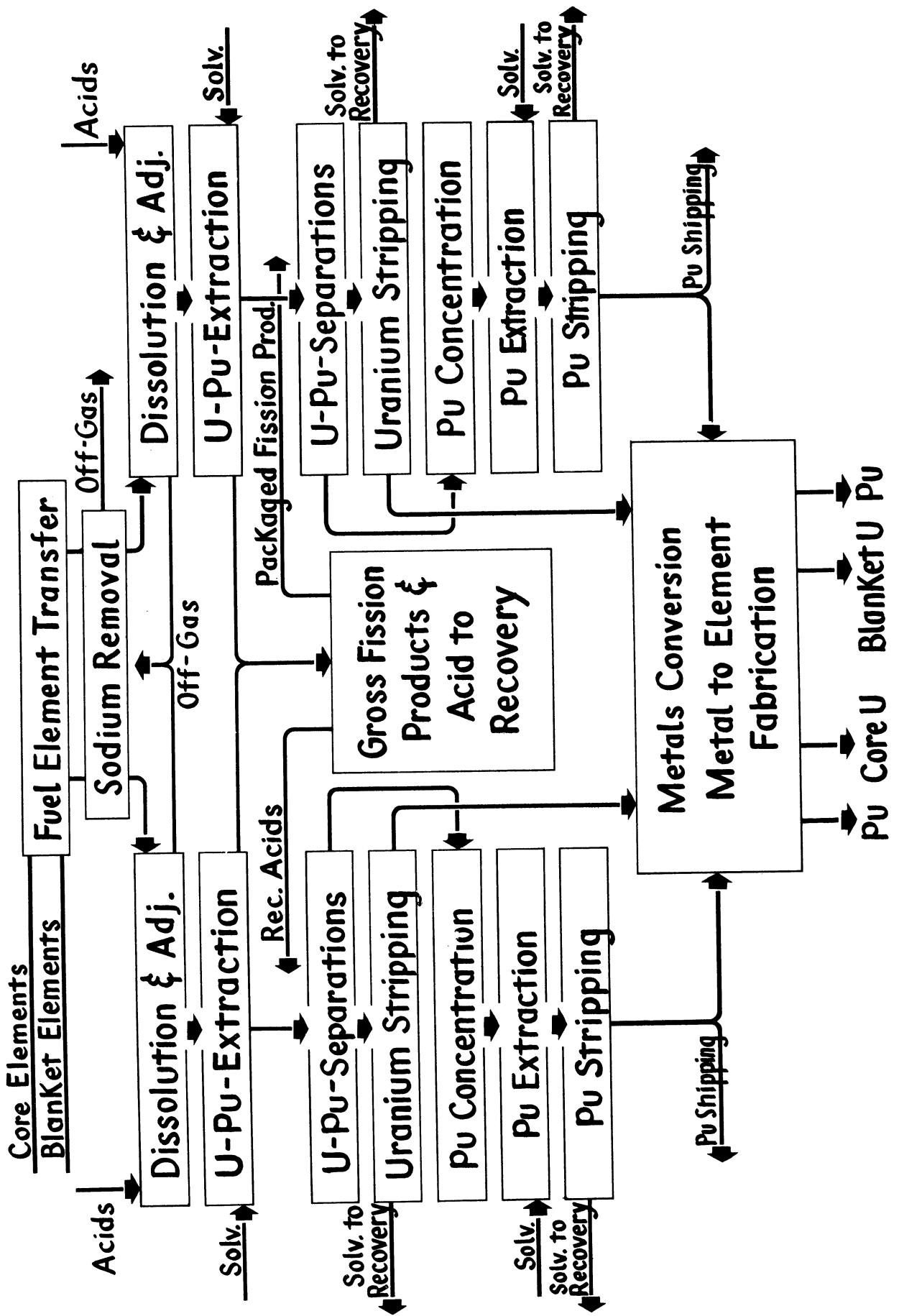
Certain operations described in the aqueous chemical process are subject to research and development investigations. However, it is believed that an aqueous process such as that described below will require a minimum of development activities in order to achieve nearly complete separations of uranium, plutonium, and fission products from each other and from structural materials of fuel elements now in use. Other methods of processing offer certain attractive advantages in achieving some of these steps, but it is not presently believed that complete separations of all components can be achieved by any method other than aqueous without greater development expenditures.

Since the process described is intended for the separation of uranium and plutonium from core fuel elements and from blanket elements of differing isotopic enrichments of uranium, it is necessary that two separate processing lines, one for each type of elements, be incorporated into the process. The processing steps required for the fuel elements and for the blanket elements are essentially the same; consequently, the procedure for only one of these is described. Structures and auxiliary services are common to the two processing lines. A block flow diagram, Figure 7, illustrates the steps as described below. The methods of chemical processing employed were developed by Oak Ridge National Laboratory and Argonne National Laboratory.

FIG. 5

BLOCK FLOW SYSTEM

MAIN STEPS



B. Storage and Handling

Upon removal from the fast breeder reactor, fuel elements will be found to have a residual coating of sodium and will be highly radioactive. Both fuel and blanket elements will undergo radioactive decay while submerged in a fluid which removes heat and protects them from the air. The elements will be transported from the reactor building to the fuel processing building while they are immersed in their protective fluid. They will remain in the protective fluid until they have undergone radioactive decay to the point where the heat released from them is small enough to permit their being handled and inspected in the air or inert gas without danger of overheating. The elements will then be removed from their cask within a shielding arrangement and transferred to a remote handling room. In the remote handling room, the elements may be inspected, identified, and then transferred for the removal of sodium. If the elements have been allowed to decay for too short a period of time so that fission product heat is still a problem, then suitable arrangements must be made for the removal of this heat.

C. Sodium Removal

Since dissolution of sodium in acid is a hazardous procedure and causes excessive consumption of acid, the removal of sodium from irradiated elements would be necessary in this process. The removal of sodium necessitates further investigations before final design decisions can be reached.

A proposed method for the removal of sodium would be to immerse fuel elements in alcohol. The alcohol would react with the sodium to form alcoholate, resulting in release of hydrogen. The alcoholate dissolved in the alcohol could be transferred from the treating vessel, mixed with water, and the alcohol formed from the alcoholate could be redistilled and returned to the treating vessel. Sodium hydroxide solution could be removed from the bottom of the distillation

column. It is likely, however, that considerable radiation damage to the alcohol would occur if fuel being processed has been permitted to decay for only short periods of time. If short-cooled fuels are to be processed, alternative provisions might be made to treat the fuel elements coated with sodium by superheated steam, sprays of water, or by combinations of these methods.

D. Dissolution

In a method of chemical separation of irradiated fuel elements employing solvent extraction of source and fissionable materials from aqueous solutions, it is necessary to convert heterogeneous fuel elements to aqueous solutions, usually by means of an acid dissolution. The chemical properties of these aqueous solutions must be such as to permit solvent extraction of uranium and plutonium from the remainder of the solution of fuel elements. The chemical methods of dissolution are subject to investigation for each type of metallurgical composition employed for fuel and blanket elements. Investigations by Elving (7) indicate that catalyzed nitric acid may dissolve the uranium from both the fuel and blanket elements.

A block flow diagram of the process of chemical separation by aqueous means is shown in Figure 5. The fuel elements are dissolved in nitric acid, and provisions have been made to conduct this operation continuously. A group of fuel elements would be lowered into the dissolver through a quick-opening cover, and acid of the proper concentration would be introduced continuously at a controlled rate. With such a procedure, a solution may be discharged from the dissolver with a controlled concentration of uranium salt in an acid solution together with other associated solutes.

Nitric acid will dissolve most of the fuel or blanket elements, cladding, alloy, fission products, and source and fissionable materials. Following the completion of the optimum amount of dissolution of the source and fissionable materials in nitric acid, all nitric acid may be removed from the dissolver.

Sulfuric acid may then be added to dissolve the residual chromium used in these elements, and to dissolve any remaining source and fissionable materials. This solution of salts also flows to the extraction system. In the particular schedule adopted for the processing of the fuels of the single 500 megawatt reactor, the source and fissionable materials would be dissolved in nitric acid during the first two days of each operating week. The remainder of the week could be spent in disposition of the residual metal with its associated source and fissionable materials, and in preparation for the processing of another load of fuel and/or blanket elements at the beginning of the following week. The blanket elements need not be processed so rapidly, since their content of fissionable materials is not so great.

E. Solvent Extraction

The solution in water of uranium, plutonium, fission products, structural metal, and excess nitric acid flows at a controlled rate from the dissolution step to the extraction step. In the extraction, pulse-plate columns are used to contact the aqueous solution with a 30 percent solution of tributyl phosphate (TBP) in Amsco, a special grade of kerosene. This step is conducted similarly to that described in Section III. Uranium and plutonium are extracted from the aqueous phase in the first column, the fission products going out as the aqueous waste stream of the first column. In the second column, the plutonium is reduced and transferred to the aqueous phase and flows to plutonium decontamination. In the third column, uranium is stripped from the organic phase by means of an aqueous stream. The aqueous uranium solution is washed with more Amsco in order to remove any tributyl phosphate which might remain suspended in this solution. The presence of tributyl phosphate in the uranium solution results in decomposition products that interfere with uranium extraction during subsequent cycles. The aqueous solution of uranium is concentrated by evaporation. The solvent extraction

operation is illustrated in the flow sheet, Figure 1.

