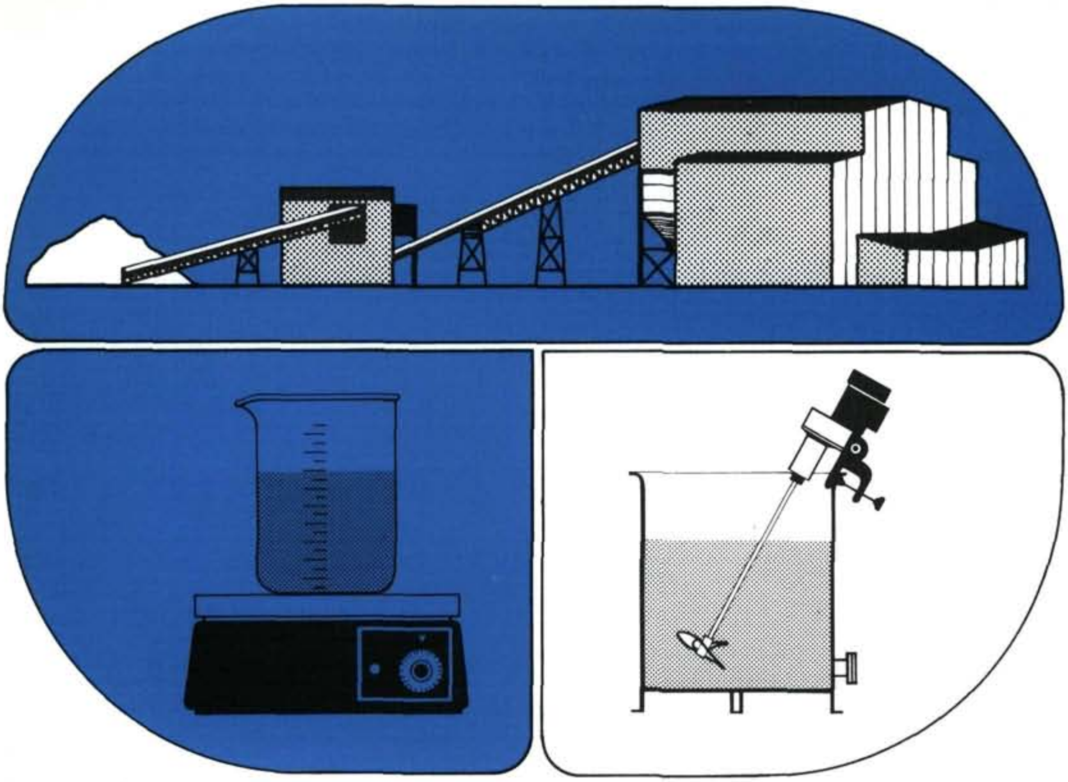

TECHNICAL REPORTS SERIES No. **314**

Guidebook on Design, Construction and Operation of Pilot Plants for Uranium Ore Processing

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1990

GUIDEBOOK ON DESIGN, CONSTRUCTION AND OPERATION OF PILOT PLANTS FOR URANIUM ORE PROCESSING

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

Printed by the IAEA in Austria
June 1990

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OF PILOT PLANTS FOR URANIUM ORE PROCESSING
IAEA, VIENNA, 1990
STI/DOC/10/314
ISBN 92-0-145290-X
ISSN 0074-1914

FOREWORD

The design, construction and operation of a pilot plant are often important stages in the development of a project for the production of uranium concentrates. Since building and operating a pilot plant is very costly and may not always be required, it is important that such a plant be built only after several prerequisites have been met.

The main purpose of this guidebook is to discuss the objectives of a pilot plant and its proper role in the overall project. Given the wide range of conditions under which a pilot plant may be designed and operated, it is not possible to provide specific details. Instead, this book discusses the rationale for a pilot plant and provides guidelines with suggested solutions for a variety of problems that may be encountered.

This guidebook is part of a series of Technical Reports on uranium ore processing being prepared by the IAEA's Division of Nuclear Fuel Cycle and Waste Management. A report on the Significance of Mineralogy in the Development of Flowsheets for Processing Uranium Ores (Technical Reports Series No. 196, 1980), Methods for the Estimation of Uranium Ore Reserves: An Instruction Manual (Technical Reports Series No. 255, 1985) and a Manual on Laboratory Testing for Uranium Ore Processing (Technical Reports Series No. 313, 1990) have already been published.

The IAEA wishes to thank the consultants who took part in the preparation of this report for their valuable contributions: A. Abrão (Instituto de Pesquisas Energéticas e Nucleares/Comissão Nacional de Energia Nuclear, IPEN/CNEN, Brazil), P. Gasós (Centro de Investigaciones Energéticas Medioambientales y Tecnológicas, CIEMAT, Spain) and D.C. Seidel (Bureau of Mines, United States of America). Thanks are also due to the consultants' Member States and organizations for their generous support in providing experts to assist in this work. The IAEA officer with overall responsibility for this work was S. Ajuria of the Division of Nuclear Fuel Cycle and Waste Management.

CONTENTS

1. INTRODUCTION

1.1. THE PILOT PLANT CONCEPT

The necessity of pilot plants for process development has been argued extensively, with the dispute centred primarily on the need for piloting processes that produce organic chemicals. The circumstances differ, however, for hydrometallurgical processes such as the recovery of uranium from its ores, because the raw material, uranium ore, has a decisive influence on the process. Since the uranium minerals and the composition of the gangue are both variable, it is risky to scale up the laboratory results using standard chemical engineering principles and projections.

Unless one has extensive experience with similar ores, it is advisable to verify the laboratory results in a pilot plant: either in a complete flow sheet or, at least, in the most complex parts of the process where recirculating streams could accumulate impurities over long periods of time.

The successful recovery of uranium from an ore body requires a sequence of activities, beginning with the study of the ore body, followed by laboratory scale exploratory studies of the first phases of the process, mainly the leaching operations.

As the knowledge of the ore body improves and representative samples become available, a detailed experimental laboratory project is carried out. The aim of this research is to define the most advantageous flow sheet and to develop the design and operating information. This information will lead to the prefeasibility studies which, if positive, will be used to develop engineering criteria for the industrial plant.

The design of a commercial plant can be unsuitable if the available experience is not extensive enough to scale up the information from bench scale laboratory tests, or if the uranium ore has some peculiarities in its uranium or host rock minerals. Baekeland's [1] famous comment, "Commit your blunders on a small scale and make your profit on a large scale", can be applied to this situation where the pilot plant represents an intermediate stage between the laboratory studies and the industrial plant. The necessity of the pilot plant will depend on the complexity of the ore and the experience available.

The pilot plant must be understood not as a scale-up of laboratory equipment [2], but as a small scale simulation of the future industrial operations. Results of the laboratory studies will be used to choose the most suitable process for the ore deposit and will lead to the selection of the equipment for each stage of the flow sheet (for instance, pneumatic or mechanical stirred tanks for leaching, thickeners or filters for counter-current washing, etc.). If the prefeasibility studies are positive and if pilot plant studies are judged to be necessary, the pilot plant will be designed to simulate the industrial operations. It is not always necessary that the pilot plant include all of the flow sheet stages, but it must include at least those which (a) differ fairly markedly from conventional practice; (b) require equipment not frequently used; (c) have caused some problems at the laboratory scale; and (d) have some elements, even trace elements, that might build up in some streams, for example in solvent extraction.

In pilot plants for new chemical processes it is usually desirable to use the same materials of construction that will be used in the industrial plant. In the case of uranium plants, however, there is extensive experience and information about materials of construction. Therefore it is not generally necessary to use the same materials in the pilot plant as in the full scale plant, unless some special ores must be tested.

1.2. PILOT PLANT OBJECTIVES

The main objective of the pilot plant — to check, on a reduced scale, the process developed in laboratory studies — has already been described. As a result of experience with a pilot plant, the decision to proceed with the full scale plant project will be based on a proven process, and on a more reliable economic estimate. This, however, is not the only purpose of a pilot plant. There are other objectives which can be fulfilled simultaneously and in some cases these other objectives may be the definitive considerations for the decision to build the pilot plant.

For example, in the case of uranium recovery, because the raw material (uranium ore) often varies throughout the life of the ore body, it may be necessary to change the operating conditions in order to achieve the highest efficiency. In this case, a pilot plant can be very useful. Studies of the process can be carried out in the pilot plant while the industrial plant is working. In this way, it is possible to determine the most suitable economic operating conditions, which depend on the characteristics of the ore. In a case such as this where both plants work simultaneously, the objective of the pilot plant is to find the best conditions of operation. On the other hand, when the pilot plant is built as an intermediate stage between the laboratory studies and the industrial plant, its main objective is to confirm the design characteristics of the full scale plant.

In some ores the uranium is associated with other elements which can be profitable by-products. In this case, a pilot plant facilitates the study of alternative flow sheets and the choice of the most suitable one. At the same time it is possible to obtain samples of the by-products which can then be examined for potential commercial value. Furthermore, in a pilot plant enough uranium concentrate can be obtained to determine if commercial specifications are met. The yellow cake product also can be useful for the study of subsequent stages of the fuel cycle.

Another important objective of a pilot plant is personnel training, especially in countries where similar hydrometallurgical processes do not exist. In this case, personnel will be trained not only for operation of the different types of equipment, but also for control of the process. This training will help get the full scale plant in operation, reducing the time needed to reach its design capacity, and avoiding damage to some of the equipment as a result of improper operation. Training is a very important objective, then, since a delayed start would probably imply lower outputs than those which were forecast in the project, and consequently would hinder the economic success of the exploitation.

The objectives of a pilot plant, therefore, can differ depending on the specific circumstances of each project, and the decision for its construction can include one or several of the following objectives:

— To optimize the operating parameters of the process,
— To study the effects of recirculating process streams and of accumulation of impurities over long periods,
— To obtain process information necessary to specify and design the full scale plant,
— To test process control systems and procedures,
— To test materials of construction,
— To optimize the design of the equipment,
— To obtain sufficient information to prepare detailed and reliable estimates of capital and operating costs and to prepare a reliable economic evaluation of the project,
— To gain operating experience and to train the personnel that will operate the full scale plant,
— To identify hazards in the process and ensure safety in design and operation, including the disposal of radioactive wastes,
— To produce a reasonable amount of uranium concentrate for characterization and for use in subsequent stages of the nuclear fuel cycle.

1.3. PREREQUISITES FOR PILOT PLANTS

A pilot plant requires a substantial investment and often long term operation is needed to achieve the desired objectives. Thus a thorough analysis must be carried out before a decision is made to build a pilot plant. Drawbacks such as expenses and length of the project must be weighed against the expected advantages to be gained in fulfilling the objectives of a pilot plant.

A pilot plant is usually not considered until the project is sufficiently advanced and well defined to the extent that there is reasonable assurance that the overall project is feasible. This presupposes that an ore body has been identified and developed, that a mining method has been selected at least tentatively, that a suitable hydrometallurgical process has been defined, that the capital and operating costs have been estimated and that these estimates indicate that the ore can be processed economically. With this information the pilot plant project can be undertaken.

Given the above prerequisites, it is also assumed that a process development laboratory and an analytical laboratory are available. Both will be used during the operation of the pilot plant.

1.3.1. Ore body data

The following information should be available.

1.3.1.1. Type of ore body

The classification of ore bodies by type is not always straightforward. Nevertheless it is useful to know the nature of the ore body in question, at least in regard to the main types generally recognized (e.g. sedimentary and sandstone type, quartz pebble conglomerates, vein type, Proterozoic unconformity and stratabound, and surficial).

1.3.1.2. Size and morphology

The size and morphology of the ore body (in three dimensions) should be known. The information must include plans and sections of the ore body as well as borehole data and data from other development work.

Ore reserve estimates prepared by any of the standard procedures and estimates of the mean ore grade should also be available.

1.3.1.3. Degree of homogeneity

The degree of homogeneity of the ore body or ore bodies should be known. While no ore body is entirely homogeneous, there are many cases in which the degree of homogeneity is sufficient to allow the use of a single metallurgical process. In other cases the inhomogeneity is so great as to require process modifications during the life of the plant.

1.3.1.4. Chemical composition

Chemical composition, mineralogy and petrography of the ore should be studied. Uranium bearing minerals and other associated minerals should be identified. The host rock must be characterized.

1.3.2. Mining methods

From the ore body information outlined in the previous section it will be possible to define the expected production rate and production life of the mine.

A suitable mining method or methods can be selected or proposed on the basis of the geological information and the production rate.

A mining method having been selected, the grade and tonnage of minable ore and the ratio of ore to waste rock can be calculated.

1.3.3. Bench scale metallurgical data

The following information should be available:

— Process description
— Process block diagram
— Operating conditions
— Materials and energy balance
— Per cent recoveries.

1.4. PLANNING OF EXPERIMENTS

One of the main objectives of the pilot plant is to verify and optimize the process flow sheet and the process parameters.

1.4.1. Experimental planning

An experimental programme must be drawn up at the very beginning, even before designing the plant. Planning should begin with a study of the report from the laboratory test work, the process parameters as determined in the laboratory tests and the recommendations made in the report. One should devote greater effort to the critical aspects that have a large effect on capital cost and operating costs. One must determine:

— Which parts of the process need to be verified and optimized,
— What data must be obtained and how they will be processed and ultimately used,
— Which experiments and tests must be done,
— What the scope of each experiment will be,
— How long each test should last,
— In what sequence the tests will be made.

Test work may start with leaching only. The major costs are those associated with crushing, grinding, leaching and solid–liquid separation. How fine should the comminution be? Overgrinding is expensive and in turn makes solid–liquid separation more difficult and expensive. How much acid will be consumed? How should it be dosed? The use of excess acid means that an excess of lime will be needed for neutralization. The appropriate retention time for leaching must be determined. Are there any problems with the solid–liquid separation? The physical characteristics of pulps are likely to be different in the pilot plant and in the laboratory. This may affect solid–liquid separation operations such as filtration.

During laboratory testing one may produce only small amounts of yellow cake, of the order of grams or tens of grams. These amounts may be sufficient for some analytical determinations and thermogravimetric tests which require only a few hundred milligrams of yellow cake, but it may not be possible to do much more with such small quantities. The pilot plant, however, will provide larger amounts of yellow cake. The choice of the type of yellow cake may be confirmed (sodium diuranate, ammonium diuranate, etc.) and filtration tests may be done, probably for the first time. It may now be possible to determine the size of the filters for the industrial plant. It is probably a good idea to stop the tests here. Drying and calcining of yellow cake are very well known operations. It will be difficult to make meaningful tests on the small amounts of concentrate available and too much ore would have to be processed to provide enough yellow cake to make any meaningful tests.

1.4.2. Sampling

Chemical and instrumental analyses are essential for monitoring and controlling the metallurgical process. A sampling programme must be carefully drawn up. It is necessary to determine what samples should be taken, how often they should be taken and which analytical methods should be used. The samples should be properly homogenized by quartering or by other techniques commonly used. Pulp samples should be fresh because aged samples have different characteristics.

1.4.3. Reagent preparation

Sulphuric acid may be used directly or may be diluted to an appropriate concentration. Flocculants must be prepared following the instructions of the manufacturer. The organic solvents for solvent extraction must be prepared as indicated by the laboratory tests. Ammonia may also have to be diluted.

1.5. GENERAL CONSIDERATIONS

Once the decision has been made to construct the pilot plant as an intermediate stage between laboratory results and the industrial plant project, and once the main objectives have been fixed, it is time to analyse a sequence of very important items in order to achieve the highest efficiency in the final project.

1.5.1. Partial or total pilot plant

First, a decision must be made as to whether or not the pilot plant has to comprise the whole process or just some of the different unit operations within the process. Such a decision will depend, in part, on the complexity of the flow sheet resulting from the laboratory studies. In a complex process, with recirculating streams between stages that could result in buildup phenomena, it would be advisable to check the whole flow sheet. Otherwise, if the laboratory studies reveal that the uranium ore does not present any special problem and if it is possible to use a simple flow sheet where there are doubts about only a few operations, it would be sufficient to include only these operations in the pilot plant.

Apart from the laboratory results, if one of the pilot plant objectives is personnel training, or if the pilot plant is built to determine the best operating conditions, working simultaneously with the full scale plant, then the pilot plant would have to include the whole flow sheet.

Therefore, before deciding which activities are to be included and what the appropriate size of the pilot plant should be, all factors, objectives and circumstances relating to this decision have to be carefully analysed.

1.5.2. Pilot plant flexibility

In the design of a pilot plant, attention must be paid to flexibility. Obviously, flexibility is basic to the pilot plant concept, because one of the main objectives of the pilot plant is to check a process that has been established at laboratory scale and involves an ore which is subject to changes in its characteristics.

This flexibility must be considered in the flow sheet, in the equipment and in the operating conditions. The flow sheet will be conceived such that changes can be easily made, especially in the more uncertain parts of the process. Therefore, potential modifications must be considered in the design and, if necessary, it should be possible to implement such changes with a minimum effect on plant operation.

As far as equipment is concerned, the plant must be designed keeping in mind the possibility that changes may occur in existing equipment or that new equipment may have to be introduced. For example, it might happen that it has been decided to use a particular type of equipment in the clarification stage, and that once it is working, the expected results are not achieved. Then an alternative type of equipment will have to be installed. The modification will be less time consuming and the costs lower if this possibility has been foreseen. A similar situation could occur when analysing the plant results. For example, an additional tank might have to be installed to increase the residence time of the leaching section or in a case where it has been decided to incorporate a new stage in the counter-current washing system.

Laboratory test results provide design and operating parameters which will be used to prepare the pilot plant project. While the values of these parameters (size distributions, reaction time, reagent doses, temperatures, etc.) have to be considered as central values, it may be necessary to make adjustments to obtain the most favourable values for the process. Therefore, the pilot plant has to be designed with adequate flexibility, keeping in mind the possibility of modification of any of these parameters. It will also be important to analyse how these changes can affect the next stages of the process. For example, if the leaching residence time has to be changed, then a modification of the feed pulp rate may be necessary. Such a change could affect the following stages in the flow sheet. Another way to adjust the residence time without changing the pulp flow rate could be modification of the volume of the tanks.