The control of uranium concentrations in the solvent extraction system is sometimes a problem, since operations are conducted remotely, and the analysis of radioactive streams for uranium is a time-consuming procedure. The development of continuous analysers to determine the concentration of source and fissionable materials in processing streams appears promising. The use of such continuous analysers is considered in this example study. Such devices would be valuable in permitting control over the accidental transfer of source and fissionable materials to the fission product recovery operation and in simplifying the procedures for accountability of source and fissionable materials. A continuous instrument analysis and record of process stream compositions would assist in preventing transfer of source and fissionable materials to waste tanks. Since only micro-quantities of source and fissionable materials can be permitted to be lost in any processing operation, it would be necessary to rework the contents of waste tanks in order to recover these materials, if amounts of uranium and plutonium in excess of the allowable accountability limits should inadvertently be diverted to waste tanks.

F. Reduction of Uranium Solutions to Metal

The product of the solvent extraction and concentration steps is a solution of uranyl nitrate hexahydrate, called UNH. The uranyl nitrate cannot be obtained in an anhydrous form without decomposition by heating, and it is consequently handled as a solution of uranyl nitrate melted in its own water of crystallization.

In order to convert the UNH to uranium metal, the following procedure is employed. The UNH is transferred to the top of a vertical bank of furnaces which are electrically heated and internally agitated by means of open-flight screw conveyors. In the first furnace, the UNH is dehydrated and denitrated to uranium trioxide powder. The powder is transferred through a gas-tight feeder to a second furnace where hydrogen is introduced and the uranium trioxide is

reduced to the dioxide. The dioxide in turn flows through another gas-tight feeder into a third furnace, where hydrogen fluoride is introduced, resulting in the conversion of the dioxide to the uranium tetrafluoride. Uranium tetrafluoride is mixed with magnesium metal in a crucible and heated inside a steel container. The uranium salt is reduced to metal, which is then allowed to settle out of the slag while molten. The metal in the form of a button, or regulus, is chipped free of slag (by remote means if the metal still contains uranium-237) and is transferred to the fuel refabrication operation for re-use in the nuclear reactor.

G. Plutonium Decontamination

From the second solvent extraction column, an aqueous stream containing the plutonium is discharged. This solution of plutonium is first concentrated, and is then subjected to additional cycles of decontamination. The plutonium is oxidized and is then extracted from the aqueous solution by means of a solution of 30 percent TBP in kerosene. The plutonium is then stripped from the TBP-kerosene solution to an aqueous solution in a second solvent extraction column. The decontaminated aqueous plutonium nitrate is then concentrated, either for shipment as a salt solution according to plans for this example study, or for possible conversion to metallic form. Provisions were made in this example study for the possible use of a second cycle of plutonium decontamination by passing the plutonium from a core stream through the blanket plutonium decontamination facilities, or vice-versa. If completely decontaminated plutonium solution is required as a product, it might be necessary to add still a third stage of plutonium decontamination.

H. Treatment and Storage of Fission Products

The processing of fission products into highly concentrated form is one of the major areas of development for economical use of aqueous chemical processing.

The aqueous solution of fission products and nitric acid released from the first extraction column might be processed as follows. The solution is transferred

to an electrically heated evaporator, where the solution is concentrated to a molten salt. Nitric acid and water are removed by the evaporation process and separated in a series of two columns. The condensate from the second column is discarded, and the concentrated nitric acid from the first column is recovered for possible re-use. The mixture of molten nitrates of the fission products and of the cladding and alloying materials is cast into molds made of lengths of pipe. If processing is conducted sufficiently soon after the elements are removed from the reactor, it is possible that the fission product evaporator could operate on the heat released by the fission products after start-up has been achieved. In this situation, an outside source of heat might not be necessary. Control of the evaporator might be achieved by the addition of water to the concentrating column for the removal of heat. If sufficient heat were to be released from the fission products, molds filled with fission product salts would emit considerable quantities of heat. Maximum design surface temperatures of 600-800°F might be reached on the cylindrical containers assumed in this example study. Such containers might be used as sources of heat, although the rate of heat release would probably decrease rapidly due to fission product decay. It is possible that if large quantities of heat are released initially, the temperature of the melt of fission product nitrates would increase to a value which would result in the denitration of most of the fission product nitrates. The result should be a bed of oxides remaining in the storage cylinders. It was assumed that the cylinders might require storage in a nearly horizontal position with the open end elevated sufficiently to prevent the molten salts from running out. NO and NO₂ would be released during denitration and they would have to be collected, decontaminated and disposed of. After emission of gas had ceased, the cylinders could be capped by a remote welding device.

In addition to a compact storage of fission products and a resulting rod-like source of radiation and/or heat resulting from this method of storage,

further advantageous characteristics of such sources are visualized. One of these is that specific isotopes could be removed selectively from the mass of fission product oxides remaining in storage cylinders. Furthermore, if it were found that source and fissionable materials had inadvertently been released to the aqueous waste stream as a result of improper operation of the separation equipment, it would be relatively easy to recover these materials by redissolving the cylinder containers with their contents by a dissolution process similar to that described in Section D.

I. Waste Treatment Methods

During the removal of sodium and the dissolution of fuel elements, quantities of radioactive gases are produced containing water vapor and products of decomposition of nitric acid. These gases are conducted through a treating system where they are purified and freed of radioactivity and other objectionable materials, and then released to the plant stack. Purification of the gases will take place in a special system that would consist of scrubbing, catalytic oxidation of the nitrogen oxides, drying, and the adsorption of rare gases. The resulting gas stream would consist essentially of pure nitrogen.

Vessel off-gas streams and air streams from laboratory hoods are freed of any radioactive materials by being passed through a scrubbing operation and through filters before being released to a central reactor plant stack.

Ventilating air is washed free of dust, conditioned, and distributed to the office space of the processing plant. Parallel streams go to the control room and to the laboratories in the hot cells. Some exhaust is taken from each of these ventilating areas, and the exhaust air from the hot cells is removed by means of exhaust fans through ducts which interconnect with the general plant air cleanup system and plant stack.

Mixtures of organic solvents used in extraction operations are subject to radiation damage, particularly in the first extraction column where core material

is treated. An allowance for discarding portions of solvent has been provided. The organic solvents, which have been subject to radiation damage or otherwise fail to be of further use, may be disposed of by storage or other means meeting to the requirements of safety. The remaining solvent is treated with water, caustic soda, and acid, and it is then recycled to the extraction operation for further use.

The primary safeguard against external discharge of radioactive materials due to a vessel or piping failure is a provision made for rapid process shutdown with a minimum holdup of materials. The aqueous streams, mainly cooling water, are discharged from the chemical processing plant through a settling basin where chemical wastes can be treated to permit discharge of the material. The inlet of the settling basin is monitored for radiation at all times and provisions are made for plant shutdown in the event that any excessive quantities of radiation are present. Further measures for correcting this situation may be then taken as follows. The settling basin provides sufficient holdup to prevent the discharge of activity before the plant may be shut down. If radioactive materials are discharged into the settling basin, they may be stored until the source of radiation leakage is repaired. The contents of the settling basin can be recycled through the evaporators for decontamination. The condensate from the evaporators is considered to be decontaminated sufficiently to permit disposal.

VI. PLANT FACILITIES FOR AQUEOUS PROCESSING

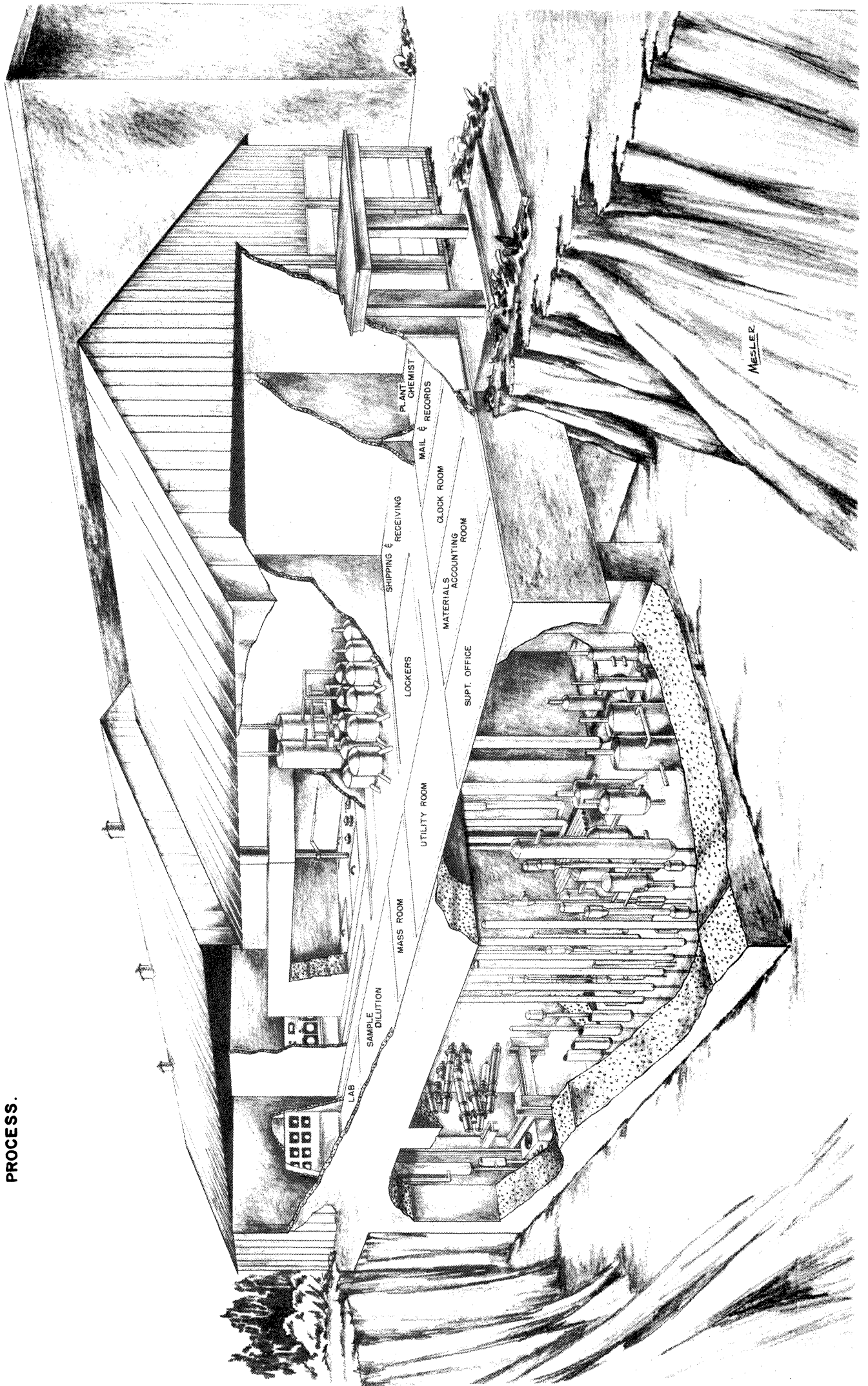
A. General Arrangement

The perspective drawing, Figure 6, illustrates the proposed arrangement of equipment and structures for this example study of a chemical separation plant.

B. Influence of Shielding and Throughput Upon Plant Economics

There is likelihood that a certain minimum productive capacity exists for fuels processing plant below which no significant decrease in capital cost may be expected, regardless of how small the productive throughput may be. This consideration imposes economic limitations upon the design capacity of such a plant. There is a lower limit to the size of structures required for shielding of a chemical separations plant regardless of the processing rate. This situation arises because the equipment required for an aqueous chemical reprocessing plant is a function of the number of separate chemical steps required to conduct the reprocessing, assuming no duplication of equipment in order to meet throughput requirements. Since the equipment in this example study would be designed for the possible containment of fissionable material, the spacing of the equipment is controlled by criticality considerations. Once it is specified that aqueous processing will be conducted upon enriched uranium, then the minimum size is nearly fixed for the shielded cell needed to conduct this operation. The fixing of the minimum size for the shielded cell is also determined by the fact that there are required at least a probable minimum number of theoretical stages of extraction for the separation process. This required number thus specifies that, although the equipment may be quite small in diameter, its required height will not vary greatly with throughput. Since a certain minimum amount of labor must be done in the fabrication of any piece of equipment, regardless of its size, it is also apparent that a certain minimum expenditure would be required for the processing equipment. Consequently, fabrication, labor and handling costs which are not greatly dependent upon equipment

FIG. 6
PERSPECTIVE OF BUILDING AND
EQUIPMENT FOR PROPOSED
PROCESS.



size may tend to fix the lower limit of required investment for equipment in such a plant.

In the example study plant presented here, no significant saving in capital cost could be realized at a productive capacity of less than 300,000 pounds per year of source and fissionable materials. However, the contemplated unloading schedule for the fast breeder reactor requires the processing of only 75,000 pounds per year of source and fissionable material, or approximately 25 percent of the productive capacity. A productive capacity of 300,000 pounds per year of source and fissionable materials was chosen for this example study, and equipment was sized to handle this throughput or any smaller throughput down to 75,000 pounds per year. Design considerations permitting this flow rate variation specified the adjustment of concentrations of source and fissionable materials in solution, and the control of mass velocities within extraction equipment.

C. Processing Equipment Cell Layout

It was decided to place all aqueous processing equipment within a single cell. Such a layout of equipment was conceived because the example study plant would contain essentially no inventory between processing steps. Consequently, if any part of the plant had to be shut down, the entire plant would become inoperative. It was therefore considered unnecessary to provide for the separate operability of different stages of processing. In addition, a maze or labyrinth of piping galleries and other inner-connections between separate cells necessary for multiple cell operation were eliminated. In the event aqueous processing becomes superseded by some simpler method of processing, such as pyrometallurgical, the cell provided for the storage of fission product wastes could be cleared of such materials, and pyrometallurgical equipment could be installed without interruption of the aqueous process operation.

Figure 9 is a plan view of the cells in which the process equipment is placed. The layout of the equipment is evident from this view, which shows the aqueous processing equipment and the auxiliary solvent treating and off-gas equipment in one cell, the kilns and furnaces for metal conversion in a separate cell, and a space for the storage of radioactive waste materials in the third cell. Also shown in this view is the location of the reactor building and of a canal connecting the chemical processing plant with the reactor building.

D. Operating Area

Figure 8 shows the layout of the processing plant at the operating level, which is directly above the equipment shown in Figure 7. At this level, not only the operation of the plant is conducted, but there are also available laboratories, materials shipping and receiving rooms, and general offices. It should be noted that the processing equipment has been so laid out and the sample dilution room and laboratory have been so located that samples may be taken from the process directly to the sample dilution room, and thence to the laboratory by a direct route.

E. Remote Handling Area

In Figure 11 it can be seen that the materials, i.e., the fuel elements, the product of the metal conversion unit, and the rods containing fission products, must be handled by remote manipulators. There, materials are generally located so that access can be gained to them from one large remote handling room which is located at the operating level and contains suitable lifting and manipulating devices. Items of mechanical equipment located in the shielded area are positioned so that they can be removed or repaired without decontamination of the cell. Fuel elements, when discharged from the reactor, would be moved into the remote handling room where they may be inspected and transferred through hatches into the appropriate processing facilities. The fission products, once they are cast into rod form,