Thus, as the project is being developed with the necessary flexibility for a plant of this type, every stage has to be analysed, different ways to accomplish the possible modifications have to be considered and the effects on the rest of the flow sheet must be studied. On the basis of these considerations, the design which is easiest to implement can then be chosen.

1.5.3. Size of the pilot plant

A pilot plant is a reduced scale model of a commercial plant. Given this definition, the next problem is to select the scale-up factor, i.e. the ratio of the size of the pilot plant to the size of the commercial plant.

A larger pilot plant will provide more reliable information and will reduce risks in the overall project. It will, however, be more expensive to build and operate and it will also be more difficult to provide feed material and to dispose of the mill tailings.

On the other hand, controlling the flow rates and handling the pulps can be difficult in a small pilot plant, which may be impossible to operate in a continuous and uniform manner. The information obtained from such a plant may not be reliable enough.

A compromise has to be found. In practice it has been found that capacities below 100 kg of ore per hour should not be considered. This is the lower limit that allows a uniform operation that will produce reliable results.

In a pilot plant of this capacity, not all of the equipment can be just a small scale model of that in the full scale plant, because the smallest sizes of some of the equipment available on the market have still higher capacities than required. This happens, for example, with slurry pumping. Most uranium mills use different types of centrifugal or diaphragm pumps for this operation, with minimum capacities which are much higher than the required ones, especially in the case of centrifugal pumps. There is extensive experience in slurry pumping, however, and for the usual distances and heights in a uranium ore plant, the knowledge of the characteristics of these pulps (size distribution of solids, density, viscosity, etc.) usually will be adequate for the industrial plant project.

A similar situation can occur in the case of grinding, when the use of large diameter autogenous or semiautogenous mills has been envisaged. In these and other similar situations where larger scale pilot plant experimentation has been judged necessary, a loop can be set up for testing a particular circuit or a sample can be sent to an equipment supplier who will carry out the pertinent tests.

The upper capacity limit of a pilot plant will be determined by several factors: economic considerations, the availability of uranium ore supply and the disposal of tailings generated in the process.

In general, it is reasonable to say that an acid leach pilot plant with a capacity of about 100–200 kg of ore per hour will be large enough to obtain all the necessary data with an acceptable level of reliability. For production plants with capacities between 1000 and 5000 tonnes of ore per day, this feed rate range will give scale-up factors that are usually considered acceptable for most of the equipment.

If, however, ore reserves and prefeasibility studies justify a production plant with a feed capacity greater than 5000 tonnes per day or if the ore has specific processing problems, a larger pilot plant would be justified.

1.5.4. Pilot plant location

Initially, two possibilities may be considered for the location of a pilot plant: the vicinity of the ore body or the research centre where laboratory studies have been carried out.

The research centre has the advantage of having the necessary infrastructure for plant operation (maintenance workshops, analytical laboratories, etc., are available). These centres, however, are usually located rather far from the ore bodies, a factor of particular significance when the pilot plant throughput is large. Since it would be necessary to transport large amounts of ore and dispose of the generated tailings, such a location would increase the complexity and expense of the operation.

In the case of uranium ores, there is another problem with building a pilot plant at the research centres, which are usually located in urban areas. The radioactivity associated with uranium ores would involve the establishment of a security guarantee in order to avoid the appearance of an undesirable risk in such areas. This complication would reduce the likelihood of such a location being chosen for the pilot plant.

Therefore the most suitable place for a pilot plant appears to be near the ore body. On the one hand, the cost of transport of both ore and tailings is reduced, and on the other hand, suitable zones for tailings are available and radiation protection can be dealt with under existing ore body protection requirements. Nevertheless, it will still be necessary to provide the infrastructure and services needed for plant operation, if they are not already available. With regard to analytical services, a laboratory can be prepared close to the plant for the more urgent analyses, while the more complex can be done at a central laboratory.

If, however, the pilot plant is small or if only some unit operations will be included in the pilot plant, it may still be advisable to install the plant near an existing research centre where support facilities are available.

1.5.5. Other considerations

The radioactivity of uranium ores introduces a special problem since, in general, every country has its own legislative regulations. The pilot plant has to be planned according to the legislation in force, necessary authorizations, etc., and these factors can influence both the investment in and the length of the project, especially in countries where the legislation on radioactive installations is very strict.

In cases where a country does not have regulations on this type of installation, it is advisable to follow the IAEA recommendations.

As has been explained, the realization of a pilot plant project is a complex task from both the economic–technological and the legal point of view. Since it is not likely that personnel in the working group that developed the process will be qualified in all of the areas involved in the overall project development, it is advisable to enlist the help of experts who can contribute their specialized knowledge. Such collaboration will provide maximum efficiency in both project development and in the later operation of the plant.

1.6. LIMITATIONS OF PILOT PLANTS

When the construction of a pilot plant is considered, it should be kept in mind that subsequent use of the information from the pilot plant in the actual industrial plant project will be somewhat limited, depending on the type of feed, processes, equipment, etc. Therefore, several aspects of the pilot plant will have to be analysed in order to know the actual value of the information obtained.

Pilot plant results apply only to the particular feed material tested. In the case of hydrometallurgical plants, this aspect is very important because, in contrast to what happens in many chemical processes, the mill feed (i.e. the run of mine ore) will probably change during the life of the ore body. For this reason, it is convenient to have in-depth information on the ore body in order to study all of the different types of feeding ores in the pilot plant. The more complete this information is, the more reliable the results will be.

Moreover, some aspects of the process, such as the buildup of impurities in solvent extraction or ion exchange, or resins degradation, etc., will require long periods of operation of the pilot plant in order to be detected. Furthermore, phase separation in a solvent extraction process can be significantly affected by room temperature. Short periods of operation can result in overly optimistic information, far removed from the industrial plant reality. If the full scale plant project is then designed according to the results obtained during a short lived pilot plant operation, serious problems can arise.

Likewise, it is necessary to warrant that the pilot plant has reached steady state. This may require long periods of operation.

Some operations may be difficult to study at the pilot scale, especially if the size of the plant is relatively small, because it is difficult to find reduced models whose operations can be scaled up. This can be the case for some types of mills, thickeners, clarifiers, etc.

In some circumstances, it is not possible to operate the whole plant continuously. As uranium ores are generally of relatively low grade, it is necessary to work with large amounts of ore in order to obtain a small amount of concentrate. Therefore, studying the last phases of the process may require the storing of the product from an earlier stage, in order to ensure a large enough flow for the later stages. The ageing of the stored products, however, may affect the results.

2. PROCESS SELECTION AND DESIGN

2.1. SIZE SELECTION

An analysis of the different factors that must be considered in determining the size of a uranium ore processing pilot plant has been presented in Section 1.

A minimum throughput of 100 kg of ore per hour is suggested because available pumping equipment for pulps cannot reliably handle smaller flow rates.

On the other hand, if autogenous or semiautogenous grinding is chosen, the minimum size of a pilot plant may be determined by the comminution operations. In this case, the minimum throughput of the grinding section will be of the order of 500 kg/h, because mills with a minimum diameter of 1.5 m are needed to provide reliable information.

Another question to be considered is the amount of ore that will be needed to carry out the tests. The total amount required depends on plant throughput, the length of the test programme, the type of process used (e.g. thickeners or filters in solid–liquid separation), the retention time and other factors. The length of a pilot plant study must be carefully considered as a function of its special requirements. A minimum operation time of not less than two to three months, however, can be expected. As a consequence, sample availability is an important factor to be considered when the pilot plant size is defined.

In some cases, the throughput of the pilot plant may differ from one section to another. Thus, the capacity of the first sections of the flow sheet is determined by the amount of ore to be processed, while the capacity of the last sections (precipitation, drying, etc.) is defined by the amount of uranium in the ore. In the case of low grade uranium ores the flow rates in the last sections are generally very small and these sections are often designed for intermittent operation, storing the stripped product liquor and any intermediate stream that is to be recycled to other parts of the process. In this way, the equipment in different sections can be so designed that the system operates continuously.

2.2. PREPARATION OF BLOCK DIAGRAMS

The process that will be studied at pilot plant scale is based on the results of laboratory tests. The flow sheet should be defined as precisely as possible, and the most favourable alternatives chosen. Any alternatives not applicable to the ore being studied should be rejected.

At this stage of the project the type of leaching reagent (acid or alkaline) has been chosen and the various unit operations of the process have been defined. If enough information is available, the most suitable kind of equipment will have been selected (e.g. thickeners or filters in solid–liquid separation). In some instances, however, the pilot plant may include the different alternatives. If corrosion problems are expected, the pilot plant programme will include testing of suitable construction materials.

In general, all sections of the pilot plant will use continuous flow operation, as happens in a full scale plant. In some instances, however, it may be necessary, or at least convenient, to use batch equipment for operations such as the final product preparation (yellow cake).

By-product recovery should be considered if the uranium ore contains other elements that can be economically recovered. In this case, the appropriate stages will be included in the pilot plant.

At this point in the planning process it is advisable to seek advice from experts who can analyse the available information and focus on those points that must be studied in more detail. This procedure will help ensure that the pilot plant achieves the desired objectives.

The design strategy for the pilot plant should be planned with all of these points in mind. It is usually not necessary, and may not even be desirable, to prepare detailed engineering such as that required for a full scale plant. Excessive documentation is also unnecessary. Strict standards on drawings and other documents will increase both engineering costs and the total time required to complete the project. The pilot plant must be flexible; there will probably be changes not only in the flow sheet but also in the equipment [3].

The first step in pilot plant design is to prepare a block diagram. This consists of rectangular blocks which are connected by arrows according to the flow sequence; each block represents a unit operation in the pilot plant.

These block diagrams are very useful in the early stage of a pilot plant project because they give a general view of the overall process that has been envisaged from laboratory information. In addition to the unit operations, the block diagram can include the reagents and utilities that will be used in the pilot plant.

A block diagram of a uranium ore processing pilot plant is shown in Fig. 1. This diagram includes:

— Ore comminution in two stages, crushing and grinding.
— Ore leaching with sulphuric acid, an oxidant and steam to heat the pulp up to the temperature which has been defined by laboratory tests. This heating method can be advantageously replaced by electric heating at pilot plant scale.
— Solid–liquid separation by counter-current decantation in thickeners using water as washing liquid and flocculant for improving settling and thickening characteristics of the pulps. Pregnant solution is clarified before sending it to the next stage.
— Solvent extraction to purify and concentrate the uranium solution. The raffinate is sent to effluent treatment. The organic phase is stripped with ammonia and a solution of ammonium sulphate coming from the concentrate thickening stage, which is made up with water to the appropriate concentration. The organic phase is recycled from stripping to extraction, new organic phase being added to compensate for losses in the process.
— Yellow cake precipitation from the stripped product liquor with ammonia.
— Thickening, washing and filtration of yellow cake pulp. A part of the overflow from the first thickener is recycled to the stripping stage.
— Drying of the yellow cake to obtain the uranium concentrate.
— Effluents neutralization with lime, and addition of barium chloride to the effluents to decrease the concentration of radium, which is eliminated with the barium sulphate.
— Tailings disposal.

The block diagram gives a general view of the whole plant and the main streams, but it does not take into account the equipment and internal flows of the different sections. These are developed in the following phases of the project.

2.3. PRELIMINARY MASS AND ENERGY BALANCES

The next step in the project is to calculate the different streams that enter or leave the sections of the block diagram, and also reagent consumption in the process.

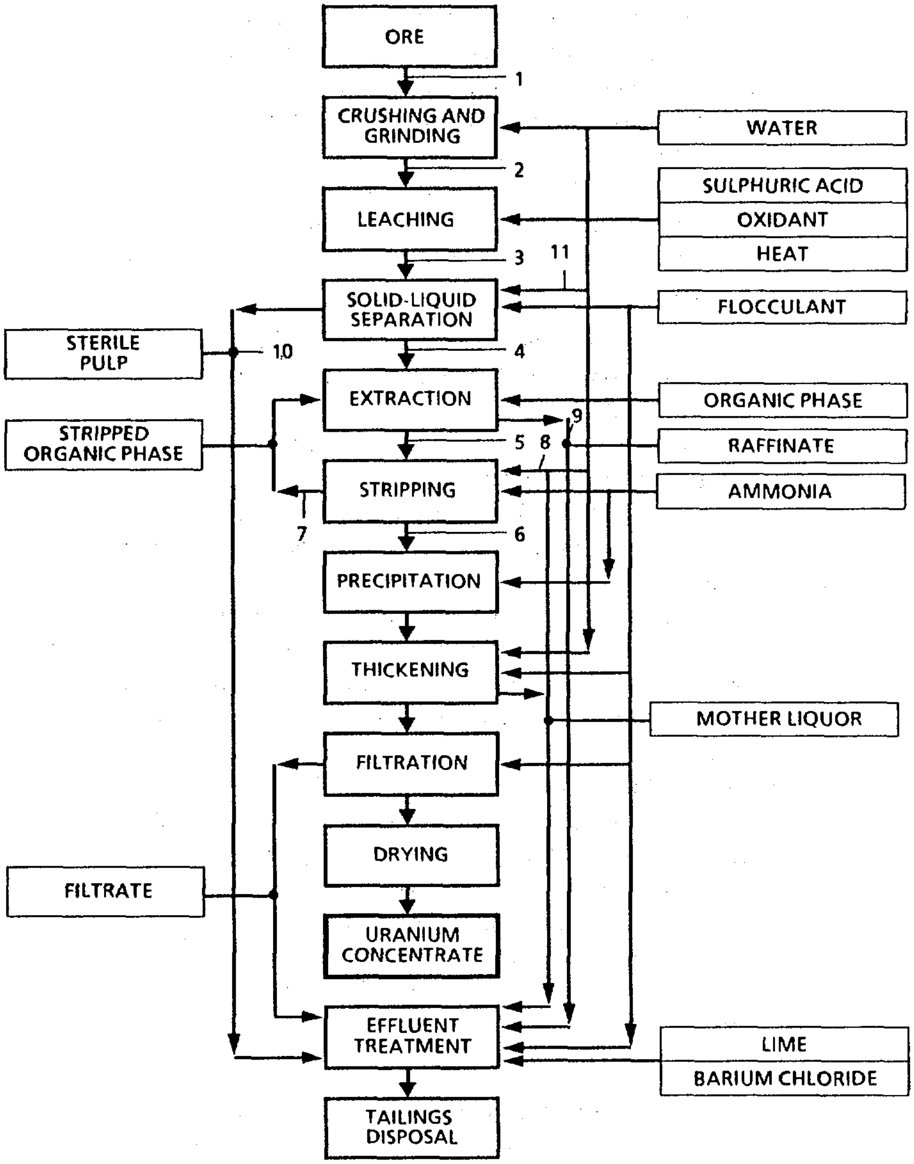


FIG. 1. Block diagram of a conventional uranium ore processing plant.

To carry out these calculations some basic data of the process are needed: throughput, reagent dose requirements, solid–liquid ratios in the pulps, retention times, temperatures in the different unit operations, etc. The basic data are presented in the Annex. The figures in the Annex are for the calculation of mass balances relating to the block diagram of Fig. 1. Units are chosen in such a way that figures from the calculations are easy to handle.

In this way main streams are computed, including all of the parameters (flow rate, specific gravity, solids concentration in the pulps, uranium concentration, etc.) that define the flow. Characteristic data of some streams of the block diagram in Fig. 1 are given in Table I. These figures have been computed from the data in the Annex. With this information it is possible to calculate reagent consumption and utilities that will be needed for pilot plant operation.

Energy balances have to be considered only as a rough estimation, because equipment in a pilot plant is so small and its surface/volume ratio so large that heat losses are very large as compared with heat needed for the process. Energy balance is important only in the early sections of the flow sheet where all ore is processed and, in general, it affects only the leaching stage in most of the processes. Drying of yellow cake represents such small figures at this scale (0.28 kg U_3O_8/h in the example) that it is not worth computing because batch equipment with electric heating will be used and it will not be possible to scale up the results.

When energy balances are calculated, not only must the process parameters be considered, but also other conditions such as the climate and whether the equipment will be indoors or outdoors.

In this kind of pilot plant, if it is not too large, electric heating has some advantages over steam heating, particularly if a steam generator is not available and has to be installed.

2.4. PRELIMINARY SELECTION OF EQUIPMENT

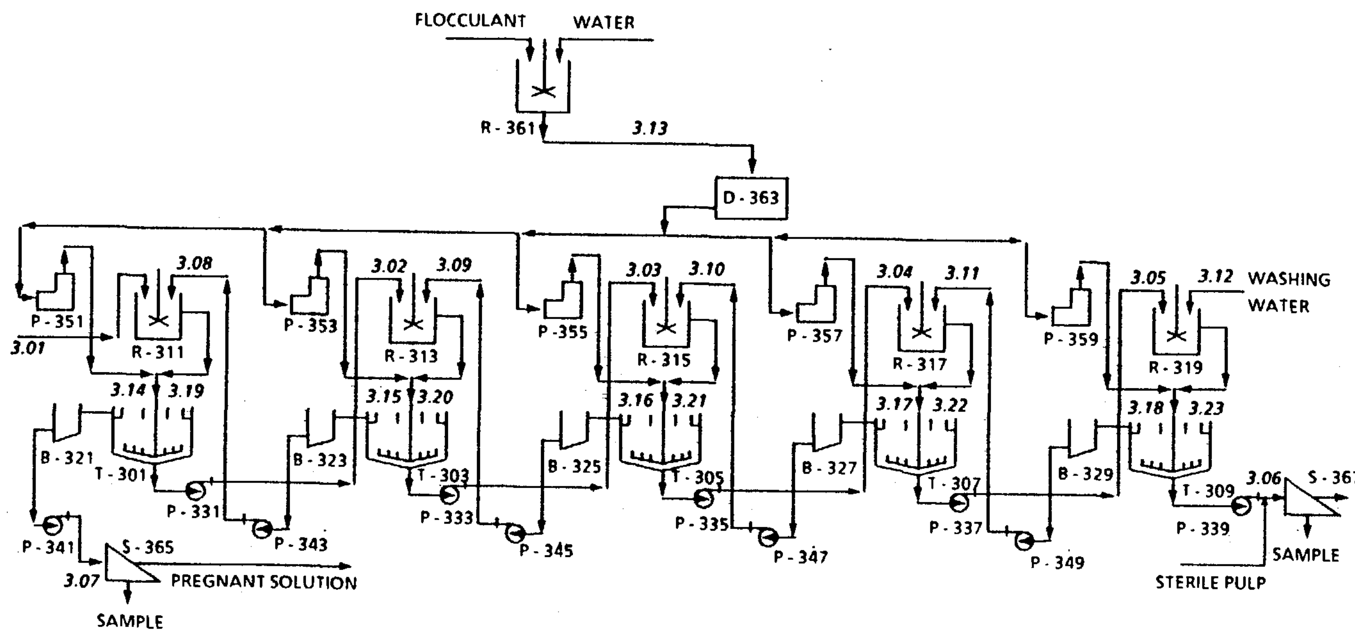
A block diagram provides a general view of the process but it does not give any information about the different sections of the process. Consequently, it is necessary to further develop these sections through process flow diagrams which include all of the equipment in a given section, represented by standard symbols. Streams between equipment are represented by lines with arrows to indicate the direction of flow. Major streams are generally represented by heavy lines.