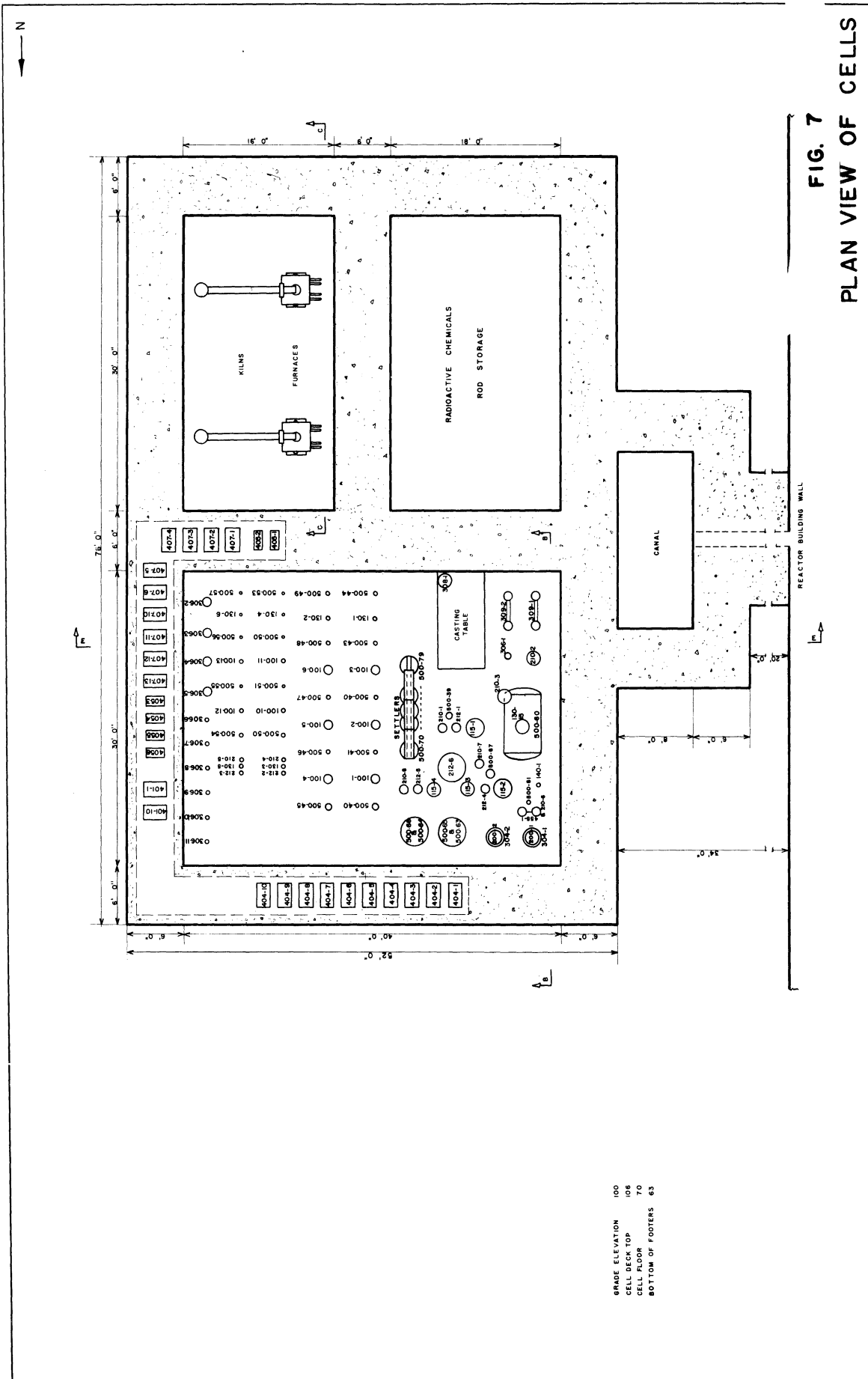


FIG. 7
PLAN VIEW OF CELLS

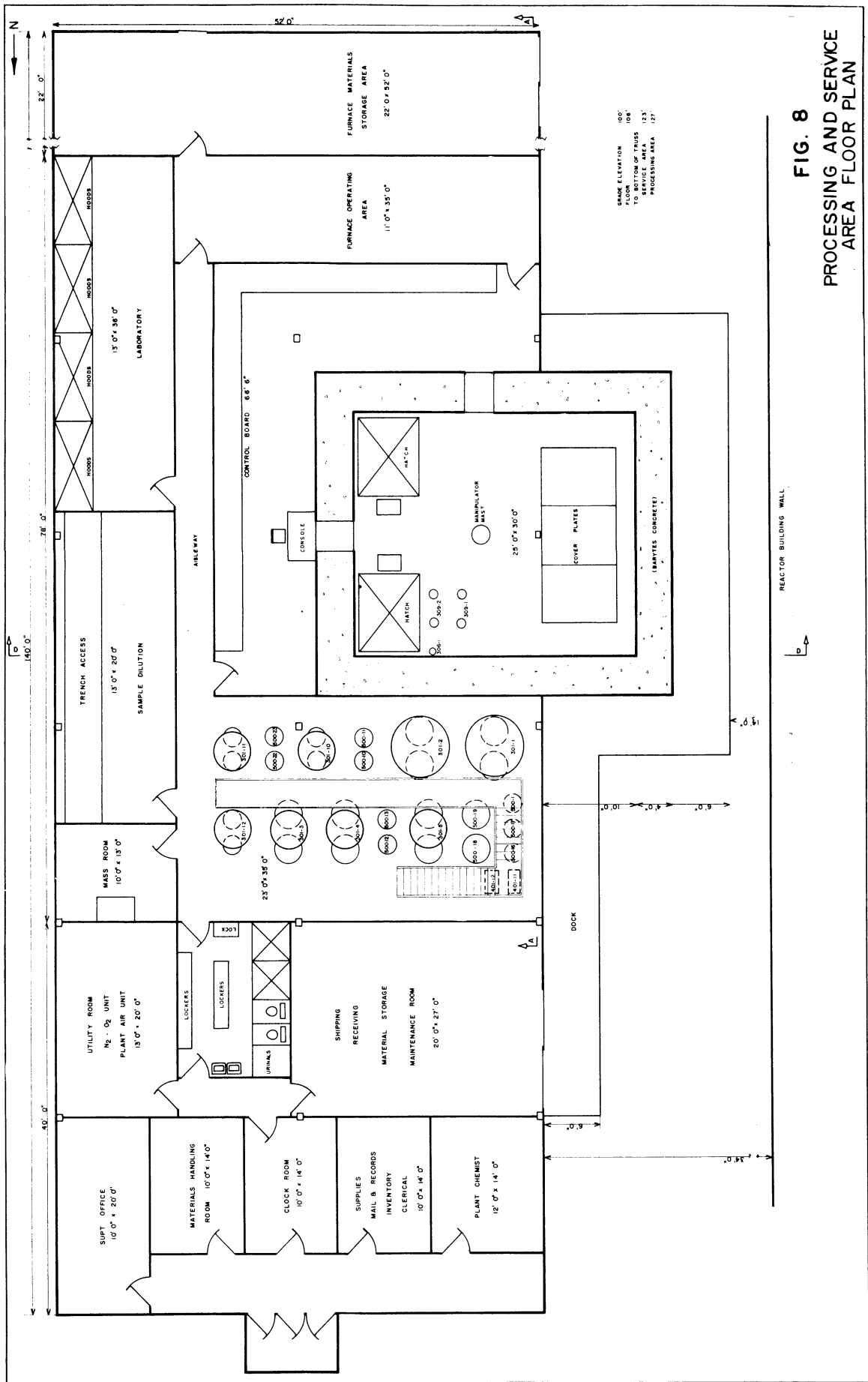
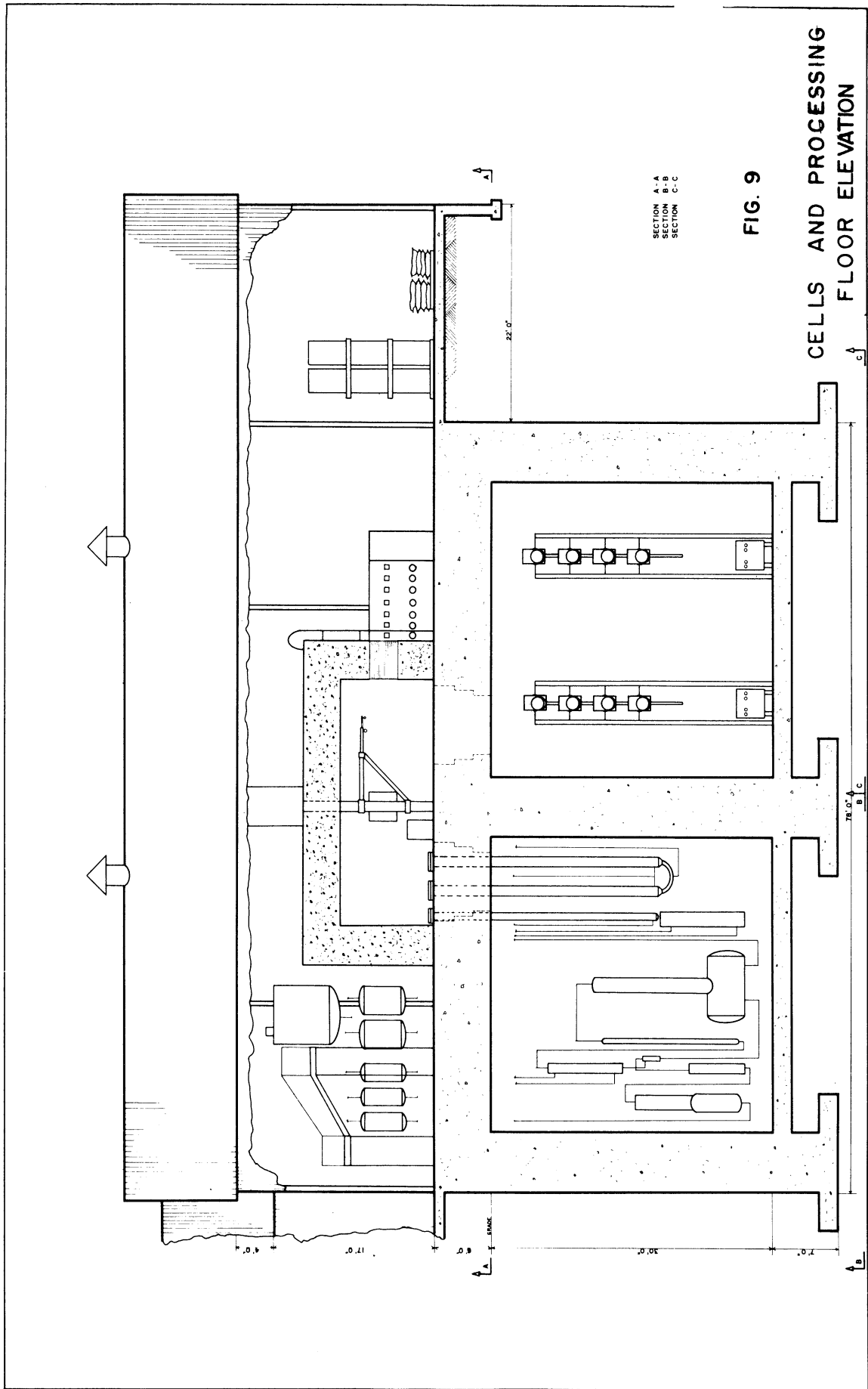


FIG. 8
PROCESSING AND SERVICE
AREA FLOOR PLAN



SECTION A-A
SECTION B-B
SECTION C-C

FIG. 9

CELLS AND PROCESSING
FLOOR ELEVATION

may be transferred through the remote handling room from the aqueous processing area and then into the fission product storage area. The metal, once it is produced in the conversion area, may likewise be transferred through the remote handling room by appropriate means into the fabrication area (not shown on figure). A mast-type manipulator, Figure 9, for handling many of these lifting chores would be complemented by means of auxiliary hoists.

F. Maintenance

All possible equipment, both mechanical and chemical, and especially that in the make-up and transfer areas, would be located outside of the hot cells. Pumps, pulsing mechanisms, and other equipment subject to some contamination would be located in a trench beneath the operating deck so that operators would be shielded from intermediate to mild levels of activity which might occur. Such intermediate shielding would permit the access to this mechanical equipment for maintenance.

If access were required to the hot cells, it would be necessary to suspend operations and decontaminate the entire cells sufficiently to permit access and maintenance. All equipment placed within the aqueous processing hot cell could be designed to operate for a period of five years without maintenance. This would be particularly true of the vessels and piping, the valves, and other such equipment. Equipment for which a five-year life could not be foreseen would be placed elsewhere.