In general, a process flow diagram is prepared for each block in the block diagram, unless there is a particular relation between two blocks. In such a case, it is advisable to include both sections in a single diagram. Thus the process flow diagrams, which include all of the equipment, provide a view of each one of the sections, with the process streams and operations quite apparent. It should be noted that in this type of process flow diagram, pipes, electrical details and utilities distribution are generally omitted.

A process flow diagram of the solid–liquid separation section in the block diagram of Fig. 1 is shown in Fig. 2. Washing is carried out with five thickeners in series, with repulping of streams entering the thickeners and pumping of overflows

TABLE I. CHARACTERISTICS OF MAIN STREAMS OF THE BLOCK DIAGRAM IN FIG. 1

Stream	Solid			Liquid				Pulp			
	kg/h	g U_3O_8/t	g U_3O_8/h	L/h	g U_3O_8/L	Density (g/L)	g U_3O_8/h	L/h	Density (g/L)	Solids (wt%)	g U_3O_8/h
1	200	1500	300	17.4							
2	200	1500	300	163.6		1000		237.7	1530	55.0	300
3	197	91	18	170.3	1.656	1050	282	243.3	1545	52.4	300
4				578.5	0.486	1015	281.2				
5				98.3	2.975	800	292.4				
6				14.04	20	1150	280.7				
7				98.3	0.120	800	11.8				
8				14.04	0.004	1150	0.06				
9				578.5	0.001	1015	0.58				
10	197	91	18	197	0.004	1000	0.79	270	1459	50	18.79
11				589.4	0	1000	0				



LIST OF EQUIPMENT

T - 301 / T - 309	THICKENERS	R - 361	AGITATED TANK
R - 311 / R - 319	AGITATED TANKS	D - 363	STORAGE TANK
B - 321 / B - 329	BINS FOR CENTRIFUGAL PUMPS	S - 365 / S - 367	SAMPLERS
P - 331 / P - 339	PUMPS FOR THICKENERS UNDERFLOW		
P - 341 / P - 349	PUMPS FOR THICKENERS OVERFLOW		
P - 351 / P - 359	RECIPROCATING PUMPS FOR FLOCCULANT		

FIG. 2. Process flow diagram for solid–liquid separation.

and underflows. In this diagram, flocculant preparation and distribution system and sampling points are included. Clarifying equipment is not included.

It is very important that these diagrams give clear and accurate information at a glance. A simple and precise reference has to be assigned to each piece of equipment. References allotted to the equipment in the process flow diagram of Fig. 2 consist of one capital letter and three numbers. The letter gives the code associated with a type of equipment, the first number refers to the section in the block diagram (for example, the number 3 has been assigned to the solid–liquid separation section) and the last two numbers are a sequential listing for equipment in that particular section.

Basic data and mass balances from block diagram calculations provide enough information to compute the internal streams of each one of the sections. These calculations will be used for the sizing of pipes and equipment. The most important characteristics of different flows in the solid–liquid separation section are given in Table II. It is advisable to include these parameters in the process flow diagram; they are used to size the equipment for the plant.

From the process flow diagrams, equipment lists with their references are prepared, followed by calculation sheets for each piece of equipment (mills, pumps, thickeners, etc.) including information on flow rates and basic data (Annex). After sizing of the equipment, specification sheets listing characteristics, dimensions, construction materials, fittings, standards, etc., are completed.

With this information, tenders for commercial equipment are prepared. If special equipment is needed, the specification sheets will be used for its design and construction. It is advisable, however, to use standard commercial equipment if available.

2.5. PREPARATION OF COMPLETE FLOW SHEETS

The next step in the project is the preparation of piping and instruments (P&I) diagrams. These drawings include equipment, instruments, pipes for streams between equipment, valves, etc.

Each piece of equipment, with the same reference as in the process flow diagram, is represented with all its fittings for connection with process and utilities pipes. Drawings of these fittings show their relative positions in the equipment.

Instruments are represented with symbols and Instrument Society of America (ISA) standards are commonly used. A reference is assigned to every instrument, using the same method as for equipment.

In these P&I diagrams, all pipes — utilities as well as process pipes — are included. A reference including diameter, type of fluid, section and ordinal number, and specification is assigned to every pipe. An example is shown in Fig. 3.

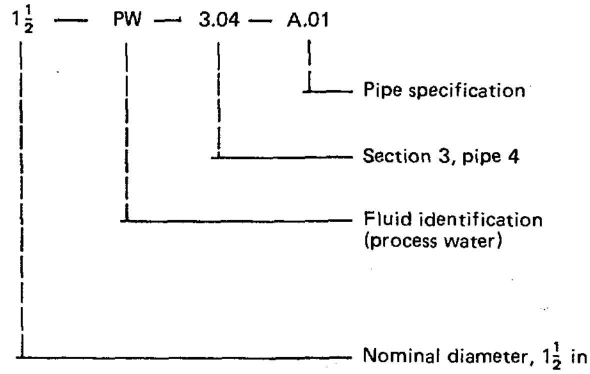


FIG. 3. Typical pipe reference.

A list of fluids, with the symbols assigned to each one, has to be prepared. Piping specifications are also prepared for the pipes to be installed in the pilot plant.

These specifications will include sizes, schedule, fittings, type of valves for different sizes, etc. It is advisable to use a standard for piping design specifications. A list of lines is prepared for each section including all pipes in the section. This list will show at least the following information (Fig. 3): pipe size (1½ in), process fluid (PF), series number (3.04), specification (A.01), connection points (references of equipment connected by this pipe), working temperature and thermal insulation (if any).

Data sheets showing the flow rate, temperature, precision level, control valves, etc., will be prepared for each of the different instruments. Specifications, including general characteristics, standards, etc., are also prepared for every type of instrument. At this point, enough information is available to prepare tenders for instruments, valves, pipes, etc.

After the P&I diagrams are completed, a preliminary plan including all of the equipment in the pilot plant must be made ready. As previously stated, since the pilot plant will be subject to flow sheet and equipment changes during its operation, a more detailed development of the project is not justified at this point. Finally, to achieve a successful project, it is important to utilize the advice of experts whenever that seems appropriate.

TABLE II. CHARACTERISTICS OF STREAMS IN SOLID-LIQUID SEPARATION SECTION

Stream	Solid			Liquid				Pulp			
(Fig. 2)	kg/h	g U_3O_8/t	g U_3O_8/h	L/h	g U_3O_8/L	Density (g/L)	g U_3O_8/h	L/h	Density (g/L)	Solids (wt%)	g U_3O_8/h
3.01	197	91	18	170.3	1.656	1050	282	243.3	1545	52.4	300
3.02	197	91	18	197	0.486	1015	95.7	270.0	1470	50.0	113.7
3.03	197	91	18	197	0.159	1005	31.3	270.0	1463	50.0	49.3
3.04	197	91	18	197	0.051	1002	10.0	270.0	1461	50.0	28.0
3.05	197	91	18	197	0.016	1001	3.2	270.0	1460	50.0	21.2
3.06	197	91	18	197	0.004	1000	0.8	270.0	1460	50.0	18.8
3.07				578.5	0.486	1015	281.2				
3.08				598.9	0.159	1005	95.2				
3.09				594.2	0.051	1002	30.3				
3.10				592.6	0.016	1001	9.5				
3.11				591.0	0.004	1000	2.4				
3.12				589.4	0.0	1000	0.0				
3.13				15.77		1000					
3.14				6.30		1000					

3.15				4.73		1000					
3.16				1.58		1000					
3.17				1.58		1000					
3.18				1.58		1000					
3.19	197	91	18	769.2	0.490	1015	377.2	842.2	1161	20.1	395.2
3.20	197	91	18	791.2	0.159	1005	126.0	864.2	1148	19.9	144.0
3.21	197	91	18	789.6	0.052	1002	40.8	862.6	1147	19.9	58.8
3.22	197	91	18	788.0	0.016	1000	12.4	861.0	1144	20.0	30.4
3.23	197	91	18	786.4	0.004	1000	3.2	859.4	1144	20.0	21.2

3. BASIC ENGINEERING

3.1. INTRODUCTION

Once the preliminary process book (flow sheets, material balances and other information developed from laboratory data) has been prepared, it is possible to start development of the basic engineering project. For this purpose the first documents required are: a technological manual, the conceptual project document, the basic engineering project document and the detailed engineering project document.

3.1.1. Technological manual

The technological manual presents a brief description of the main process parameters together with the relevant information needed for the development of process engineering for the several unit operations of the pilot plant.

3.1.2. Conceptual project document

The conceptual project document describes the studies and definition of the process systems, including the main project criteria. The preliminary documents that must be prepared for this purpose are listed below.

3.1.2.1. General engineering document

— Conceptual description of the chemical process,
— Organization chart and project schedule for the pilot plant,
— Co-ordination procedures including technical standardization and administration of drawings and reports,
— Lists of drawings and reports,
— List of pilot plant operations.

3.1.2.2. Process document

— General description of the chemical process,
— Selected criteria for the process,
— Chemical reactions and products (yellow cake and by-products),
— Process block diagram,
— Process flow sheet,
— Equipment sizing calculations,
— Equipment list.

3.1.2.3. Instrumentation description

— Generic description of the system and its main instruments.

3.1.2.4. Electrical system description

— General description of the electrical system,
— Criteria for the electrical project,
— Power requirements.

3.1.3. Basic engineering project document

The basic engineering project consists of the establishment of the layout of the unit operations of the process and the issuing of documents for the pilot plant. In the basic project the criteria for the project must be described and the following main topics considered: the chemical process, mechanical engineering, instrumentation, piping, electrical engineering, services, and civil and architectural engineering.

The basic project document must include process information such as the following items: an engineering flow sheet, a list of equipment, equipment sizing calculations, data sheets for the equipment (dimensions, wall thickness, corrosion problems, operating temperature, volume and mass of reagents), preliminary drawings for each unit operation, data sheets for the instruments and a preliminary plant layout.

The basic project document must also include mechanical engineering information such as general and technical specifications for the equipment, detailed drawings of the pieces of equipment and their sizing calculations, general arrangements, mechanical assembly drawings and mechanical detail drawings.

For the instrumentation, the following documents must be provided: a list of the instruments, their general and technical specifications and the instrumentation diagram (dimensions, flow rate, volume and operating temperature).

For the piping, the project must define the design criteria, the specifications for the piping material, detailed piping and plumbing layouts, and working and fabrication details.

For the electrical engineering the following should be prepared: general specifications and power requirements, a single line diagram, the equipment sizing calculations for the electrical equipment and its technical specification, the electrical layout and the lighting drawings and the circuit schedules and details. The electrical drawings must include the single line diagrams, schematic diagrams, interconnection diagrams, lighting layouts, electrical equipment layouts, instrumentation loop diagrams and panel layout.

With respect to services, a simplified description of the main utilities, especially the water and electricity requirements, should be provided.

The civil–architectural design must include the following documents: design of earthwork, design of the structures, design of the concrete foundations, design and detailing of all non-process buildings and structures, civil and structural drawings, drainage plans, concrete drawings, structural steel drawings and architectural arrangements.

3.1.4. Detailed engineering project document

The detailed engineering project is the most advanced stage of the plant project and describes the details for all equipment, lines, instrumentation, structures for the unit operations and systems, a revision of the documents issued for the preliminary stage and final versions of all documents for this advanced stage. There must be included here the following documents: isometric drawings of the pipelines, dimensions for the pumps, equipment fabrication specifications, civil engineering design and purchase and inspection procedures. Generally speaking, the manufacturer is responsible for the construction drawings of the equipment.

The general manager for the engineering project must organize the project according to the categories described below.

3.1.4.1. Chemical process description

The chemical process description includes the process diagram; utilities diagram; list of equipment; data sheets for the process; schematic drawings for tanks, reactors, columns, vessels, heat exchangers, pumps, compressors and special equipment; selection of piping materials; instrumentation data sheet; equipment layout; engineering flow sheet; instrumentation layout; detailed layout and designs for materials handling; the operating manual; and the analytical manual.

3.1.4.2. Mechanical project description

The mechanical project description shall include the specifications for the purchase of vessels and tanks; the layout and procurement procedures for the solids handling equipment; and design and procurement details for stairways, platforms, skid-mounted unit operations and the ventilation system.

3.1.4.3. Piping description

The piping description includes the general plan, isometric drawings, a materials list, technical specifications for the materials and specifications for the purchase of materials, and for mounting, installation and the necessary tests.

3.1.4.4. Instrumentation description

For the instrumentation, the engineering project description includes the proposed criteria, the sizing calculations for each instrument, the data sheet and specifications for the purchase of instrumentation panels and materials, the instrumentation plan and details for installation, the diagrams for the instrumentation, a list of alarms and set points, the network diagram, the logic circuit, specifications for the installation, and checking procedures and tests for the instrumentation.

3.1.4.5. Electrical system description

The following must be considered: details for the single line diagram and interconnections; plans and details for the power distribution and grounding; lighting and communication plans; the list of materials and specifications for the mounting, installation and tests; and data sheets for the purchase of the equipment.

3.1.4.6. Civil engineering description

The engineering project description includes the criteria for the civil engineering structures and architecture, the details for the foundations and concrete structures, the project for the drainage and waste disposal system, and the industrial engineering.

3.1.4.7. General

Finally, the overall engineering project description includes other items such as a technical analysis of the suppliers' drawings, an estimate of the capital and operating costs and the schedule for the pilot plant construction.

3.2. SITING

The selection of a site for the installation of a pilot plant for uranium ore processing is affected by various factors, including the water supply, the electrical power supply, the ore supply, roads between the pilot plant site and the supply centres, and a location for the waste disposal system.

Before a first pilot plant can be built in a country that has no such installation, a decision must be made to install the pilot plant (a) where the ore is located, or (b) near a city or village with sufficient infrastructure to support the enterprise, in which case the ore will have to be transported to the pilot plant. Depending on circumstances such as distance and the occurrence of different ore bodies, the latter may be the preferable choice. Such a pilot plant may be capable of treating several different ores and can be supported by material infrastructure and manpower existing at any centre, such as a university, technological institute or private industrial centre. This type of arrangement would be quite desirable for a developing country.

In deciding on a suitable site, factors such as climate, meteorology, hydrology and flooding, geology and mineralogy should be considered. In addition, it is important to keep in mind that the impact of the facility (especially the industrial plant) on the environment and human health must be acceptable to the competent authority. The effect of the facility on land use, flora and fauna must be carefully considered.

For example, the annual precipitation and evaporation at a site virtually determine whether all of the liquid wastes can be retained in the waste retention system or whether they will be discharged to the environment through controlled releases. The magnitude and frequency of floods must also be considered in the siting and design of a pilot plant and its waste management system.

A knowledge of the frequency, strength and duration of atmospheric inversions is needed for the calculation of airborne contaminants arising from mining and milling operations. In order to assess the wind erosion of wastes and dust transport, wind direction and speed should be considered, especially in arid locations. Temperature inversions also have to be considered in assessing the effect of radon emanation from the ore body and from wastes. All of these factors must be taken into account for the design and engineering of both the pilot plant and the waste management facility. The processes used in both mining and milling operations will have a direct influence not only on the performance, size and cost of the pilot plant but also on the waste management requirements.

In planning the pilot project, the mineralogy of soils and the subsurfaces of areas being considered for the mill site and the waste retention system must also be studied. The choice of the uranium extraction process is largely determined by the effects of gangue minerals which, as a consequence, have a major impact on waste management technology.

The hydrology of the site is another important factor since the wastes could contaminate surface water or groundwater.

The nature of aquatic and terrestrial habitats influences the degree of environmental impact that would result from waste treatment practices. For example, discharge acidity affects plant nutrition. Fish are very sensitive to heavy metal ions and the softer the water the more sensitive they are. Discharge of long chain amines reduces phytoplankton productivity, an effect which is more pronounced if kerosene is also present.

The climate and operating conditions should be defined in detail so that the instruments, piping and fittings that are used will be suitable for the environment and not subject to damage such as corrosion due to humidity.

In order to gain public acceptance, concerns over the siting and its environmental effects must be carefully considered. The site should be large enough to support all of the operations necessary for the facilities; however, the size of the installations should be kept conveniently modest. The installations should be as simple as possible and problems related to site availability, adequate water and electricity supply, and transportation must be dealt with responsibly.