G. Shielding

The design, operation, and anticipated maintenance of the metals conversion units would present large areas of uncertainty since much of such equipment is presently being developed for direct operation. Methods of indirect maintenance for these units have been assumed in this design. Because the metals conversion units are of a somewhat different character than the aqueous processing unit, the metals conversion unit has been placed in a separate cell from that of aqueous

processing. A third cell has been provided for the storage of containers of fission products, since this facility again represents a function distinctly different from both an aqueous processing unit and a metals conversion unit.

A minimum of 6 feet of ordinary concrete around all of the cells and in the cell decks has been provided for personnel shielding. In the walls and roof of the remote handling room, a thickness of 4 feet of barytes concrete has been employed. The smaller thickness is used to facilitate inspection of materials being handled and to reduce the shielding thicknesses through which the remote handling equipment must be operated.

Throughout the design studies, materials of construction were selected that would be adequate for resistance to the particular conditions. For example, in the chemical make-up area outside of the hot cells, ordinary industrial standards of corrosion resistance were employed.

VII. COST ESTIMATING

A. General

Preparatory to cost estimating, a complete inventory by equipment number was prepared of all equipment and auxiliaries, such as instruments, piping, and electrical equipment. These were described further by outline drawings and by specifications. Structures were listed in detail and were similarly described. The objective was to list each item required in the entire plant so that errors of omission would be at a minimum. Pursuant to the ground rules listed in section II, C., capital utility facilities, security guards, plant fire protection equipment, land and certain other capital items were not considered in this estimate.

An estimate was first drawn up of the quantities of materials required by weight, volume, or some other suitable index of cost for each structure and piece of equipment, and unit costs were then applied to these indices. Further allowances were made for office and field engineering, procurement, construction, field construction engineering, and for testing, calibration, dry runs, cold runs, and start-up activities.

It was further specified as a fundamental qualification of the estimating procedure that the work to be done in development, operator training, engineering, procurement, construction, and start-up would follow an integrated coordinated effort such as that presented in the proposed schedule shown in Figure 10. If the work described were to be pursued on an accelerated or "crash" basis, the sums of cost presented would have to be re-estimated.

B. Capital Costs

In Table No. I, there appears a summary of the capital costs of the entire example chemical processing plant, estimated in accordance with the procedure specified in VII-A. The costs are itemized for various categories: processing equipment installation is \$2,294,505; buildings, structures, and electrical power and lighting,

TABLE I
ESTIMATE SUMMARY
CAPITAL COST REQUIREMENTS FOR AQUEOUS RECOVERY PLANT

<u>Category</u>	<u>Subtotal, \$</u>	<u>Total, \$</u>
Process Installation		
Vessels	465,910	
Mechanical Equipment	676,360	
Instruments	162,785	
Piping	608,050	
Spare Parts	381,400	2,294,505
Buildings and Structures	1,683,680	
Electric Power and Lighting	214,050	4,192,235
Field Indirect Costs	424,700	
Engineering	600,000	
Contingencies	521,300	
Total Installation		5,738,235
Plant Start-Up	265,370	
Total Capital Estimate		6,003,605

\$1,897,730; field indirect costs, engineering, and contingencies, \$1,546,000; and plant start-up, \$265,370; for a total capital estimate of \$6,003,605. The significance of these costs in relationship to the entire required capital investment may be seen readily in Figures 11, 12, 13, and 14, in which the relative percentages required for each category are designated by bar graphs. As shown in Figure 11, the percentages of total capital cost required for process equipment and for structures are 50.2 percent and 49.8 percent, respectively. As shown in Figure 12, the capital costs in dollars for raw material facilities are \$847,735; for processing units, \$2,622,490; for process auxiliaries, \$934,355; and for general plant facilities, \$1,333,655; showing a total capital requirement of \$5,738,235. These costs amount to a total less than the \$6,003,605 mentioned above, by the amount of cost of start-up. Figure 13 shows the distribution of capital costs in dollars for the following categories: vessels, \$701,555; mechanical equipment, \$1,018,440; instruments, \$245,120; piping, \$915,580; structures, \$2,535,230; electrical, \$322,310; showing a total requirement of \$5,738,235. This figure does not include development costs or plant start-up.

Figure 14 shows the distribution of capital costs in percentage of the total cost for the same categories used in Figure 13. These are: vessels, 12.23 percent; mechanical equipment, 17.75 percent; instruments, 4.27 percent; piping, 15.95 percent; structures, 44.18 percent; and electrical, 5.62 percent, showing a total of 100 percent of the capital costs, not including development costs and plant start-up.

C. Operating Costs

In estimating annual operating costs, the following items were considered. The variable costs of payroll, materials and maintenance were estimated on a production basis and at standby condition without production. To these costs were added the cost of amortization. This amortization allowance was set equal to the

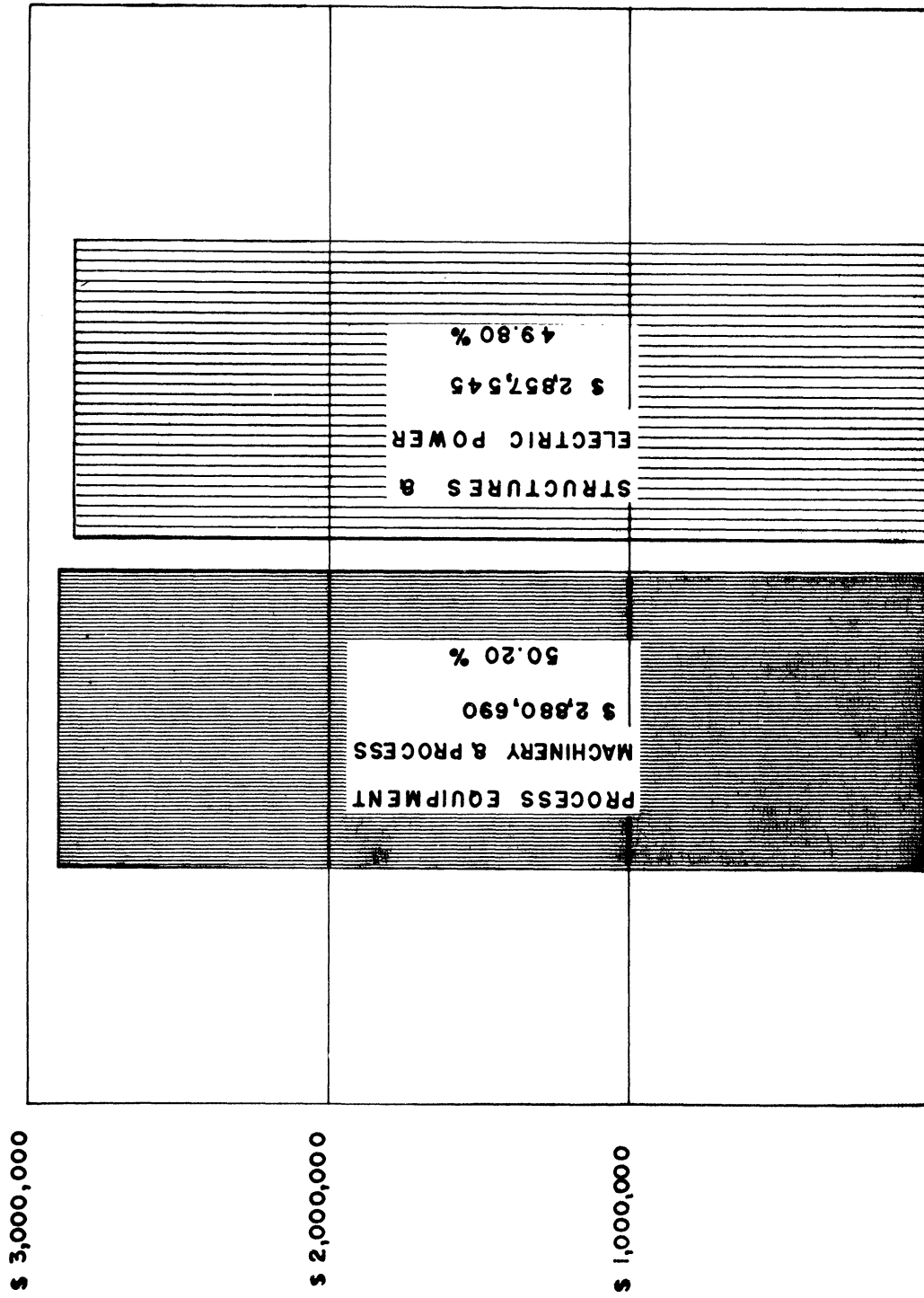


FIG. 11
 CAPITAL COSTS OF STRUCTURES
 AND PROCESSING EQUIPMENT

DISTRIBUTION OF ESTIMATED CAPITAL COSTS
IN TERMS OF FUNCTIONAL RELATIONSHIPS

TOTAL COST ESTIMATE: \$5,738,235

DOES NOT INCLUDE:

1. COSTS OF DEVELOPMENT
2. START UP

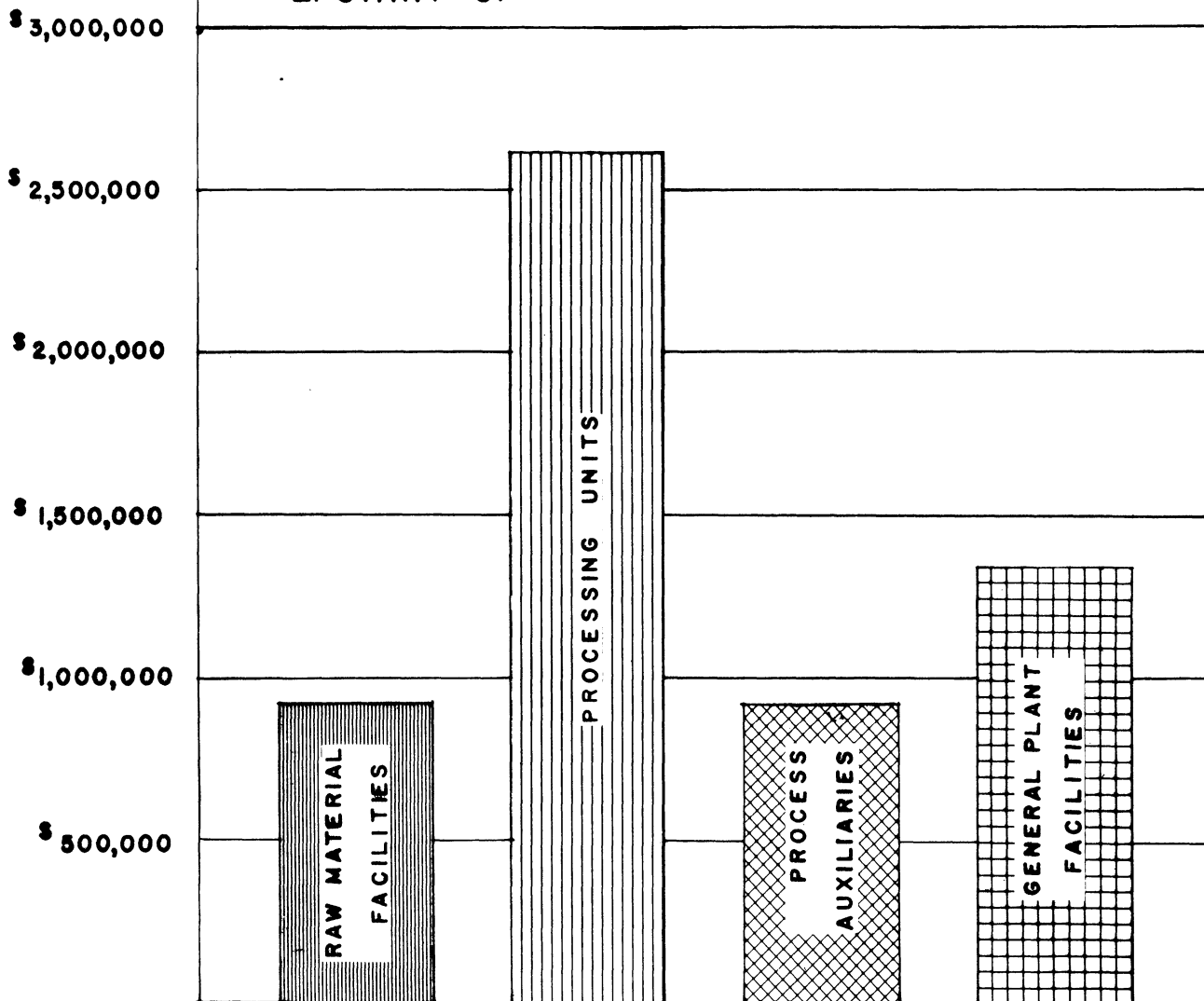


FIG. 12

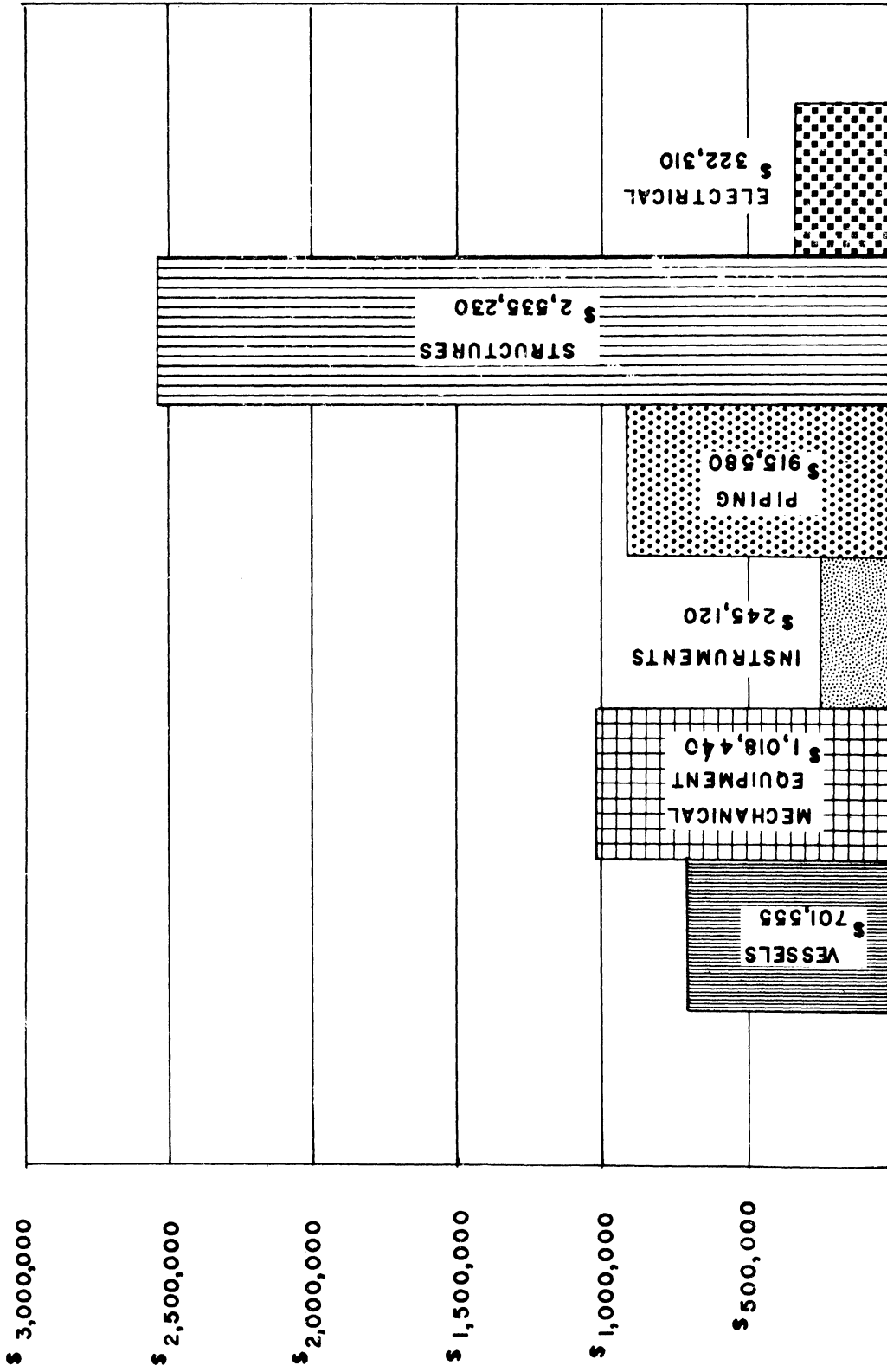


FIG. 13
 DISTRIBUTION OF CAPITAL COSTS
 BY EQUIPMENT CATEGORIES

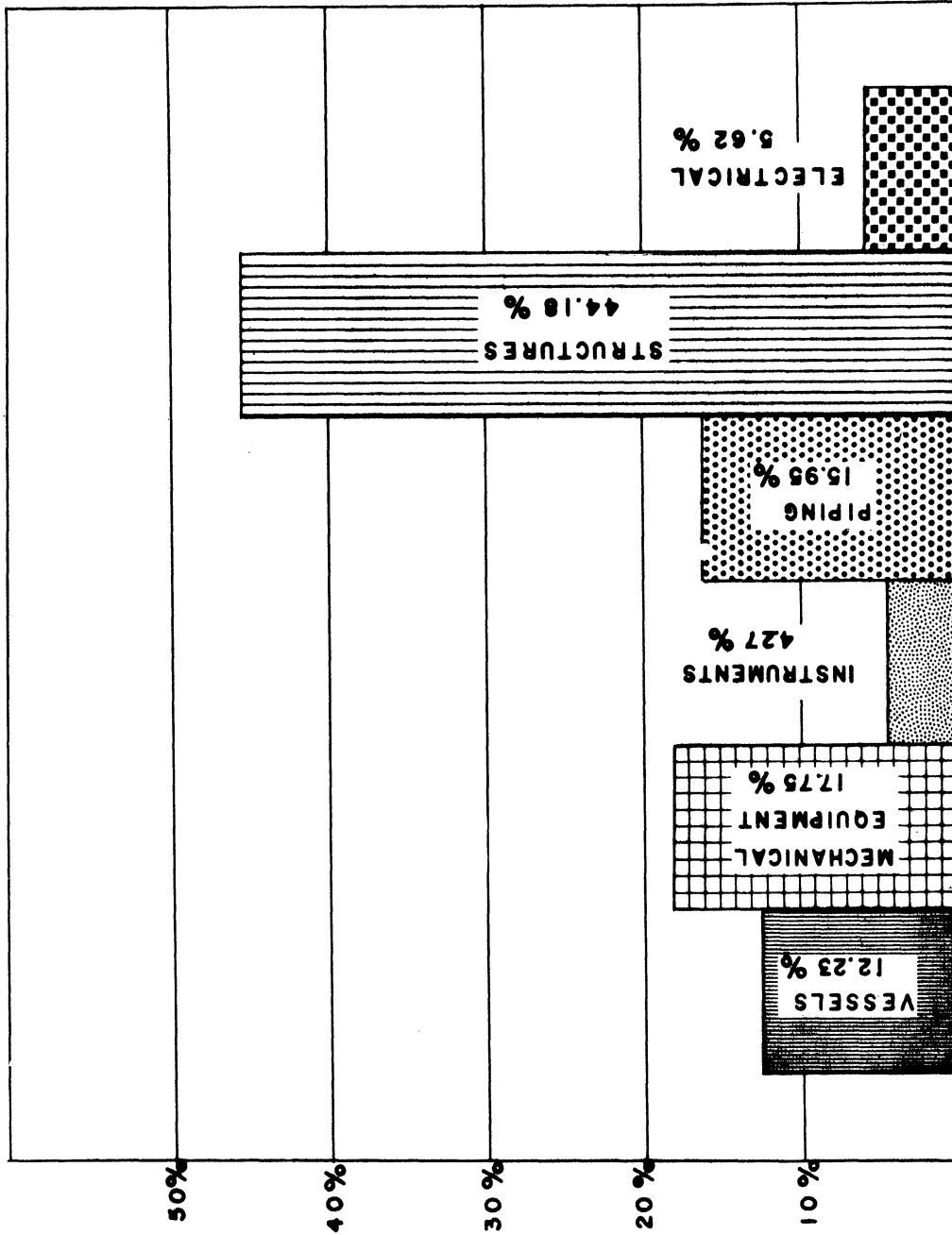


FIG. 14
 PERCENTILE DISTRIBUTION OF
 CAPITAL COSTS OF EQUIPMENT

weighted average rate of depreciation of the entire capital structure. Equipment was assumed to depreciate to zero value in five years, and structures, in twenty years. The weighted average rate of depreciation for the total capital investment was 11 percent.

Cost of money and other indirect charges were not included in the operating cost. The operating cost in terms of charges per unit of production has been presented in Figures 17, 18, and 19. As indicated by the dashed lines above the costs considered in this estimate, there are the additional costs of money and other indirect charges which might increase the operating cost approximately by a factor of two. In this example study, however, if all operating charges are assessed against the annual processing throughput of fissionable material of all kinds, then the cost per unit of production would be as shown in Figure 15. These costs range from \$.37 per gram at the currently required rate for a 500 megawatt reactor down to \$.127 per gram at the productive capacity of the plant. In Figures 15, 16, and 17, the amount required for the direct operating charges and the amount required for amortization are shown separately. If, as shown in Figure 