Waste management issues are also significant and must be considered before the installations are committed, constructed and placed in operation. Again, the two major constraints for the pilot plant need to be stressed: (1) the supply of water and electricity, and (2) the impact of the radwaste. From the point of view of the environment, virtual elimination of the heavy elements, especially manganese, from the mill circuits and effluents is of great importance. This means that the decision to use pyrolusite (MnO_2) or Caro's acid (H_2SO_5) as the oxidant for uranium must be carefully considered, since the presence of manganese when pyrolusite is used is significant and requires special treatment.

Although it is desirable to place the mill as near as possible to the ore body or the mine, in the case of small pilot plants the ore can be transported to the site where the pilot plant is being erected. If the pilot plant is near a city or village, the potential for making use of the infrastructure of that location should be explored.

When the pilot plant is based on the heap leach process, the necessary site preparation may include conditioning of the ground for heaps, ponds, roads, foundations for buildings, and in some cases footways.

Another important aspect that must be taken into account is the presence of natural radioactive isotopes — U, Th and their daughters — which involves authorization, regulation and local laws. In planning for the plant location and ore body exploitation, permission must be obtained from the local authorities and local legal regulations covering such isotopes must be followed.

The project must also provide some orientation in matters pertaining to licences and environmental concerns.

3.3. PLANT LAYOUTS

The basic philosophy for the design of the pilot plant is to keep it compact and simple. The equipment should be distributed and assembled within a relatively small area, but allowing sufficient space to facilitate equipment operation. The flow sheet process must be optimized at the pilot plant, after which the engineering for the commercial plant, if a decision is made to have one, shall be carried out.

A general layout for the arrangement of the construction and equipment depends on the characteristics of the particular pilot plant and on the available land. A rational and well planned layout contributes to the efficiency of the pilot operation, to the ease of operation and maintenance, and to the safety and economy of the installation.

The first step to take in planning the layout is to list all of the primary pilot plant components: process unit operations; areas for stockpiles of raw materials, reagents, by-products and final products; utilities such as power and water supplies; the waste disposal system; the machine shop, warehouse, laboratories and office building. After the list has been completed, the size of the area needed for each component is estimated, with some space reserved for future expansion of the pilot plant.

The distribution of the land area for a pilot or commercial plant depends mainly on the general operation of the installation. The total length of the piping (an economic factor) and the movement of materials and people are primary considerations. Generally speaking, the areal distribution may be according to the following criteria: administration buildings (offices, restaurant, medical service) should be near the site boundary or the main entrance; unit operations should be in the middle of the site; areas reserved for oil, kerosene and other flammable products should be away from the internal streets and roads; the power supply station and electricity installations should be away from the areas and installations subject to dangerous atmosphere and leakage of flammable products; and the storehouse, machine shop and warehouse should be near the entrance.

The following items must be considered for the layout as well: land topography, location of the sources of water and electricity, and the predominant wind direction.

The unit operation should be viewed as a whole and the equipment located in accordance with the operational flow sheet and the requirements for the interconnection of equipment. All of the equipment that must be located at a higher position must be placed close together so that the same support structure can be used. In general, equipment is placed at the lowest possible height for ease of operation and maintenance as well as economy.

As a rule, the distance between the wall and equipment is kept at a minimum although enough space must be provided for mounting, maintenance, repair and operation of the equipment. For example, pumps must be kept one metre from the wall, whereas the minimum distance for vessels can be one to two metres from the wall. The rotating machines, for example centrifuge pumps, must be installed at floor level and valves, instruments and equipment that require maintenance should be located on a platform or other supporting structure to facilitate access.

Finally, the preparation of the plant layout must take into consideration the distribution of the exhaust and ventilation systems.

3.4. SELECTION OF EQUIPMENT

The selection of equipment is based upon the process flow sheet. The project must organize a list and description of all equipment necessary for the pilot plant, including the following:

— Equipment for crushing,
— Equipment for grinding,
— Equipment for leaching,
— Equipment for solid–liquid separation,
— Equipment for uranium recovery,
— Equipment for precipitation and drying.

Equipment for grinding, for example, can be ordered after a choice has been made between having the ore wet ground or dry ground. The advantages of having the ore wet ground include elimination of dust problems, lower energy consumption and simpler classifiers. Dry ore dusts are normally generated during crushing and dry screening operations and must be removed by dust collection, which requires hoods, ducts, fans, cyclones and wet scrubbers in order to capture particles and return them to the process stream.

3.4.1. Crushing

The first operation is crushing. The amount of ore to be processed at a small pilot plant is correspondingly small. As a result of the experiments previously run at the process development laboratory, a decision may be made to install a simple heap leaching facility followed by solvent extraction or ion exchange recovery of uranium. Such a choice would involve setting up a small crusher. To reduce the cost of the crushing operation, it may be possible to arrange a contract with some company or mineralogical technical facility already existing in the country. Usually it is reasonably easy to find a firm or facility that can accept this type of contract. Since it would be necessary to transport the ore from the ore body to the site where it will be processed, it is advisable to consult with the local authorities. If, on the other hand, a decision is made to buy and install equipment for the pilot plant, the simplest small standard crusher that is commercially available should be chosen.

3.4.2. Grinding

Depending on the type of ore and the process selected, the mineral should be ground from 32 mesh (0.5 mm) to about 325 mesh (0.044 mm). The dimensions of the ground ore must be defined by the bench scale tests at the process development laboratory before the pilot plant is developed and the mill should be equipped to grind the ore to the required dimensions. It is strongly recommended that grinding be a wet operation using either a conventional grinding circuit or a semi-autogenous mill.

The characteristics of the ore determine how fine the grinding is to be and whether an acid or alkaline treatment should be used.

3.4.3. Leaching

The leaching process requires more attention and technical innovations and must be studied very carefully. It should be mentioned that quite frequently the pulp (slurry) exhibits unexpected characteristics. Today a commercial autoclave usually presents no special problems, but may require special attention to certain details. This type of equipment, used for alkaline leaching, involves the technique of pressure leaching usually applied to carbonate leaching. The technique requires high temperature and pressure, and an autoclave constructed in low alloy steel. The leaching of the uranium ore is improved by the addition of oxidants, air, oxygen and hydrogen peroxide being the common reagents.

Pressure leaching, a technique used today for both alkaline (carbonate) and acidic (sulphuric) solutions, is applied in the case of ores which are difficult to leach [4–6]. The equipment consists of an autoclave operating at 50–150°C and a pressure of 10–12 atm (1–1.2 $\times$ 10^6 Pa), usually under oxygen pressure. It is clear that the decision to use an autoclave depends on knowledge of the ore characteristics [6, 7]. Although this type of equipment results in over 90% extraction of uranium, there are problems with the lining of the autoclave (lead, acid proof brick, titanium) and with the impellers. Some laboratory autoclaves of about 100 g ore capacity are commercially available for treatment of highly refractory ore and ore with high sulphide content. The scale-up of this technique to pilot or industrial plants is a particularly difficult task.

The engineering project must recommend the type of autoclave to be selected. Data sheets for different types of equipment must be compared in order to gain information on the capability and performance of vertical or horizontal autoclaves and to determine which type has the simplest layout and whether it is readily available and offers flexibility. Before deciding on the purchase of an autoclave, the following factors should be considered: the actual volume of the equipment, the construction material, whether it is a batchwise or continuous operation, the oxidant and the type of impeller to be used.

Conventional acid leaching uses Pachuca type reactors or stirred reactors; acid pressure leaching can be carried out in vertical or horizontal autoclaves.

In any case, the selection of the equipment for leaching the uranium ore has to take into account chemical attack parameters such as granulometry (grinding), pulp density, temperature and pressure, time of digestion, concentration of reagents and oxidants, and whether acid or alkaline leaching is used [6].

3.4.4. Solid–liquid separation

In the process laboratory, solid–liquid separation of leached ore is normally investigated using standard thickening and filtration tests. For a continuous process, it is necessary to establish all of the conditions needed to meet capacity requirements. The tests for the selection of the pilot plant filters and other types of solid–liquid separation equipment must be performed at the process development laboratory.

Counter-current decantation (CCD) using a series of a minimum of two and a maximum of eight stages (conventional construction today) and provided with the facility to neutralize the underflow to be sent to the tailings pond is a highly recommended technique. The overflow from the CCD thickeners containing the uranyl sulphate is directed through the filters to the clarification section and sent finally to the solvent extraction section. The acidity of the pregnant solution must be controlled to a value of about pH1.0.

The use of repulper and thickeners must be recommended by the process development laboratory experiments. Depending on the type of ore, the residue after leaching can be repulped and washed by decantation in a series of two or more thickeners.

For a small pilot plant probably one thickener can suffice for data collection, but for a final commercial installation a series of decanters–thickeners is mandatory for economic reasons.

The pilot plant flow sheet designed after the process laboratory experiments may include rotary drum filtration followed by clarification of the pregnant filtrate and solvent extraction (considered as standard technology). In the case of CCD some economy of size is possible because of the linear relationship between cost and thickener diameter, whereas capacity is proportional to surface area.

The main operational parameters must be defined by experiments performed at the process development laboratory and shall include the type of filter, its area for filtration, the filter area for washing the cake, the amount of pulp filtered and the volume of water for washing as well as its flow rate (volume/time). The filtration is also dependent on the size of the ground ore.

Today the moving belt type of filter is commercially available in pilot plant sizes [8]. The pulp is transferred by means of a peristaltic pump. The filtration area, the throughput and the area of its washing section are defined by experiments performed at the process development laboratory.

It is clear that there are certain fundamental technical advantages and disadvantages inherent in the various possible process routes that must be considered in the selection of the technique for the pilot plant which is to be extended to the future commercial plant. For example, a common option can be CCD–clarification–solvent extraction. This option is well known today and presents certain advantages including a minimum number of moving parts, a small number of large units and the possibility of recycling the raffinate. On the other hand, the above mentioned combination of techniques produces a large volume of low grade solution which must be treated to reclaim the uranium.

3.4.5. Equipment for uranium recovery

For economic reasons, the direct precipitation of uranium to obtain the yellow cake is rarely used today since the concentration in the leached solution is usually very low and would require preconcentration. The current methods of choice for uranium recovery are the ion exchange (IX) and solvent extraction (SX) techniques [9]. One of these methods must be selected.

Currently the great majority of commercial plants recover the uranium by SX, others apply solid IX and some use a combination of the two processes (IX–SX) (e.g. the ELUEX process).

For SX, the sulphuric acid is the chemical system which requires the extraction of uranium with a long chain amine diluent. For the common mixer–settler process, the enormous volumes and low uranium concentration must be considered before the equipment is chosen. The type and selection of the equipment depend on several factors such as technical feasibility, local suppliers or manufacturers, and economic and even environmental considerations which will be important for the commercial plant as well.

The designed mixer–settler unit must be tested at the process development laboratory before the construction of the equipment for the pilot plant is ordered. The mixer–settler equipment is used primarily for the extraction of uranium from completely clear solutions or partial solutions.

The type of equipment used for a fixed bed IX process is usually a conventional column to accommodate the IX and requires a filtered, well cleaned pregnant solution. The fixed bed columnar operation can be applied to the fixation of uranium from acid or alkaline solution. While uranium can be reclaimed advantageously from acid solutions (sulphuric or phosphoric medium), by either SX or IX, the only suitable technique for obtaining the uranium from carbonate leach solutions is anionic IX.

The primary requirement for loading uranium onto an ion exchanger inside a fixed bed column is that the pregnant solution be well clarified. Alternatively, equipment specially designed for operation as a fluid bed ion exchanger [10] or the well known technique of resin in pulp (RIP) may be used. The fluid bed IX technique allows the use of liquors of low suspended solids (a preclarified solution with a maximum of 1% solids) while the RIP process can tolerate a high solids content (slurries). Several models of the equipment mentioned for this technique are commercially available [11]. The fluid bed IX or continuous IX technology is gaining more recognition today and can be considered as a strong contender technology for uranium recovery [11, 12].

One claimed advantage for the RIP process is that it avoids solid–liquid separation and for this reason reduces the plant capital costs. The selection of an RIP contactor must be done after the preliminary experiments at the process development laboratory; for example, the chemical composition of the pregnant uranium solution must be known before experiments are performed using IX.

Before deciding to apply the RIP process, the following information on the physical and chemical properties of the resin load should be obtained from experiments performed at the laboratory: (a) the density and type of the resin, and (b) the mesh size required for design parameters such as the screen selection, number and size of stages, residence time, resin inventory and kinetics, and loading parameters.

It is important to know about the leaching rates of the ore and the treatment of the pulp in order to determine the settling rate and filtration characteristics, factors which must be considered in making the decision to filter the pulp or to go through the RIP process. The RIP technique must be considered by the project since it is economically attractive. One possible disadvantage of this technique, however, is the degradation of the resin due to the abrasiveness of the pulp. If the process development laboratory determines that the type of pulp is extremely abrasive, then the RIP process should not be considered. It should be emphasized that each ore is different and for each one the corresponding data available from the process development laboratory must be studied.

The recovery of uranium from pregnant solutions usually takes into account the large stream volumes involved, and for this reason mixer–settler extraction equipment is generally used. Until recently, pulsed columns had not been commonly used. The Société industrielle des minerais d'ouest (SIMO), in France, recently commissioned the first industrial pulsed column [13].

3.4.6. Equipment for precipitation and drying

Equipment for the precipitation of yellow cake consists of one or two precipitation reactors, pumps and flow meters, and a thickener with a pump and a storage tank for the thickened uranium yellow cake product are also recommended.

Precipitation can be accomplished simply by the addition of base. Gaseous ammonia (NH_3), ammonium hydroxide or sodium hydroxide may be chosen for this purpose. In a few cases magnesium oxide has been the chosen base. Alternatively, hydrogen peroxide may be used for the precipitation. In each case the reactor may simply be a conventional agitated tank. In the case of a small pilot plant a batch operation is recommended.

After the uranium is precipitated from the pregnant strip solution, the yellow cake is dewatered by filtration or centrifugation in order to obtain a product with about 50% moisture. At this point, in the case of a small pilot plant, the yellow cake can be dried using a simple drying oven.

The dry diuranate (yellow cake) should be removed from the oven and handled under adequate exhaust ventilation. Air containing yellow cake particles may be scrubbed with dilute acid or water and filtered. Product drying and packing operations require similar dust removal and recovery equipment.

3.5. MATCHING EQUIPMENT SIZES

Pilot plant equipment must be selected carefully for each operation. Some small pilot plants have been non-integrated operations, because the equipment sizes required for full integration were not available. In such cases, either surge capacity must be provided for intermittent operation or only a fraction of the output stream is processed in the following section; the remaining portion is discarded. Other possibilities can be considered, according to the specific requirements of each pilot plant. The uranium ores most frequently treated have grades between 0.1 and 0.5% U_3O_8, although ores graded ten or more times higher are currently being processed. Therefore a large amount of ore must normally be treated to obtain small quantities of yellow cake. Flows in the sections that handle the ore (for example grinding, leaching, solid–liquid separation) are much greater than those of the last sections of the flow sheet (yellow cake precipitation, drying, etc.).

If a pilot plant with a throughput of 200 kg/h of uranium ore with a grade of 0.2% U_3O_8 is considered, the flow rate of pregnant solution coming from a CCD section would be approximately 500 L/h, but the flow rate of the solvent extraction product solution to the precipitation operation would be only 10–15 L/h. The very small equipment sizes required for the 10–15 L/h flow may not produce reliable scale-up information. If special design information is needed for this part of the process, the solvent extraction product solution can be accumulated in a storage tank, and the yellow cake precipitated periodically using larger equipment. The effect of storage should be considered, however, as it can affect this unit operation. If the barren liquor from the uranium precipitation operation is to be recycled to the solvent stripping section, an appropriate storage tank must be included in the flow sheet.

Storage of pulps should be avoided if at all possible because extended agitation can affect the particle size distribution, and the information from the subsequent sections may not be reliable.

In contrast, the storage of solids does not pose any problems and it is generally used between the crushing and grinding sections.

3.6. INSTRUMENTATION AND CONTROL

Generally speaking, the instrumentation and control circuits in a pilot plant raise the capital costs significantly. Since these circuits are the same and have the same size as those used in an industrial plant, it is recommended that sophisticated instrumentation be avoided in the simple pilot plant.

Initially the pilot plant requires only simple instruments such as a pH meter to control the leaching and precipitation stages, equipment to measure the oxidation potential during leaching, manometers to control autoclave pressure, flow meters for monitoring fluid flow and thermometers for temperature measurement. If uranium is to be oxidized to the hexavalent state using Caro's acid (H_2SO_5), the demand for oxidant must be controlled so as to maintain the oxidation potential that was established by laboratory testing [14]. This can be done using a simple valve with manual control and a rotameter. A simple conductometric bridge may be used to control the purity of the demineralized water.

3.7. PIPING AND INSTRUMENTATION DIAGRAMS

The project establishes design criteria for the instrumentation engineering requirements and standards for the complete design, calculations and detail drawings. The criteria should include codes, standards and regulations established by the local atomic energy authority.

Any device used directly or indirectly to measure and/or control a process variable is considered an instrument. Such devices include those used for flow, temperature, pressure, tank level, analytical and weight measurements; transmitters; indicators; recorders; controllers; gauges; control valves; safety valves; alarms; and shutdown systems.

Each device recognized in ordinary engineering practice as an instrument should be assigned a tag number, described on an instrument specification sheet and listed in the instrument index.

Piping must be designed, fabricated and tested in accordance with the appropriately recommended code, for instance that of the American National Standards Institute (ANSI). In addition to the containment of internal pressure, piping design shall consider the following: thermal expansion movement and forces, support of piping elements and associated equipment, the effect of corrosion, and the safety of operating and maintenance personnel, with special attention to the selection and arrangement of piping used to handle sulphuric acid and ammonia.

The minimum vertical clearance for the piping should be maintained at:

- 3.7 m over access ways within project limits,
- 2.3 m within buildings and over stairways.

The minimum horizontal clearance should be maintained at:

- 75 cm where access way is required,
- 50 cm where no access way is required,
- 75 cm on platforms.

Buried lines should have a minimum size of 2 in (5 cm). Solution lines should be sized for economy, especially in the case of lines containing alloy materials. Slurry lines should be sized according to velocity, with 1.5–2 m/s maintained regardless of the materials used.

Compressed air lines should be sized so that the drop in pressure along the line will not exceed 10% of the original line pressure, with full capacity being delivered at the end of the line.

Steam lines should be installed to provide for the following conditions: conservation of heat for piping over 120°C and adequate personnel protection in cases where personnel may come in contact with the piping at temperatures over 60°C.

All process, service and utility piping should be hydraulically or pneumatically tested in accordance with the governing codes or standards.

All piping materials should conform to the selected codes and standards where applicable — ANSI, DIN (Deutsches Institut für Normung) or ASTM (American Society for Testing and Materials) — or even local regulations may be consulted.

Based on the process flow sheet, the piping and instrumentation diagrams are designed in a document that gives in detail all of the unit operations for the chemical process and designates the required equipment, piping and accessories, process instrumentation and controls. In brief, the following items must be indicated: process equipment, electric motors, equipment accessories such as reducing regulators, auxiliary cold systems, lubricating and heating elements, safety valves, gauges, steam separator, expansion joint, thermowell and insulators. The piping for processes and utilities with indication number, diameter, material codes, flow codes and insulation should also be included. A list of piping accessories is prepared including insulation, vapour and electrical traces, orifice plate, relief valves, purgers, filters, retention valves, check valves and plugs. In addition, a list of all required instruments is prepared with their respective numbers, signal lines, connections, identification of signal type and loops. Instrument Society of America (ISA) standards are recommended.

A process is any operation or sequence of operations where a variation of at least one physical or chemical characteristic for any material is observed. Modifications of such characteristics are followed by the indirect control of the main process variables such as pressure, temperature, flow, level, density, humidity and weight. In some instances the measurements are made directly, using automatic controls. These can be grouped as follows:

(a) Primary elements (sensors): flow, level, pressure, temperature, weight, viscosity, velocity, density, electrical conductivity, pH.
(b) Secondary elements (intermediary): transmitters, controllers, converters, switches, transducers.
(c) Final elements (regulators): alarms, control valves, recorders, indicators, regulators. Examples are automatic regulators, hand control valves, level regulators, pressure reducing regulators and back-pressure regulator.

The project must indicate the piping and instrumentation lines to be distributed according to the following categories:

(1) Piping for the process — serving the main activities which constitute the process itself, the stockpile of materials and the distribution of fluids.
(2) Piping for utilities — including the piping of auxiliary fluids for the cooling and heating systems and piping used for maintenance and cleaning systems, fire hydrants, service water, condensed steam and compressed air.
(3) Piping for hydraulics transmission — piping for liquids under pressure that serve the command and hydraulics servomechanism.
(4) Piping for instrumentation — for transmission of signals by compressed air to the control valves and automatic instruments.
(5) Piping for drainage — especially with the function of collecting the several liquid effluents and sending them to the appropriate site.

To select and specify the materials needed for each service, it is necessary to analyse the main parameters that influence their selection: (a) work service conditions — pressure and temperature, and (b) fluids — concentration, pH, toxicity and flow. Safety concerns, the cost of materials and their local availability, and the time required for procurement and supply must also be considered. The most common materials used for some conventional services are the following: carbon steel for treated water, cooling water, compressed air and low pressure steam; PVC, polypropylene or stainless steel 304 for demineralized water; stainless steel 304 for ammonia piping and condensed steam; stainless steel 304 L piping for nitric acid and uranium solutions; and galvanized stainless steel for nitrogen piping.

3.8. UTILITIES

Services for the pilot plant start with electrical power and water supply. In a small pilot plant, the water consumption is relatively low, probably in the range of 2000–4000 L/t ore. The lower value applies in cases where recycling of the extraction effluents is carried out.

3.8.1. Electrical services

Electrical energy is taken from the public grid, if available, or from a diesel generator whose power must be calculated by the project. In cases where no grinding is used (the heap leach process), the electrical power is relatively low.

After considering the source of electrical energy, it is advised that all master controls for plant equipment be mounted on control and instrumentation panels from which the entire pilot plant can be controlled and monitored.

Because of the corrosive conditions of the processes, all electrical wiring should be run in PVC conduit and all conduit within the building should be exposed. The only underground duct will be encased in concrete between the substation and electrical equipment rooms.

In accordance with the layout, the electrical substation (or the power supply generator) should be located as nearby as possible and the site should be free of corrosive vapours and sources of waste, to avoid their accumulation on the electrical insulators. If possible, the substation (or power supply) should be oriented in relation to the wind in such a way as to avoid potential problems.

The voltage systems in common use include 110/220, 480, 2400, 4160, 6900 and 13 800 volts. The most commonly used voltages are:

— 110/220 V, three phases, two wires,
— 110 V, one phase, two wires,
— 220 V, one phase, two or three wires,
— 220 V, three phases, three wires.

The project must indicate the selected voltage for the pilot plant. The choice of voltage will depend on the local electricity company supply, the size and type of load and the special equipment requirements. The project should consult with the company about the supply and other information concerning the voltage, number of phases, power factor, frequency, measurement instrument and its location. The project must provide information on the required maximum installed power, maximum power demand and estimated monthly demand. The project must also calculate the power requirement for each pilot plant section.

The electricity supply system must have an efficient grounding to maximize personnel protection and avoid damage to the equipment. Not only the electrical system but also any equipment or part of the installation (metallic structures and supports, connectors, conduits, metallic fences, cabinets and equipment housing) must be grounded as a safety precaution for personnel. The lighting system must also be included in the grounding project.

It is desirable to have a provision for the installation of an emergency power supply, operated with gasoline or diesel oil. The project should reserve space and indicate a place for this equipment.

The safety aspect of the electrical project is of maximum concern. Accidents and malfunction are a consequence of poorly designed and constructed installations. The potential risk must be eliminated during the planning of the electrical system and the preventive maintenance must be rigorous. Exposed parts, equipment or wiring that can be subjected to mechanical or water damage are potential areas of risk. The electrical insulation material can be damaged by heat.

The electrical system must be safe and reliable. Its reliability depends on such factors as supply source, distribution grid, load capacity, voltage variation, frequency variation, power factor and waveform.

3.8.2. Process water requirements

The project shall estimate the total amount of water necessary for the pilot plant, indicating the annual consumption. The water demand must be distributed among the following areas: crushing and grinding, leaching, extraction, precipitation, effluents, fire, utilities, drinking water and steam generation.

Where there is no possibility of using municipal treated water, it is necessary to provide a capture system for the water stream by means of a pump and a storage tank. The capacity of this tank is a function of the size of the pilot plant. A reasonable volume could be in the 10–20 m^3 range. Part of this volume (4 m^3) can be reserved for fire protection and the rest pumped to the treatment station.

The fire protection system must have hydrants located in the critical areas, previously defined by the layout. The use of a foam system can be planned as well. Each hydrant must be fitted with a 2.5 in (~6 cm) hose with a minimum length of 30 m and a jet to reach 10 m distance, with a flow rate of 40–60 m^3/h. The project must recommend a pump with the capacity to accommodate a demand of two or three hose connections operating simultaneously.

For the chemical treatment, water is pumped from the storage tank to the station. The conventional addition of aluminium sulphate and flocculant and calcium hydroxide (lime) for pH control is followed by chlorination for oxidation of iron and organic matter. The treated water is directed to a decantation tank and then filtered. The filtered water is treated with lime for pH adjustment and then finally stored in a tank with a capacity of about 10 m^3. The slurry from the decantation tank is pumped to the effluent treatment section.

3.8.3. Drinking water

Drinking water is obtained by the chlorination of treated water until there is an excess of about 0.2 ppm free chlorine after a minimum contact time of 30 min. The potable water is stored in a clean tank and distributed for human use in the showers and sanitary and eye washing equipment in the plant and laboratories.

3.8.4. Demineralized water

Demineralized water is used in the feeding of steam generators, in the pilot plant and in the laboratories. For a small pilot plant, the equipment should have a capacity of 0.1 to 1.0 m^3/h and the following sequence: an activated carbon filter, a cationic ion exchange (H^+ form) column, an anionic ion exchange (OH^- form) column and an optional refining column of mixed bed cationic (H^+ form) and anionic (OH^- form) columns. The service for regeneration of the resins must consist of a sulphuric acid tank, a dosimeter pump for the sulphuric acid, a sodium hydroxide tank and a dosimeter pump for the alkali. The system must also have a conductivity meter on-line to follow the quality of the demineralized water and to indicate when the resins are exhausted and require regeneration. The purified water must be stocked in a lined tank with a capacity (1–5 m^3) as outlined by the project.

The effluent from the regeneration and washing of the resins is sent to a deposit and then neutralized before being disposed of in the waste pond.

3.8.5. Steam generation

It is recommended that steam be generated from demineralized water for reasons of safety and the long life of the equipment. Certain additives such as hydrazine can be put into the water for the removal of traces of oxygen. The final content of oxygen will be 0.01–0.05 mg/L in the water to feed the steam generator. The use of morpholine is recommended to achieve a feedwater pH in the range of 8.5–9.0. Morpholine has the additional effect of preventing corrosion.

Even with the use of demineralized water for steam generation, some industries advise the addition of phosphate to prevent corrosion and to precipitate some cations such as iron. A final concentration in the range of 20–30 mg/L of iron is recommended. As the amount of both the morpholine and the phosphate used is small, tanks of 100–200 L capacity for the preparation of stock solutions must be provided.

The project must define the required amount of steam and indicate the demand for superheated steam at 240°C and normal steam of 5 kg/cm^2 gauge. The steam line must be equipped with a condenser for the unused steam and must provide for the recycling of the condensate. The project must define the capacity and type of the steam generator, and in accordance with the site must specify whether electricity, oil, coal or even wood is to be used for the heating system.

3.8.6. Compressed air

Compressed air is supplied by a compressor whose specifications, defined by the project, must include its type, capacity, pressure and drying system if there are instruments in the pilot plant that require dried compressed air. Usually the air is dried with a tower of silica gel and then filtered. Two towers, one in service and the other as a stand-by, are recommended. The silica gel is regenerated by heating with hot air from a heat exchanger unit using 5 kg/cm^2 steam.

3.8.7. Laundry

The establishment of a laundry facility is extremely convenient for both the process laboratory and for the pilot plant. Personnel must not take home contaminated clothing. The radioprotection technicians must monitor both the personnel and their clothing.

3.9. EFFLUENTS TREATMENT AND TAILINGS DISPOSAL

The waste treatment system is designed to meet industrial safety and regulatory requirements. To achieve this goal, the project must organize the following items: the control systems, process flow sheet, equipment data sheet, layout, specifications for the equipment and instruments, piping plan, and procurement.

For the operation of waste management facilities the more specific information which may be required includes the following: a description of the design, construction and operation of the facility; and a detailed description with drawings of the facility, including all structures and equipment designed to retain and control the tailings, the quality and quantities of all effluents and emissions from the facility, the expected volume and flow rates of all liquids handled by the pilot plant, and the points of discharge. An operational procedure manual, including the operating procedures for all components and a description of the sampling techniques and analysis methods, is also helpful.

The main pilot plant effluents are solid waste and acid washing solutions from pulp treatment, and acid raffinate from uranium solvent extraction or ion exchange effluent. Solid ion exchange has some advantage over solvent extraction because it introduces less organic contaminants. These effluents must be pumped to their respective storage units and then neutralized before disposal into the pond.

Acidic effluents must be neutralized with limestone or lime and then disposed of in the tailings pond. All tailings should converge and be fed to the neutralization operation as a slurry. Safety control at this point is mandatory to prevent the runoff of liquids which may have leached ^{226}Ra, a nuclide which could be transported to the surface water or groundwater. The acid liquid barren effluents are also neutralized and then specially treated to co-precipitate radium into barium sulphate, before the effluents are sent to the pond. The radium co-precipitation must be done carefully to guarantee that the depleted solution contains less than 0.37 Bq/mL.

The pond for the waste must be designed by the project in accordance with the local legislation for accepting effluents depleted in radium. All of the discharged slurries and solutions are contained in the tailings pond, the dimensions of which must be determined by the engineering project. The pond, usually located at the site where the ore body is exploited, must be completely constructed prior to startup of the mill and must be ready to accept the solids from the leach wastes and ^{226}Ra sludge. These solids quickly settle in layers and incorporate the radioactive material, contributing to diminished radiation. Normally, for economic reasons, the waste facility is sited close to the mine and mill facility, but other factors can contribute to the decision on the final location.

Wastes generated at the process laboratory (e.g. solid and liquid samples, waste solutions, reagents and organic materials) should be contained in suitable containers and disposed of in appropriate places or at special waste sites while awaiting disposal in the pond prepared for the pilot plant [15]. The same local legislation must establish the limits of tolerance for other elements, especially heavy elements. Such limits take into account the climate, seasonal evaporation rates and geology.

3.9.1. Liquid effluents

The principal characteristics of the liquid effluents are the acidity of the raffinate after the extraction of uranium by solvent extraction or retention by ion exchange and the alkalinity of the filtrate of the ammonium or sodium diuranate, whose volume is quite small. The acid filtrate of the yellow cake must also be considered if peroxide is chosen for the precipitation.

The main chemical reactions in the liquid effluent treatment are shown below.

(a) Neutralization:

$$H_2SO_4 + CaCO_3(s) \longrightarrow CaSO_4(s) + CO_2 + H_2O$$
$$H_2SO_4 + Ca(OH)_2 \longrightarrow CaSO_4(s) + 2H_2O$$

The precipitation of insoluble carbonates and hydroxides (Fe(III) and Mn(II)) must also be considered.

(b) Causticization:

$$(NH_4)_2CO_3 + Ca(OH)_2 \xrightarrow{\text{temp.}} CaCO_3(s) + 2NH_3 + 2H_2O$$

This reaction need be considered only if for economic reasons there is an interest in developing the process of ammonia recovery for use in a future commercial plant. The ammonium carbonate is treated with excess CaO and then distilled and condensed before recycling.

In the case of the industrial plant, instead of alkalinization and distillation, ammonia can be sold as fertilizer after crystallization of the ammonium sulphate.

A recommended procedure for the neutralization of liquid effluent involves two stages: in the first reactor, limestone is added until pH3–4 is reached, and in the second stage (reactor), neutralization to pH7 is achieved by the addition of lime. After neutralization, the treated effluent is sent to the thickener and the clear overflow is treated with barium chloride to co-precipitate the radium. The $Ba(Ra)SO_4$ sludge is usually allowed to settle out of the treated decant liquid in the settling pond, where it is normally allowed to remain. Alternative procedures for effluent treatment which may be acceptable are solidification followed by burial at the site either in the tailings pond or in the mine.

3.9.2. Solid effluents

The main solid effluent (leached ore slurry) must be treated in a mechanically agitated reactor, and the final pH adjusted to 6.5–7.0 by the addition of lime. A minimum residence time of 30–45 min is recommended. The used lime should have a minimum of 90–95% available $Ca(OH)_2$. The neutral pulp is pumped to the waste dam. The main process for the treatment of acidic mill effluents is neutralization with lime or a combination of limestone and lime [15]. With this treatment sulphuric acid is neutralized, some sulphate is precipitated, most heavy metals are precipitated or adsorbed, and to a large extent ^{226}Ra is removed. Amines used in the solvent extraction are removed by adsorption on precipitated solids. To complete the removal of radium after the neutralization, barium chloride is added to the decanted liquor.

3.9.2.1. Co-precipitation of radium

After ore leaching and recovery of uranium the ^{226}Ra content in the solution must be drastically reduced by co-precipitation with barium sulphate. This technique provides for the disposal of liquid effluents with radioactivity of less than 10 pCi/L (0.37 Bq/L). The co-precipitation of radium is achieved with a solution of 50 g/L $BaCl_2$ with an estimated consumption of 15 g $BaCl_2 \cdot 2H_2O/m^3$ effluent. The reaction time is relatively short, about five minutes, and the mixture in the reaction vessel must be well agitated. Before disposal a flocculant should be added to the mixture, followed by adequate clarification.

3.9.3. Waste treatment flow sheet

Preliminary studies for the identification and definition of the flow sheet for the waste treatment are done at the process laboratory. These studies start with the characterization of the effluents and include, for example, the chemical composition of the solid waste, with special attention directed to (1) the residual uranium content and the composition (free acidity and uranium), and (2) the specific activity (radium) of the raffinate from solvent extraction and of the effluent from the anionic ion exchanger. The radium content must be analysed throughout the leaching circuits and in the neutralization circuits.

After the treatment of effluents and before their disposal into the pond, it is necessary to establish an analytical control to determine the level of impurities such as arsenic, cadmium, copper, manganese, mercury and selenium, and to ensure that these levels are in accordance with the recommended legal values and the established local environmental standards [16]. The streams to be disposed of must also be analysed for soluble species, especially for sodium, sulphate, fluoride and phosphate. It is useful to compare these values with the limits established for drinking water.

Usually the solid tailings range from 0.004 to 0.05% U_3O_8 depending on several parameters, including ore mineralogy, grinding (size of grain), leaching conditions (i.e. the amount of sulphuric acid used per tonne of ore), temperature, oxidant and residence time. Generally an increase in the amount of acid per tonne of ore decreases the tailings, but there is a practical and economic limit for the acid consumption. Both parameters, i.e. ore mineralogy and acid requirements, have important effects on the uranium leaching and, as a result, on the tailings.

Installations set up to operate with a simplified flow sheet based only on crushing and heap leaching usually recover only 70–80% of the uranium. For a pilot plant based on the heap leach process, the main solid wastes remain on the leaching pad and can be covered with soil and stabilized, but regulatory requirements should be checked. The liquid effluent must be neutralized and disposed of together with all of the other wastes, including the barium sulphate which was used to retain the radium.