16, all of the charges of operating the plant are assessed against the total plutonium produced, then the cost will be \$6.37 per gram of total plutonium at the rate required for the 500 megawatt reactor, and it will be \$2.16 per gram of total plutonium if the plant is operated at capacity. If, as shown in Figure 17, the entire cost of production is charged against total source and fissionable material, then the cost will be \$17.00 per pound of total SF material at the required rate of production, and it will be only \$5.79 per pound of total SF material at the productive capacity of the plant.

The cost estimates are thought to be reasonably accurate within the limitations of the basic assumptions stated, with the exception of the step for conversion of uranium tetrafluoride to metal. This operation is not currently

FIG. 15

PLOT OF UNIT COSTS per Gram of Fissionable Material Processed at Various Plant Throughputs.

All Estimated Costs Allocated to Fissionable Category
U235 + Pu 239

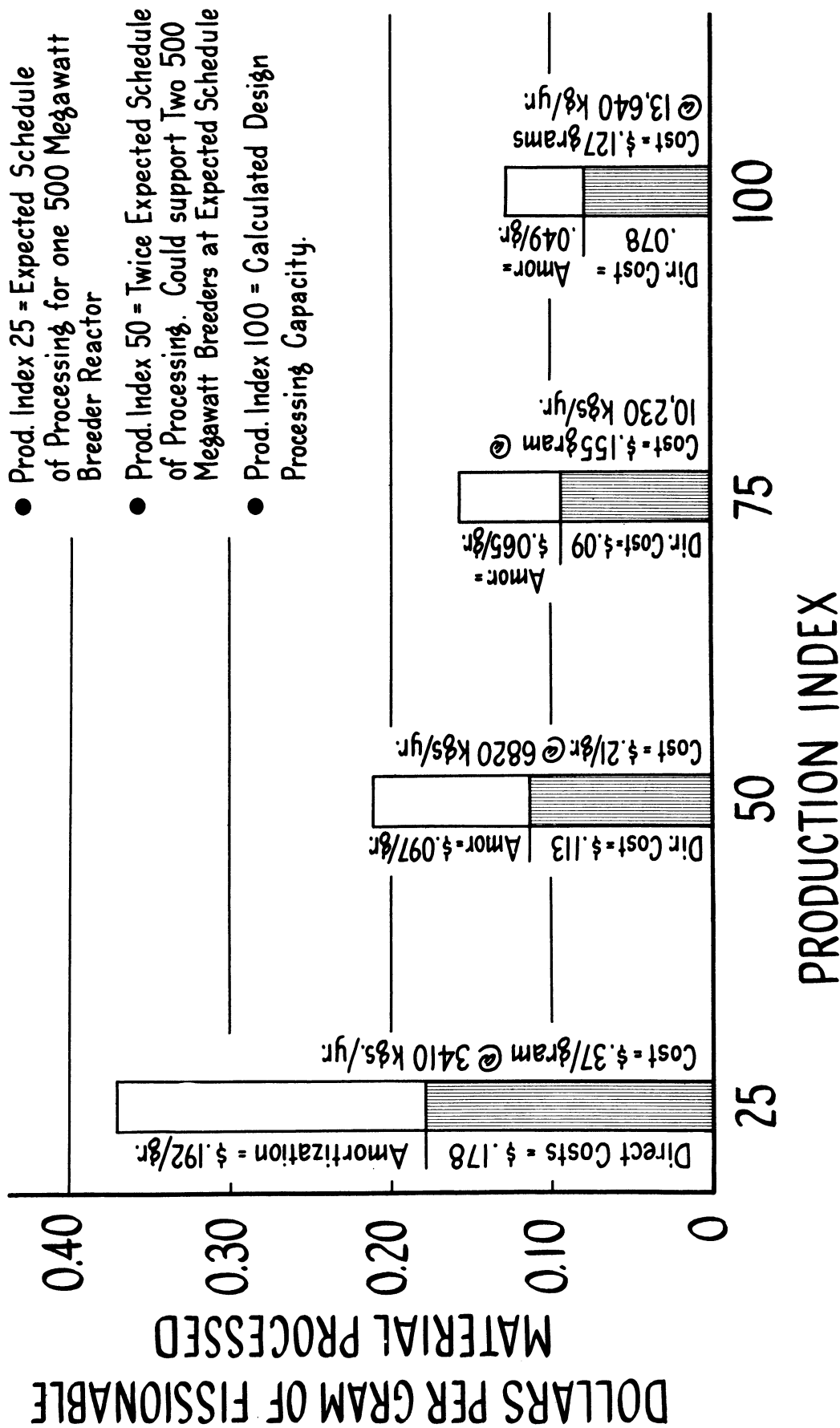


FIG. 16

PLOT OF UNIT COSTS per Gram of Total Calculated Plutonium Produced at Various Plant Throughputs.

All Estimated Costs Allocated to Plutonium Product Category.
No Charges to Recycling U²³⁸ and U²³⁵

- Prod. Index 25 = Expected Schedule of Processing for One 500 Megawatt Breeder Reactor
- Prod. Index 50 = Twice Expected Schedule of Processing. Could Support Two 500 Megawatt Breeders at Expected Schedule
- Prod. Index 100 = Calculated Design Processing Capacity