For a pilot plant based on the heap leach process, the site for the piles must be planned so that drainage from them can be collected and treated for the recovery of uranium. This is done in an already existing mill when possible. The leaching solution may be recirculated or, after the extraction of uranium, released with other liquid effluents. Long after the recovery of uranium, however, rain water will seep through the pile and may continue to extract small quantities of uranium, radium and heavy metals. Care must be taken to analyse and properly dispose of all waste solutions.

The more conventional plants, which include crushing, grinding, leaching and solid–liquid separation, in many cases can recover over 90% of the uranium. The tailings generated from this type of pilot plant still contain some uranium, and treatment of these tailings must also be considered. Today the most common grade of ore contains 0.1–0.2% U_3O_8. On the basis of data and assuming a 90% recovery of uranium, a plan for the tailings disposal is drawn up.

The volume of liquid effluent should be kept as low as possible by recycling. The section in charge of effluent treatment will consider the temperature and pH recommendations, the biological and chemical oxygen demand and the amount of total soluble salts, uranium and radium. In the case of some by-products recovered from the process (in commercial plants), for example ammonium sulphate, ammonium nitrate and sodium sulphate, special attention must be paid to any residual uranium and radium. Reuse of mine water requires special treatment to eliminate solid materials and radium.

For environmental protection, returning all solid residues from the leaching operation to the exploited ore body site should be considered, especially when it is an open pit mine.

Particularly in areas like the yellow cake section where solid products are handled, the engineering project must guarantee an extremely low level of solid particulates, about or less than 0.25 mg/m^3 of uranium in the yellow cake handling area and less than 5 $\mu g/m^3$ in the filtered air returned to the surrounding building. Treatment of solid residue must be in accordance with the norms of each country.

Wastes from the mining and milling of uranium create potential health problems as a result of radioactivity (U, Ra and daughters) and heavy metal contamination. A technical report [17] describing the practices and options for confinement of uranium mill tailings was published by the IAEA in 1981.

Professionals (managers) involved in this type of work must identify the wastes and provide for their management in such a way as to minimize public health risks and both radiological and non-radiological environmental impacts. Specialized literature on waste management [18–21] is available to the personnel responsible for planning, designing, constructing and operating the waste facilities. Requirements for the management and control of radioactive solid, liquid and airborne (radon) wastes must be fulfilled. Information about non-radiological contaminants in uranium mill tailings must be considered as well [16]. It is quite common that wastes from the mining and milling of uranium also contain potentially hazardous non-radioactive components, such as arsenic, usually encountered in the barren solution. To avoid any risk, the competent authority must consider this possibility.

Wastes from the mining and milling of uranium ores (and thorium as well) include solids, liquids and airborne effluents containing radioactive gases (radon) and particulates (uranium). Prior to operation of the pilot plant, each step of the process (e.g. exploration, mining and milling) must be examined with assistance from the process development laboratory. Liquid and airborne effluents may contain a significant proportion of the daughter products of the uranium and thorium in the ore. Radon and its daughters may be released from the tailings and dispersed into the atmosphere. Radium and other daughter radionuclides may reach the surface water or even the groundwater. For proper operation of a waste facility a manual on operation, maintenance and monitoring as well as adequately trained personnel are needed.

Usually the effluents from a pilot plant are very low in uranium. Liquid effluents correspond to an estimated volume of about 1.5–4 m^3/t ore.

The wastes generated by the mining, milling and leaching of the uranium ore include radionuclides which give rise to radiological hazards. The radionuclides involved are those descending from the first members of the natural decay series, i.e. ^{238}U and ^{235}U. Whenever the ore body contains ^{232}Th its daughters must also be included. Uranium-238 must be viewed as the most important parent nuclide since it is the most abundant. Radium-226 is the most critical descendant to be considered. It has a long half-life (1600 a) and is the source of the radioactive gas radon. Following radium in importance and impact are ^{230}Th (half-life 75 380 a) and at the end of the ^{238}U series ^{210}Pb (half-life 22.3 a), which decays to ^{210}Bi and ^{210}Po. The latter is a very powerful poison and a high energy alpha emitter.

Because of the risks associated with its possible inhalation by persons near the mine, mill or waste sites, the emission of radon and its decay products (from the tailings) must be considered. Special attention must be paid to ventilation, particularly in the underground mines [22, 23]. The natural ^{232}Th series includes ^{220}Rn, a gaseous decay product, a descendant of radium. This family contributes two radium isotopes; the first, ^{228}Ra (mesothorium, half-life 5.75 a), deserves special attention.

Additional information on the natural uranium and thorium series is available in Refs [17, 22].

Radon is released from open pits, in mine ventilation exhaust, ore dust, and at all stages of the milling process, but especially during the crushing, grinding and leaching stages. There is, at present, no practicable method for removing this gas from ventilation exhausts. Thus the manner and rate of release have to be monitored and adjusted to comply with authorized limits.

After the uranium is extracted from the ore, most of the remaining ore material becomes a mill waste or tailings, commonly a slurry of finely ground solids. As the major portion of the ^{226}Ra remains undissolved throughout the leaching process, the concentration of radium in the tailings is only slightly less than the concentration in the ore [24, 25]. If unprotected, the tailings release radioactive material (1) to the air as radon gas and airborne particulates, and (2) to waterways as soluble or particulate radionuclides.

Backfilling of all parts of the tailings into worked out portions of the mine would appear to offer considerable promise as a means of isolating the material from the external environment.

During the early development, operation and decommissioning of any uranium or thorium mine, management of the mine waste rock is essential. This material originates from the rock that is removed from either an open or an underground mine in order to provide access to the ore body. Before rejection as waste or barren rock, the material should be analysed for its uranium content. Any potentially economic grade material, for example low grade rock, should be segregated. However, before a decision is made to use the waste rock for any purpose (e.g. as a source of uranium which can be recovered by heap leaching or to refill the trenches, especially in open mines), the mineralogy, radioactivity and chemical reactivity of the waste rock should be assessed.

If the rock is subjected to heap leaching to recover the uranium, then the extracted heap becomes a waste. Care should be taken when siting and constructing such heaps in order to minimize their eventual impact on the environment.

If the hydrogeological, radiological, engineering and economic aspects are favourable, it may be preferable to dispose of the waste rock in the mine since in this way the waste would be isolated from the external environment.

Mine drainage water consists mainly of surface water or groundwater which has entered the workings through subterranean channels or fissures, or rain water which has fallen into the open pit operations. Mine water may contact the ore body for substantial periods of time and thus may contain dissolved uranium, thorium, radium, radon, thoron or other metals. If sulphides are present, the mine water may be quite acidic. Treatment and disposal of mine water depend on local conditions such as the mineralogy of the ore body, climate, topography and the existence of an operating mill. Treatment of the water may include separation of the uranium, radium and other heavy metals followed by processes such as sedimentation, precipitation, lime neutralization, ion exchange and precipitation with barium salts [17].

Finally, it is important to point out some differences in leaching processes carried out under alkaline as compared with acid conditions.

In the alkaline leaching process, the barren liquor is recovered and reused, and for all practical purposes only the washed tailings become a waste stream. The leached, washed tailings are transported to the tailings impoundment system in a water slurry which is slightly alkaline and may be contaminated with radioactive nuclides and chemicals. These tailings may need treatment before disposal.

In the acid leaching process the solution that is normally used to transport the tailings may contain a greater concentration of contaminants. These can include sulphuric acid, heavy metals, nitrates, sulphates, organic solvents, long chain amines, chlorides and natural radionuclides [26, 27]. The acid effluents require neutralization and confinement of the radium as previously described.

If because of climatic conditions the pilot plant must depend on the release of treated waste streams into rivers, for example, information on the safe disposal of radioactive waste into rivers, lakes and estuaries is available [28–30].

It has been recommended that the pilot plant have a laundry installed. It should be noted that the laundry water will contain particulates and soluble materials washed out of clothing and will probably be lightly contaminated. Such water can be directed to the waste impoundment facility.

For other solid wastes from uranium milling operations — for example clogged filters and filter cloths — it is a normal practice to consign such material to the tailings impoundment or to a special disposal site.

4. PROJECT ADMINISTRATION

4.1. INTRODUCTION

Like all industrial programmes, a successful pilot plant requires high quality administration and management. Depending upon the size and objectives of the pilot plant programme, the management structure may vary from an almost informal to a relatively complex organization. The management functions that must be carried out, however, are the same regardless of the size or complexity of the management structure. These functions include planning, staffing and controlling the operation. The pilot plant manager is usually the key to a successful pilot plant operation.

4.2. THE PILOT PLANT MANAGER

The primary goals of the pilot plant manager are to ensure the technical quality of the work, to control the cost of the project, and to complete the project safely and on schedule. To a large extent the success of a pilot plant operation will depend upon the ability of the project manager and the authority that he/she is given. The most successful pilot plant operations have been directed by managers who are proficient in a range of disciplines covering managerial as well as engineering functions. The major disciplines include (1) engineering, (2) cost management, (3) human skills, and (4) negotiations. The authority given to the project manager should be broad in scope. Some of the more common areas of decision making authority include the following:

Technical decisions

— Directing the design approach,
— Identifying and selecting the type and scope of tests,
— Selecting the equipment to be used.

Commercial decisions

— Whether to make or buy equipment,
— Selecting or recommending vendors or subcontractors.

Administrative decisions

— Selecting and assigning personnel,
— Scheduling personnel, equipment and other resources of the project.

Monetary decisions

— Determining the expenditure of budget funds.

The project manager should be not only a co-ordinator of actions needed to achieve the objectives of the project, but he/she should also be a leader in the broadest sense of the term, and a skilled organizer, as well. As outlined above, the project manager should have broad authority over all elements of the pilot plant project. The authority of the manager should be sufficient to control all technical and managerial actions required to complete the project successfully. He/she should be able to control funds, schedules and the quality of the technical effort.

The project manager must select staff having the required competence and the capability of operating as part of the project team. The pilot plant manager should not try to describe exactly the authority and responsibility of his/her subordinates, i.e. the manager should encourage problem solving rather than role definition.

In many instances the pilot plant manager must act as chief engineer and be willing to trust his/her own judgement in making decisions of a highly technical nature. The manager, however, should not become embroiled in the details of all technical matters. The most successful pilot plant manager will have a balanced combination of technical, managerial and leadership skills.

4.3. PLANNING

The decision to build a pilot plant and the definition of the mission of the pilot plant usually involve an iterative process. The various options and needs are evaluated, and the decision process then goes through a series of cycles that culminate in a definition of the overall mission of the pilot plant operation. Once the decision to build and operate a pilot plant has been made, and the pilot plant manager has been selected, specific planning for the construction and operation of the pilot plant can be initiated. This planning involves setting goals and objectives for the organization and developing 'work maps' which show how these goals and objectives are to be accomplished. After these plans have been formulated, organization, which involves an integration of resources, becomes the primary concern. This means bringing together people, capital and equipment in such a way that the pilot plant will effectively accomplish its mission and goals.

Along with the planning and organizing, the motivation and spirit of the pilot plant team play a large role in determining how effectively the pilot plant goals will be met. Since motivation strongly influences performance levels, the planning process should carefully consider and recognize the importance of motivation for successful pilot plant operation.

Critical components of the planning function are listed below:

- Initiating and following through on licensing requirements,
- Developing action plans for budgeting, programming, and scheduling,
- Developing safety plans for the construction, operation, and shutdown of the pilot plant.

4.3.1. Licensing

Licensing requirements for a pilot plant operation may vary considerably for different countries and also for different locations within a given country. Since licensing requirements will affect nearly every aspect of the pilot plant construction, operation and closure, these requirements must be among the very first considerations of the planning process. Lead times to complete the licensing can be long because it may be necessary to deal with many different regulatory agencies. Assigning and designating specific responsibility for the licensing function are necessary. Licensing costs can be significant and should be considered carefully in the budgeting process. The use of consultants or organizations experienced in the licensing procedures can be cost effective, particularly when the licensing process is complex.

4.3.2. Action planning

The term 'action planning' has been used to designate the process of developing budgets, programmes and schedules for the pilot plant. Action planning is an iterative process, and several planning cycles may be necessary. This planning process continues throughout the pilot plant programme since modifications of the original programme are often necessary. Each planning cycle should consider potential options and provide for contingencies.

4.3.2.1. Budgeting

Preparing a budget estimate for a pilot plant involves essentially all of the steps and components of a capital and operating cost estimate for industrial scale operation. Cost estimating is primarily an art based upon a combination of factual and empirical relationships. The process consists of developing capital and operating cost estimates based on the flow sheet, material balance and energy balance that have been prepared for the pilot plant. A wide variety of books and articles on cost estimation, which can serve as references and guidelines for preparing the pilot plant budget estimate, are available [31–34].

Capital investment — Capital investment is the amount of money that must be available for construction of the pilot plant facilities and their ultimate operation. There are two types of capital: fixed capital and working capital. The investment in buildings, equipment and auxiliary facilities is called fixed capital. Working capital refers to the funds required for operation of the pilot plant. Typical components of a fixed capital estimate are listed below.

Purchased equipment	________	
Equipment installation	________	
Piping	________	
Instrumentation	________	
Insulation	________	
Electrical system	________	
Buildings	________	
Land and yard improvements	________	
Utilities	________	
Physical plant cost (subtotal)		________

Engineering and construction	________	
Direct plant cost (subtotal)		________
Contractor's fee	________	
Contingency	________	
Fees and contingency (subtotal)		________
Fixed capital (total)		________

Working capital — The working capital requirement for a pilot plant is the amount of money necessary for normal conduct of the operation. Since the pilot plant does not produce a saleable product, the working capital requirement includes all of the funds needed for completing the pilot plant programme, i.e. the total operating cost.

Operating cost — The operating cost is the sum of all the direct, indirect and fixed expenses incurred in the actual operation of the pilot plant. The principal components of an operating cost estimate are listed below.

<u>Direct costs</u>		
Raw materials and reagents	________	
Supervision	________	
Operating labour	________	
Maintenance labour	________	
Parts and supplies	________	
Utilities	________	
Safety/environmental supplies	________	
Miscellaneous	________	
Direct operating cost		________

<u>Indirect costs</u>		
Payroll overhead	________	
Laboratory services	________	
Engineering services	________	
Administrative services	________	
Safety services	________	
Security services	________	
Transportation	________	
Communication	________	
Warehousing	________	
Miscellaneous	________	
Indirect operating cost		________

Fixed costs		
Depreciation	________	
Taxes	________	
Insurance	________	
Fixed operating cost		________
Total operating costs		________

In the estimation of the operating cost of a pilot plant operation, contingency factors should also be carefully considered. Overruns are usually associated with the necessity of extending the pilot plant operations beyond the original projections. It is usually desirable to prepare operating cost estimates for both a minimum projected operating period and an operating schedule that is at least 20% longer.

4.3.2.2. Programming and scheduling

One of the most frequent objections to pilot plant operations is that they take too much time. Thorough programming and scheduling will minimize the time requirement and reduce costs. The number and type of experimental runs needed to meet the research objectives strongly influence all of the economic aspects of the programme.

Planning and scheduling the programme of pilot plant investigations start after the bench scale research and preliminary economic evaluations have defined the potential of the processing operations. A primary objective of the pilot plant programme is to provide the data and information needed to design and construct a plant that the operating department can put into maximum production with a minimum of problems. Careful planning of the experiments may also reveal needed alterations and may even demonstrate that a pilot plant is not the best method to obtain the desired design data. Additional, less costly laboratory work may be needed to support the pilot plant operation.

Statistical designs for the experiments usually uncover synergistic factors affecting performance or product quality and will provide maximum information at minimum cost. Statistically planned experiments reduce the element of human bias, and eliminate less productive avenues of experimentation by taking advantage of earlier data. In addition, the number of runs needed to define the effect of variables is reduced, and confidence in the experimental results is increased.

Scheduling for the design and construction of a uranium processing pilot plant is critical particularly if long lead times are required for the purchase and delivery of equipment. The time elapsed between project inception and data generation is often between 12 and 24 months. Table III shows typical requirements.

As mentioned above, identification of long lead time equipment deliveries can be one of the most critical scheduling items. Construction, however, can be started

TABLE III. TIME REQUIREMENTS

Task	Months
Design and materials procurement	4–12
Construction	4–8
Startup (up to and including the first run)	2–4

even before the final design is complete. For example, utilities can be brought in, and support structures can be started. It also may be desirable to build and operate subsections of the pilot plant. This procedure may prolong the overall construction time but can significantly reduce the startup time. Many short cuts are possible, but each carries a risk that should be evaluated before implementation.

4.3.3. Safety

The safety responsibilities of the pilot plant management encompass all aspects of the pilot plant operation. Safety considerations are a critical component of the initial planning phase and should continue throughout the design, construction, operation and close-out phases of the pilot plant programme. Safety must be built into the pilot plant from the beginning. It is particularly desirable to have one engineer responsible for safety considerations; this engineer should report directly to the project manager. Establishing a sound safety policy and developing the necessary rules and regulations are of utmost importance.

Potential hazards that may have been overlooked or missed in the laboratory can become critical during pilot plant operations. This is particularly true if the pilot plant is testing new technology or chemistry. Hazard assessment during both the planning and operational phases of the pilot plant operation should include the considerations listed below.

PRELIMINARY ASSESSMENT

(a) Reagent hazards
- — Toxicity
- — Flammability
- — Explosibility

(b) Reaction hazards
- — Runaway or explosive reactions
- — Contaminant effects

(c) Corrosion hazards
  — Effect on equipment
  — Effect on reactions

(d) Radiation hazards
  — Direct radiation
  — Indirect radiation (dust, etc.)

DESIGN PHASE

(a) Space requirements
(b) Pilot plant layout
(c) Buildings
(d) Equipment
(e) Piping
(f) Electrical system
(g) Instrumentation
(h) Emergency systems

CONSTRUCTION PHASE

(a) Inspections
  — Buildings and equipment
  — Utilities
  — Safety equipment

(b) Design changes and modifications

OPERATIONS

(a) Preparation of safety instructions

(b) Participation in preparation of operating instructions
  — Startup
  — Normal operation
  — Shutdown
  — Emergency procedures

(c) Participation in operator training
(d) Waste disposal
(e) Housekeeping
(f) Provisions for first aid and medical services
(g) Personal safety equipment (glasses, shoes, etc.)

CLOSE-OUT

(a) Final shutdown procedures
(b) Waste disposal
(c) Disposal or mothballing of equipment and facilities

Safety planning is particularly critical in pilot plants because for the first time operations will be conducted by and entrusted to non-technical personnel. The laboratory studies will have been handled by technically trained personnel, but the pilot plant is a new phase of the overall programme. Also, the pilot plant is the origin or 'birthplace' for the safety practices and operating procedures that will be used in the full scale plant.

The pressure of pilot plant schedules and problems can easily result in the mind of the engineer being compartmentalized. Technical criteria and specifications are carefully followed, but when it comes to even the most elementary safety precautions, these sometimes seem to be excluded from consideration. Both the pilot plant manager and the staff must recognize that any accident may retard the pilot plant programme to a much greater extent than minor errors in operation.

Additional information on pilot plant safety is presented in Appendix II.

4.3.4. Support services

Planning for successful pilot plant operations must also include provisions for adequate support services such as:

— Sample preparation,
— Analytical laboratory and mineralogy support,
— A metallurgical laboratory,
— Shop and warehouse facilities.

Although the need for these support services is crucial, the scope and extent of the on-site facilities may vary considerably. For example, an isolated pilot plant location may require all of these services to be located at the site, but a pilot plant located near an operating plant or laboratory may be able to use existing facilities. Factors that should be considered are discussed in the following sections.

4.3.4.1. Sample preparation

Pilot plants produce essentially all of the control samples that would be found in a commercial operation. These include dry or moist solids, slurry samples, and a variety of liquid samples. The equipment and procedures required for handling and preparing samples are described in Ref. [35]. The necessary equipment includes crushers, splitters, drying ovens, pulverizers and filtration equipment. Unless existing sample preparation facilities are adjacent to the pilot plant, it is almost always desirable to have equipment for filtering and handling slurry samples in the pilot plant. Sample preparation equipment should be located in a separate room with adequate dust collection facilities. It is particularly important that facilities for drying and preparing yellow cake samples be isolated from the areas where tailings samples are handled.

Bins or shelves for systematic storage of bulk samples, sample pulps and solution samples should be provided. The need for repeat analyses or additional metallurgical laboratory tests commonly arises in pilot plant operations.

Sample handling and preparation are particularly important in pilot plant operations. Cross-contamination or other mishandling can produce misleading or inconsistent data that could require expensive additional pilot plant tests.

4.3.4.2. Analytical laboratory and mineralogy

Timely and accurate analytical results are a crucial requirement for successful pilot plant operations. Providing adequate analytical support must be an intrinsic component of the pilot plant planning process. Prompt analysis of all pilot plant samples is desirable, but results for leach circuit tailings and solvent extraction raffinates are particularly critical.

Provisions should also be made for mineralogical support services. Contracting out mineralogical services normally provides adequate support for a pilot plant operation, but occasions can arise when a fast response is needed. For example, a sudden drop in uranium extraction may require prompt recharacterization of the ore. Planning for support services should include provisions for this type of contingency.

The extent and scope of any new analytical facility that is required depend largely on the location of the pilot plant. If the pilot plant is located adjacent to an existing uranium mill or metallurgical laboratory, no new facilities may be required. Additional personnel and a two shift operation, however, will probably be needed while the pilot plant is operating. Pilot plants in isolated locations will require at least some analytical support facilities. In all instances the options of transporting samples to an existing company or contracting the analytical work should be considered and carefully evaluated.

4.3.4.3. Metallurgical testing laboratory

Every pilot plant operation requires the support of a metallurgical testing or process development laboratory. Experience has confirmed that concurrent bench scale leaching, solvent extraction and precipitation tests can improve the quality of the pilot plant results and also cut costs. Parallel testing using procedures developed during prior bench scale experimental studies permits the correlation of overall metallurgical results and increases the confidence level of the data.

Again, the location of the pilot plant affects the scope of the required testing facility. If a metallurgical laboratory is close by, most of the test work probably can best be carried out at this laboratory. If the laboratory is more than 50 km from the pilot plant, at least some metallurgical testing facilities will be required. For example, equipment should be available for moisture determinations, screen tests, filtrations, acid consumption determinations, leach tests and solvent extraction shake-out tests.

The IAEA Manual on Laboratory Testing for Uranium Ore Processing [35] is a useful reference for planning the required metallurgical testing facilities. The manual also presents details of sampling and experimental laboratory procedures for uranium ore processing.

4.3.4.4. Shop and warehouse

A non-operating pilot plant is very expensive. Schedule delays due to equipment breakdowns or other mechanical problems are one of the more frequent causes of budget overruns. Even carefully designed pilot plants will encounter problems, and attempts to overeconomize on maintenance or spare parts almost always backfire.

Even if the services of a maintenance department from an adjacent operating mill are available, it is desirable to have one or more maintenance personnel directly assigned to the pilot plant operation. It is likely that a pilot plant will require essentially every type of maintenance needed for a full scale mill. In some instances, it may be both possible and desirable to arrange for contract maintenance services. The types of maintenance services usually needed are listed below:

— Pump repair and installation
— Instrument repair and calibration
— Electrical maintenance and installation
— Piping repair and installation
— Welding
— Mobile equipment repairs
— Machine shop
— General mechanical maintenance.

The first three services on the list are often crucial and require trained personnel. Instrument repair is particularly difficult if the pilot plant is in an isolated location. Sophisticated instrumentation may not be desirable for an isolated pilot plant.

Maintenance planning should recognize that significant rearrangement of the pilot plant equipment may be necessary in order to evaluate flow sheet modifications. In some instances special equipment will be needed to relocate major equipment items safely.

If relatively complete on-site maintenance facilities are not available, the pilot plant schedule should recognize and plan for the downtime that almost invariably will occur.

Warehouse space should be provided not only for equipment and instrument spare parts but also for the pilot plant reagents and general operating supplies. Safety considerations are particularly important when providing storage space for chemicals such as oxidants and acids. Separate storage areas are usually needed. Equipment for safe handling of bulk chemicals should also be provided.

The availability of spare parts for the pilot plant equipment is particularly important. Adequate supplies of items that take a long time to be delivered must be available. Replacement parts such as spare pH electrodes, pump parts, and replacement motors are almost always critical items.

The importance of pilot plant maintenance skills should not be underestimated. The availability of one or two experienced and versatile maintenance personnel can be a particularly valuable asset for any pilot plant operation.

4.3.4.5. General and miscellaneous services

The pilot plant planning should also include provisions for a number of other support services such as the following:

Office space

Functional office space for both technical and administrative personnel will be required. Overcrowding can be a detriment to effective pilot plant operation. If rented office trailers are available, they can provide cost effective temporary space.

Changehouse

Safety regulations will require shower and changing facilities for pilot plant operating personnel. Special clothing for the pilot plant operators and arrangements for laundering the clothing are likely requirements.

Communications

If the pilot plant is isolated, provisions for outside communications are essential. Telephone or radio telephone service is particularly important for all emergency situations.

Transportation

Pilot plant planning should carefully consider transportation needs. For example, if samples must be taken to another location for analysis, a specifically assigned vehicle and driver may be necessary. Special ore handling equipment could be needed for larger pilot plants.

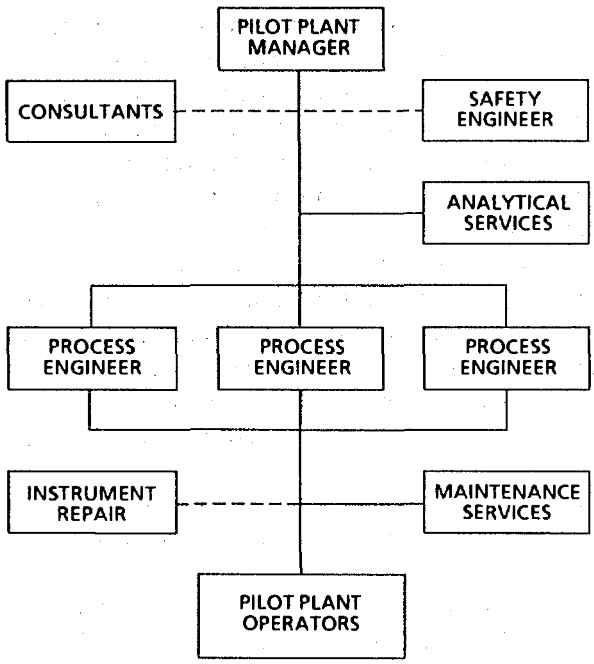


FIG. 4. Typical uranium pilot plant organization. Solid lines: direct project assignment; broken lines: as needed.

In sum, successful pilot plant operations require functional support services. The analytical and maintenance services are particularly important; without these services the pilot plant will probably not achieve its desired goals.

4.4. STAFFING

Successful pilot plant work requires a variety of talents. While professional competence is the most important of these talents, the ability to work co-operatively with others is also critical. The engineers, operators, maintenance personnel, analysts, etc., must all contribute their expertise to the successful completion of the project. To achieve maximum results the project manager must select the pilot plant team carefully. Figure 4 illustrates the typical staffing for a uranium pilot plant operation. Chemical engineers or metallurgical engineers with processing backgrounds are particularly suited for both management and actual operating supervision. Chemists with industrial training and experience have also proven to be effective pilot plant personnel. The number of professional personnel required depends on the size and complexity of the operation. Single shift unit operations may require only one process engineer, whereas six or more engineers may be needed for round the clock operations. It has often been desirable to use pilot plant operations as a training ground for the engineers or chemists who will staff the future uranium mill. Experience has shown that the best pilot plant results are most often achieved when the process engineers are directly involved in the hands-on operation of the pilot plant equipment. If the pilot plant is to be operated under a union shop arrangement, an agreement whereby process engineers can perform hands-on operation of the equipment is particularly desirable.

The number of operators or technicians required for effective pilot plant operation may vary throughout the course of the programme. If personnel from other parts of the organization are available, overstaffing during the startup phases can promote smooth operations. Pilot plants have also been used to train future mill operators, particularly in locations where experienced operating personnel may not be available.

Pilot plant safety responsibilities should be a specific assignment. As discussed in Section 4.3.3, the safety engineer should report directly to the pilot plant manager.

If possible, at least one maintenance specialist should be assigned to the project, and more could be required if extended round the clock operations are to be conducted. This would be true particularly if company or union rules prevent engineers or operators from doing maintenance work. Provision for instrument maintenance and repair should also be evaluated carefully.

The analytical requirements and particularly the turnround time for pilot plant operations are critical. Even if separate analytical services are available, pilot plant staffing for routine analytical determinations should be considered. Delays while waiting for analyses needed for the evaluation and planning of the experimental programme can be extremely expensive.

Almost all pilot plant operations require parallel support work from bench scale tests and experiments. Often this work can be performed by the pilot plant personnel, but for large pilot plant operations separate staffing for this function should be considered.

Consultants can also be an effective component of the pilot plant staff if the experience level of available personnel is relatively low. Consultants are probably most valuable during the planning and design stages of the programme.

Personnel expenses are almost always the major cost component of the overall pilot plant programme. Careful planning of the staffing requirements can be a major contribution to the success of the programme. Skimping on labour can seriously diminish pilot plant effectiveness, but overstaffing can also cause problems. As the work force exceeds the optimal number required, the rate of progress slows down. Communications fall off and co-ordination of the operation becomes more difficult. The ability of each engineer to participate in the setting of the goals towards which he/she is working becomes diminished and as a result tension can arise. It is advantageous to keep the organization as small as possible in order to stimulate rapid feedback between all stages of the pilot plant programme. Optimal staffing is a major challenge for the pilot plant management.

4.5. OPERATIONAL CONTROLS

Control of the pilot plant operation requires co-ordination of the various efforts of the pilot plant staff. This co-ordination is one of the primary responsibilities of the pilot plant management; effective communication is a must. Tools used for this co-ordination include staff meetings, operating manuals, data recording and reports.

4.5.1. Staff meetings

Scheduled staff meetings are a primary planning and control device. Experienced project managers believe that scheduled staff meetings are indispensable to effective management and high project performance. The frequency of staff meetings should be kept flexible, but weekly meetings have proven effective, particularly during the initial phases of the pilot plant programme. Special meetings are also scheduled periodically to examine particular parts of the programme or special problems.

The accountability approach has been found to be effective in a variety of organizations. This procedure is based on weekly discussions of individual accomplishments and plans. The accountability meeting agenda consists of the following three questions:

What was accomplished last week? This question focuses on the *results* that were achieved rather than on activities that were conducted. A primary objective is to recognize the difference between being busy and getting results. The supervisor should not try to intimidate the subordinate if the actual results achieved do not match the expected results identified the previous week. This component of the review is primarily an information exchange on the status of the work.

Were there any problems? All pilot plants can expect to have problems, but lack of awareness of problems can be critical. The objective of this question is not to embarrass the subordinate, but to ensure that all resources are being applied effectively to the resolution of any problems.

What will be accomplished next week? Of the three questions, this is the most important. This question focuses on what is expected for the upcoming week, and strengthens accountability by requiring commitment to specific future accomplishments. A primary objective of this question is to ensure that all efforts stay pointed in the right direction and focused on the right priorities.

Experience indicates that when the accountability meeting approach is used, surprises between the supervisor and the subordinate are minimized, and communication remains open, focused and consistent.

4.5.2. Operating manuals

The pilot plant operating manual is a key document for training personnel in the operation and maintenance of the plant. Even a preliminary manual can help prevent costly startup and operating errors. The pilot plant manuals also become the basis for the preparation of subsequent commercial plant operating manuals. The scope of the pilot plant operating manual can vary, but in general the manual should cover such functions as startup, routine operations, trouble shooting, normal and emergency shutdowns and equipment maintenance. Since the pilot plant operating manual may require significant changes as new insights are gained, it is particularly important that the manual be planned so that subsequent revisions can be made easily.

A modular approach has proven desirable for pilot plant operating manuals. Each module of the manual is devoted to a specific unit operation. A module typically contains the following information:

— *Introduction:* a discussion of the process concept for the unit operation;
— *Description:* a detailed description of the equipment;
— *Routine operation:* a detailed discussion of how the equipment is to be operated and controlled;
— *Trouble shooting:* a discussion of procedures for diagnosing equipment malfunctions;
— *Maintenance:* procedures for disassembling equipment and replacing parts, and schedules for testing and lubrication;
— *Emergency operation:* detailed procedures for emergencies such as leaks, fire and shutting down the process operations.

It is also desirable that the operating manual have an appendix containing the manufacturers' literature on the equipment provided by them together with lists and drawings of the spare parts.

4.5.3. Data recording

The full benefit of the pilot plant can be obtained only if the data are taken and recorded properly. Inadequate planning of the data recording procedures has often proven costly in pilot plant operations. Project personnel must decide in advance what information is required for the necessary calculations and projections. Hypothetical calculations can help to ensure that all of the required data are collected. Experimental data can be recorded in many ways. Filling in log sheets and filling in blanks on an apparatus sketch are two of the most common methods used. Computer data acquisition systems may also be desirable for some parts of the pilot plant operations. The application of these systems may depend at least partially upon the availability of suitable sensing and interfacing devices. The costs of data acquisition systems for a pilot plant are often equivalent to those for a commercial scale operation.

All data recording or acquisition systems should be supplemented with a log book for recording all operational difficulties, suggestions for changes and methods for overcoming difficulties. Complete and detailed records of all flow sheets should also be kept along with flow sheet changes, drawings, curves and descriptions of the progress of runs. A running photographic record of all equipment changes and modifications can be particularly useful when reports are being prepared.

4.5.4. Reports

Formal reporting of the pilot plant operations not only provides the basis for the design of the commercial operation, but also preserves the lessons of the pilot plant so that they can be used for trouble shooting future operational problems. The reporting process includes not only the final reports but also periodic progress reports. Relatively short monthly progress reports supplemented by summary reports on each completed phase of the pilot plant operation together with a final overall report have proven effective. The reporting procedure should also include final updating of the operating manuals. The pilot plant manager should allow sufficient time and funds to complete the final reports before the pilot plant team is dispersed.

Appendix I

EXAMPLE OF A URANIUM PILOT PLANT

I.1. INTRODUCTION

The equipment selected for a uranium pilot plant is unique for each operation. A generic approach has significant limitations because each pilot plant has different requirements. As mentioned in previous sections of this guidebook, pilot plant systems can vary from fully integrated flow sheets to isolated unit operations. Many of the smaller pilot plants have been non-integrated operations because the equipment sizes needed for full integration were not available. These systems required surge capacity between the various unit operations. In some instances, only a portion of the output stream from a given unit operation was processed in subsequent sections of the pilot plant; the remaining portion was discarded. Many variations on this approach are possible, and equipment selection must be tailored to fit the specific requirements of each pilot plant. The services of a consultant experienced in the selection of pilot plant equipment can be cost effective and should be carefully considered. The following sections describe various equipment that has been used successfully in several different types and sizes of uranium ore processing pilot plants.

I.2. THE GRAND JUNCTION PILOT PLANT

Integrated flow sheets are usually possible only with relatively large pilot plants. During the period from 1954 through 1959, the United States Atomic Energy Commission operated several integrated pilot plants at Grand Junction, Colorado. One of the primary objectives of this pilot plant operation was to confirm the projected flow sheet and metallurgical data development during laboratory studies on a variety of commercial uranium deposits. The overall pilot plant operation included the following processing circuits:

Feed preparation (crushing and sampling)
Carbonate leach–filtration
Carbonate leach–resin in pulp
Acid leach–resin in pulp
Acid leach–CCD–column ion exchange
Acid leach–CCD–solvent extraction.

The individual pilot plant capacities ranged from 5 to 15 tons (4.5 to 13.5 t) of ore per day. All pilot plants were operated on a 24 hour day, 7 day week schedule. The pilot plant results and related laboratory investigations are reported in Ref. [36].