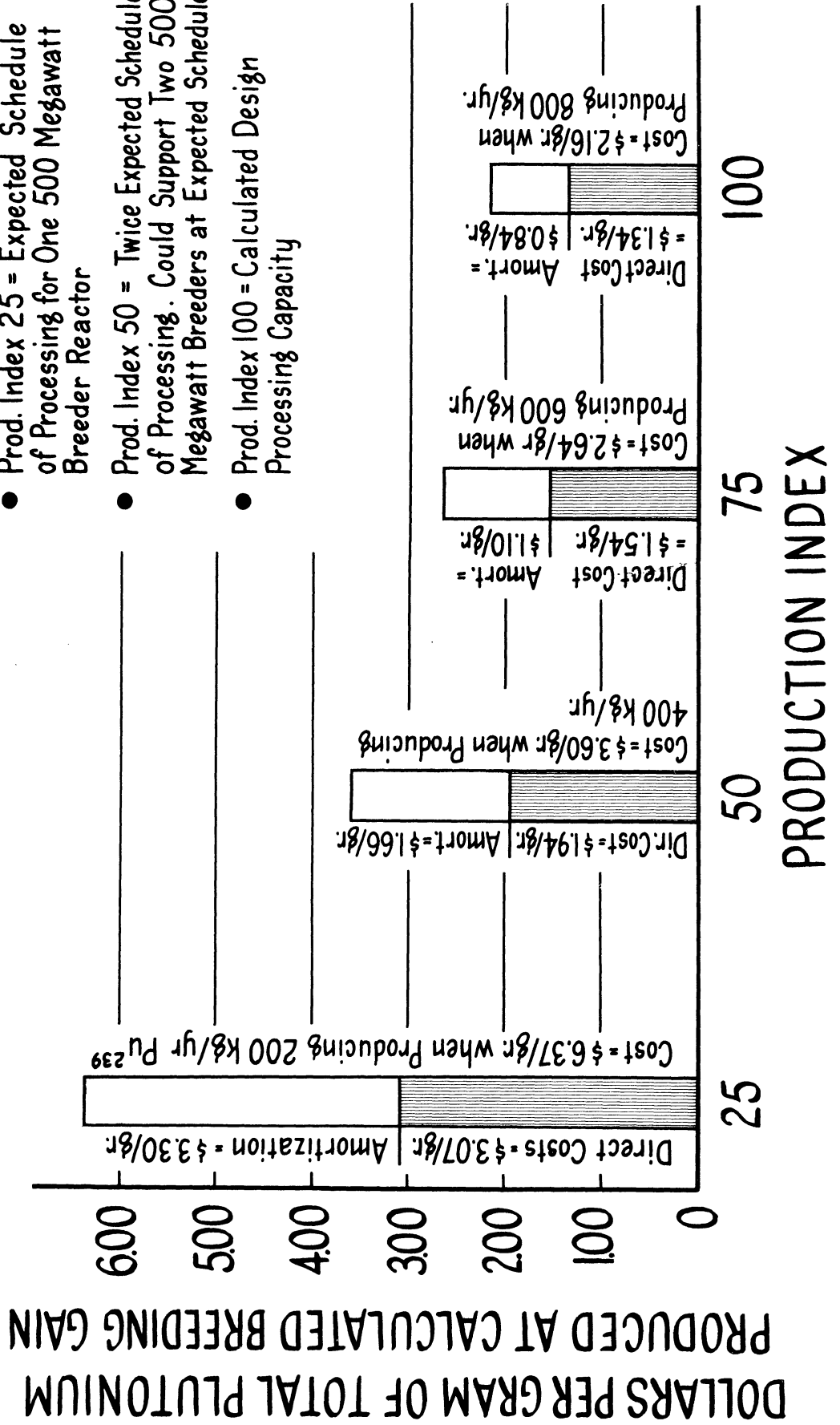
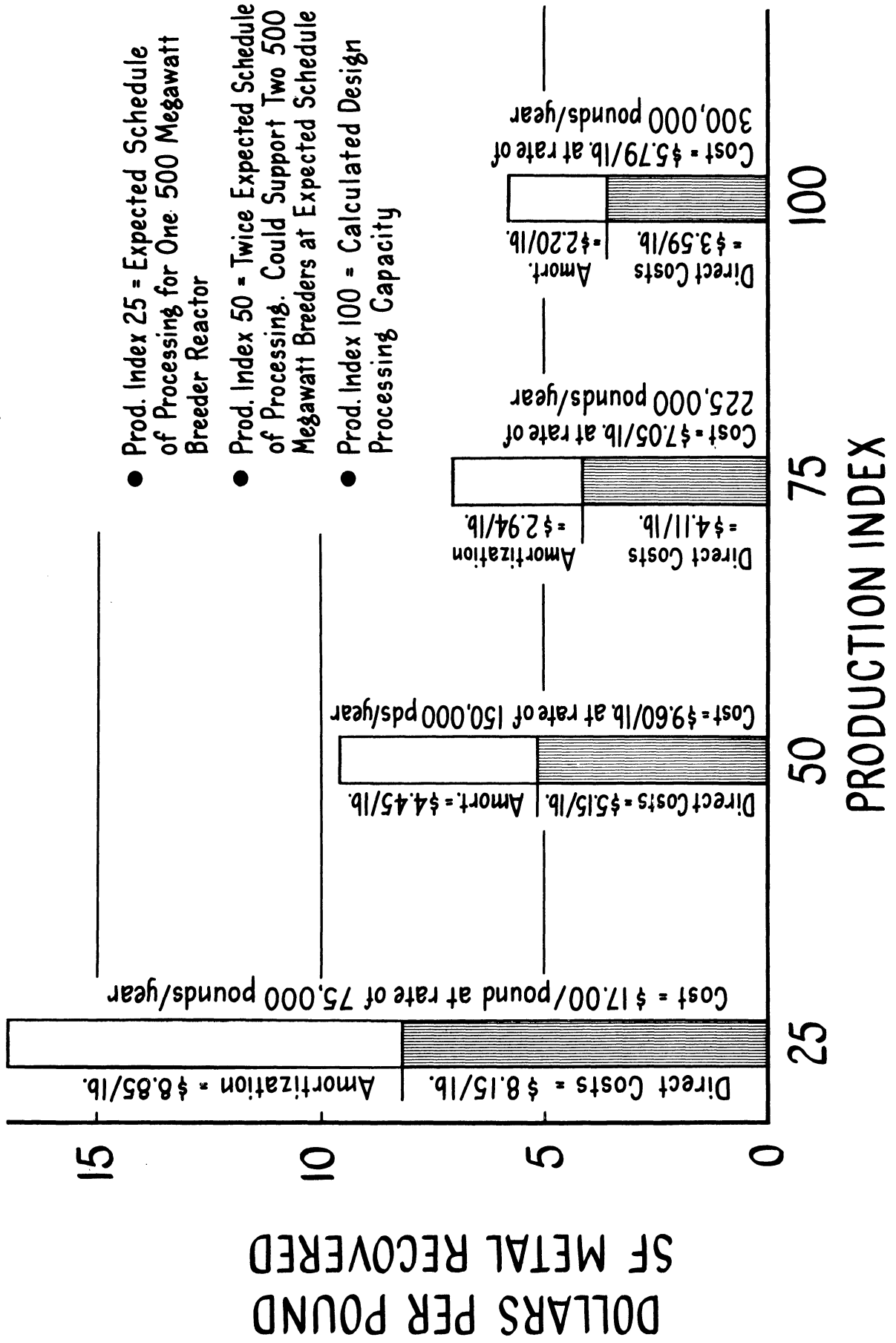


FIG. 17

PLOT OF UNIT COSTS per Pound of SF Metal Processed at Various Plant Throughputs



being done on highly radioactive uranium. Current practice is conducted with direct operation and maintenance. The high activity of the fuels described here necessitates remote operation and maintenance which are presently in the developmental stage both in governmental laboratories and in laboratories of private fuel processers.

VIII. DEVELOPMENT PROGRAM

The authors believe that a vigorous program of development must be conducted if the cost estimates portrayed in this study are to be realized. Development work is needed to resolve those problems peculiar to this study in addition to the general development work being conducted by the United States Atomic Energy Commission. Through development, a firm basis for technical and engineering designs will be achieved.

A proposed development program for the problems expressed in this study may approach a cost of \$1,350,000, in addition to the general work of the governmental laboratories. The operation of a required development facility for the purpose of operator training while such a plant is being constructed may cost an additional \$250,000.

Most of the chemical steps contemplated in this processing plant would need development with regard to the specific fuel composition of the fast breeder reactor or other specific fuel compositions in which a processor might be interested. In addition, remote metal conversion, kinetics, and operability would need investigation.

One particularly promising area of development would be that of concentrating and packaging of the fission products. It seems likely that a considerable demand will exist for the investigation of effects of intense sources of radioactivity upon chemical and biological transformations, such as the production of polymers, the cracking of petroleum, and the sterilization of biological products.

One of the chief limitations now imposed upon research by private and university laboratories into the chemical and biological effects of radiation is the lack of powerful sources of radiation. Such laboratories would probably be interested in obtaining sources of radiation in the megacurie range, such as packaged fission products of high specific activity, for the conduct of research

and development programs on the effects of radiation. These fission products thus have potential value. In addition, the proposed method of storing these materials represents a large potential saving compared with the storage of an indefinite period of these materials in aqueous form as presently practiced.

A third general area of development would be that of mechanical testing, in which the component parts of the various mechanical equipment required in this plant are developed to such a degree of reliability that their performance values may be accurately predicted.

IX. CONCLUSIONS

A. Engineering Conclusions

If a vigorous parallel program of development is carried on concurrently with engineering design and operator training activities, then a chemical processing plant may be designed to process fuel from a heterogeneous fast breeder power reactor from metal-to-metal remotely. Such a plant and a reactor fuels fabrication plant would be located at the same site and would be operated under the same management. It is concluded that this program can be achieved and that operation can be conducted safely in an industrial area.

B. Capital Costs

The capital cost requirement is approximately \$6,000,000 for a completed fuels processing plant less general service facilities, provided that a program of development and operator training totalling \$1,600,000 is conducted concurrently and that advantage is taken of the general progress of development in U. S. Atomic Energy Commission laboratories.

C. Operating Cost Conclusions

The operating costs of the chemical processing plant are exclusive of costs incurred by the reactor or by fuels fabrication and are exclusive of certain categories of charges, such as cost of money. If all costs considered are assessed against fissionable material, then the unit cost decreases from \$.37 per gram at normal operating rate down to \$.127 per gram at capacity. Likewise, if total costs considered are charged to total plutonium processed, then the unit cost will be \$6.37 per gram at operating rate and \$2.16 per gram at design capacity.

As a second alternative, if all costs considered are charged to all source and fissionable material processed, then the costs would decrease from \$17.00 per pound at operating rate to \$5.79 per pound at design capacity. It should be

emphasized that these costs include only chemical processing and metals conversion, and that for each set of costs, the same total operating cost is merely interpreted in the light of several alternative modes of assessment against the production. It should be re-emphasized that these costs do not include the cost of money and certain indirect charges, and might require upward revision if separate capital facilities were provided for an isolated fuels processing plant.

X. ACKNOWLEDGEMENTS

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