The following section discusses the flow sheet and equipment used in the acid leach–CCD–solvent extraction pilot plant.

I.2.1. Acid leach–CCD–solvent extraction pilot plant

A description of the 7 ton/d (6.4 t/d) acid leach–CCD–solvent extraction pilot plant together with typical operating results is presented in Ref. [37].

A summary of the operations and a description of the equipment used in this pilot plant investigation are given below.

I.2.1.1. Operations summary

Approximately 560 tons (~510 t) of Holly Blend sandstone uranium ore were treated in the acid leach–CCD–solvent extraction pilot plant. The ore was from Section 14, R10W, T14N, of the Ambrosia Lake uranium district in New Mexico. The average feed assays of the ore were 0.313% U_3O_8, 0.151% V_2O_5, 4.07% $CaCO_3$ and 0.021% Mo. Overall test results indicated that the ore was amenable to the acid leach–CCD–solvent extraction process.

A leach extraction of 96.8% was obtained with a reagent consumption of 158 lb H_2SO_4/ton (79 kg H_2SO_4/t), 1.5 lb MnO_2/ton (0.75 kg MnO_2/t) and a leach retention time of approximately 24 h.

When five thickeners were used in the CCD circuit, and the wash ratio was 3:1, the soluble loss was approximately 0.5% of the uranium in the mill feed. Under these conditions, flocculant consumption was 0.25 lb/ton (0.125 kg/t) of ore.

Essentially complete uranium recovery was obtained in the solvent extraction circuit. Three amine extractants were tested: a secondary unsaturated amine, a trilauryl amine, and a trifatty amine. The secondary unsaturated amine performed satisfactorily with a minimum amount of operational problems. Poor phase disengagement occurred when using the trilauryl amine, and the formation of a molybdenum–amine precipitate caused operating problems when the trifatty amine was used.

When the loaded secondary unsaturated amine was stripped with a sodium chloride solution and MgO was added to precipitate the uranium, the yellow cake product was found to contain 79.3% U_3O_8.

A material balance over the entire 87 day run, which included conditions not necessarily optimal, resulted in a theoretical uranium recovery of 94.2% compared with an actual recovery of 94.0%. Projections indicate that optimal conditions would result in an approximately 96% recovery.

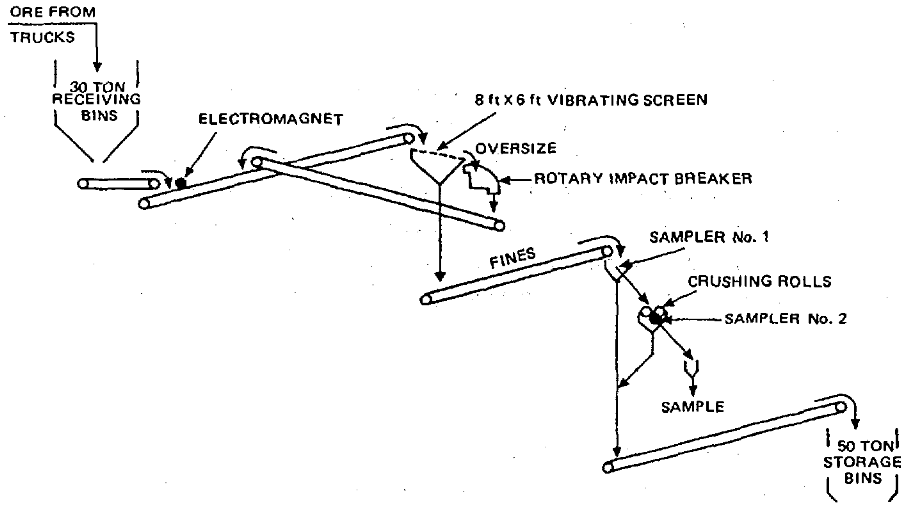


FIG. 5. Feed preparation plant (1 ton = 907 kg, 1 ft = 30.5 cm).

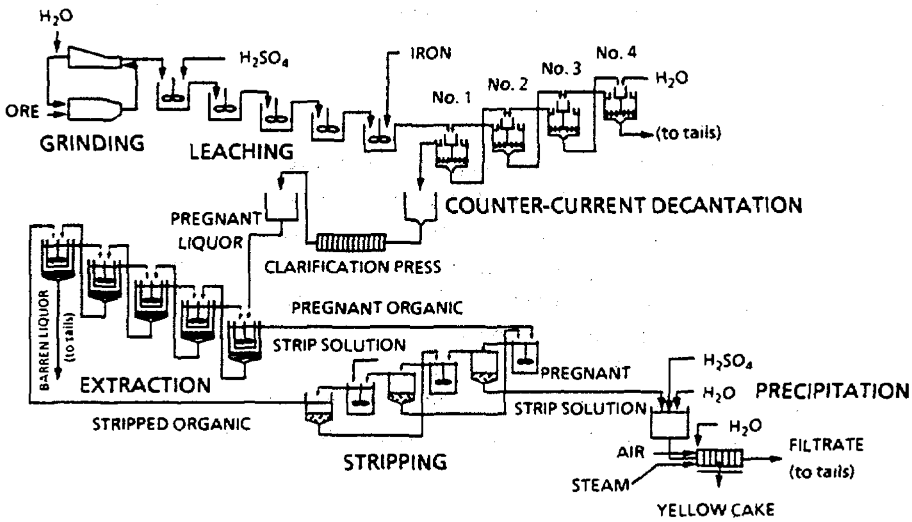


FIG. 6. Grinding–acid leach–CCD–solvent extraction–precipitation circuit.

I.2.1.2. Equipment description

The flow sheet for the feed preparation section is shown in Fig. 5. The flow sheet for the grinding, acid leach, CCD, solvent extraction, and precipitation operations is shown in Fig. 6.

Feed preparation and sampling

The 560 tons of sandstone ore were hauled to the pilot plant location in trucks. The 'as received' ore, which was approximately −6 in (approximately −15 cm), was dumped into the 30 ton (27 t) receiving bins, and then fed to the 24 in (61 cm) rotary breaker at a rate of about 10 tons/h (9 t/h). The product was approximately −3/16 in (approximately −5 mm). The roll crusher in the sampling section had a diameter of 10 in (25 cm) and 6 in (15 cm) wide rolls. The −3/16 in material was stored in five 30 ton bins and then hauled by truck to the grinding circuit feed bin.

Grinding

The −3/16 in ore was fed to a 3 ft × 5 ft (91.5 cm × 152.5 cm) ball mill that was operated in closed circuit with a 24 in (61 cm) spiral classifier. The feed rate averaged 6.5 dry tons (5.9 t) per day. Water was added to the ball mill to maintain a discharge density of approximately 1.6 and additional water was added to the classifier to maintain an overflow density of 1.4 (48% solids). The grinding circuit product was 99% −35 mesh (−0.417 mm) and 35% −325 mesh (−0.044 mm).

Leaching

The classifier overflow was pumped to the first of five 5 ft × 5 ft (152.5 cm × 152.5 cm) mild steel rubber lined tanks having 1.5 hp (1.125 kW) propeller type agitators. The feed rate to the leaching circuit was approximately 2.4 gal/min (~9 L/min). Sulphuric acid was metered to the first leach tank using an all plastic Denver type reagent feeder. The acid flow rate was controlled to give the desired pH in the fifth tank. When necessary an oxidant such as MnO_2 was added on the feed belt to the grinding circuit.

Provisions were also available for adding powdered iron to the fifth leach tank to adjust the EMF of the pulp. Disc type feeders were used for both applications.

Counter-current decantation

The pulp from the fifth leach tank was pumped to the first of five 12 ft × 8 ft (366 cm × 244 cm) rubber lined thickeners in the CCD circuit. Wash water was introduced to the fifth thickener at a rate of approximately 3.0 tons of water per ton of ore fed to the grinding circuit. The thickener underflows were pumped with air operated diaphragm pumps. The overflow from the first thickener was polished in a 1 ft × 1 ft × 3 ft (30.5 cm × 30.5 cm × 91.5 cm) stainless steel filter press. The clarified solution was fed to the solvent extraction circuit.

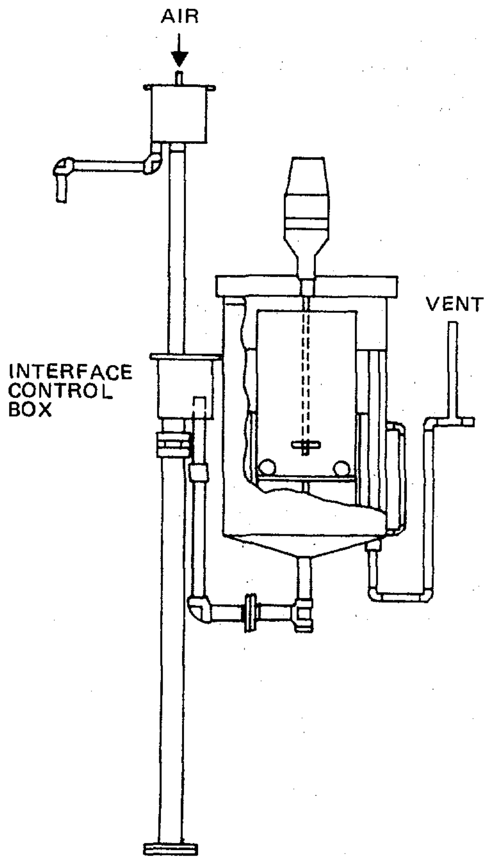


FIG. 7. Internal mixer-settler and airlift for solvent extraction.

Solvent extraction (loading)

The loading circuit was a five stage mixer-settler system, and the feed rate was approximately 4.3 gal/min (~ 16.3 L/min). This pilot plant used an internal mixer-settler system shown in Fig. 7. This system was adopted for at least one commercial uranium operation in the USA, but most plants chose to use solvent extraction systems with external mixer-settler arrangements. Each of the internal mixer-settler units consisted of an 11 in × 13 in (27.5 cm × 32.5 cm) mixer immersed in the organic phase of a 2 ft × 3 ft (61 cm × 91.5 cm) settler. Four 1.5 in (3.75 cm) holes in the side of the mixer near the bottom permit the aqueous-organic mixture to flow into the annular settling chamber. The aqueous to organic ratio in the mixer can be changed by varying the size of the holes in the mixer. The organic phase in the settler overflowed into a 1.5 in (3.75 cm) diameter standpipe. The aqueous phase underflowed through an adjustable jack leg into a 2 in (5 cm) airlift. The basic unit was constructed from 316 SS and plastic piping was used for all aqueous streams. Mixing was done by a 4 in (10 cm) diameter turbine type impeller powered by a 1/4 hp (188 W) variable speed electric motor.

Solvent extraction (stripping)

The solvent extraction stripping circuit used external mixer-settlers. Each of the four mixer-settler units consisted of two 12 in × 16 in (30.5 cm × 40 cm) cylindrical tanks constructed of polyester bonded fibreglass. One tank served as the mixer and the other as the settler. The mixer tank had four baffles. The mixer was connected to the settler by a pipe located 4 in (10 cm) from the bottom of the mixer. Each settler had an organic overflow standpipe located 3 in (7.5 cm) from the top of the settler tank. The aqueous phase underflowed through an adjustable jack leg. A sight glass was built into the side of the settler for observation of the interface level. The 4 in (10 cm) diameter turbine type impellers were driven by 1/4 in (0.625 cm) heavy duty drills connected to powerstats. A two row cascade system was used, with the mixers in one row and the settlers in another. The organic phase flowed by gravity, and airlifts pumped the aqueous phase from each settler to the next higher mixer. Plastic piping was used throughout the system. Two 6 ft × 6 ft (183 cm × 183 cm) rubber lined tanks were provided for strip solution make-up and storage. Each tank was equipped with a 3 hp (2.25 kW) mixer.

Solvent extraction (scrubbing circuit)

Since molybdenum was present in the leach liquors, a solvent scrubbing system was used to prevent significant amine losses as a result of the limited solubility of molybdenum-amine complexes. A one stage scrubbing circuit was provided. This mixer-settler unit had essentially the same dimensions as each of the four units in the stripping section.

Yellow cake precipitation

The pilot plant used batch type yellow cake precipitation. Two 6 ft × 6 ft (183 cm × 183 cm) rubber lined tanks were provided for the precipitation and pregnant strip solution storage. Each tank was equipped with a slow sweep agitator. When NaCl strip solutions were used, the pregnant liquor was precipitated by neutralizing to a pH of 7.0 to 7.2 by adding MgO. After precipitation the uranium was filtered on a 1 ft × 1 ft × 3 ft (30.5 cm × 30.5 cm × 91.5 cm) plate and frame filter press. The precipitate was washed with water, dried in a gas fired oven and packaged in small barrels. The 87 day run produced about 4000 lb (~1800 kg) of 79.5% U_3O_8 yellow cake from the 560 tons (~510 t) of 0.313% U_3O_8 ore fed to the pilot plant.

Appendix II

GENERAL AND RADIOLOGICAL SAFETY

Pilot testing of uranium ore involves risks that must be understood and guarded against. Two broad types of risk may be considered: general risks, common to most chemical plants, and radiological risks.

II.1. GENERAL SAFETY PRECAUTIONS

Most of the safety precautions that apply to a chemical processing plant also apply to a uranium pilot plant. Standard precautions against the following should be observed:

(a) Corrosive substances, such as sulphuric and other acids and caustic solutions.
(b) Explosive and flammable chemicals, including diluents and extractants used for solvent extraction.
(c) Dusts, especially ore dusts and uranium concentrate dusts.
(d) Chemical spills, including acids, leach solutions and other process pulps and liquids.
(e) Mechanical hazards, especially during the crushing, grinding and other handling of ores.
(f) Electric shock.
(g) Toxic or irritating chemicals. Virtually all chemicals used in the plant are toxic or irritating in some degree. Special care must be taken with liquids used in heavy media separations, extraction solvents and ammonia used for the precipitation of concentrates.
(h) Pressurized vessels, such as autoclaves. It is extremely important to study carefully and follow the manufacturer's instructions when using this type of equipment.
(i) Burns.

Overalls should be worn at all times. Appropriate safety equipment such as hard hats, face shields, safety goggles, gloves, respirators and hard tipped boots should be used as required.

II.2. RADIOLOGICAL SAFETY

The radiological risks in a uranium pilot plant are relatively small and can be easily controlled [23, 38, 39]. The main risks concern the inhalation of uranium ore dust and uranium concentrate dust. External irradiation and inhalation of radon and radon daughters are also possible although minor risks.

Substantial amounts of dust can be generated during sample preparation: crushing, grinding, splitting, screening, sieving and blending. Sample preparation rooms should be isolated from other areas and should be equipped with dust control systems such as hoods and filters. Access to these rooms should be controlled. The personnel preparing the samples should be properly attired with overalls, boots, gloves, dust masks and caps. Workers should also shower and change into their normal clothing before leaving the controlled area.

Inhalation of uranium concentrate dust is less likely because the amounts handled in the pilot plant are usually small, seldom more than a few hundred grams. Nonetheless, dry concentrates should be handled with care, especially during screening, blending or any other operation that can generate dust. These operations can be carried out under a hood or, better still, in a glove box. Appropriate attire should also be worn.

Radon and radon daughters normally are not a problem, provided that the plant is well ventilated. The risk of external irradiation is usually negligible, except perhaps when working with very high grade ores. It is advisable to check the level of radioactivity in the plant, especially in the sample storage room and in the area where uranium concentrates are stored. If the levels of radioactivity are significant, the risk can be controlled by limiting the residence time in these areas, although this time is likely to be small in any case.

Care should be taken to keep the plant clean at all times. Special care must be taken to clean up all spills of uranium bearing pulps or liquids. Surfaces such as bench tops and floors should be monitored regularly for possible contamination.

Eating, drinking and smoking must must not be allowed in any area of the plant.

II.3. SAFETY RULES

Safety rules, covering both general and radiological safety, should be drafted and put into effect. It is strongly recommended that specialized books on these subjects [40–42] be consulted.

Annex

BASIC DATA

The data listed below were compiled from laboratory tests and general information. These figures were used to calculate the mass balances in Tables I and II. Basic data are classified by sections.

A-1. GENERAL

Throughput, kg/h	200
Ore storage capacity, d	30
Average grade, g U_3O_8/t	1500
Average ore humidity, %	8
Specific gravity of the ore	2.7
Bulk density of the ore, g/L	1500
Maximum size run of mill, mm	200
Continuous operation, h/d	
— Comminution, leaching, solid–liquid separation, solvent extraction, effluent treatment	24
— Precipitation and thickening	8
Batch operation	
— Filtration and drying	

A-2. COMMINUTION

Bond index	14
Grinding size, Tyler mesh	−20
Solids in leaching pulp, wt%	55

A-3. LEACHING

Sulphuric acid ratio, kg H_2SO_4/t ore	60
Specific gravity of sulphuric acid	1.84
Grade of commercial sulphuric acid, %	98
Oxidant ratio, kg MnO_2/t ore	2.5
Grade of commercial pyrolusite, % MnO_2	80
Loss of weight in leaching, %	1.5
Leaching temperature, °C	50
Leach extraction, %	94
Tanks in series	6
Total retention time, h	12

A-4. SOLID-LIQUID SEPARATION

Washing ratio, m^3/t	3
Solids in thickeners underflow, wt%	50
Total dose of flocculant, g/t	80
Flocculant concentration, g/L	1
Number of thickeners	5
Flocculant distribution, %	
— First thickener	40
— Second thickener	30
— Third-fifth thickeners	10
Unit area, $m^2 \cdot t^{-1} \cdot d$	0.4

A-5. EXTRACTION

Organic phase	
— Amine, vol.%	3
— Alcohol, vol.%	3
— Kerosene, vol.%	94
— Specific gravity	0.8
— Saturation capacity, g U_3O_8/L	3.5
— Loading, % of saturation capacity	85
Raffinate, g U_3O_8/L	0.001
Phase ratio in mixers, A/O [a]	1.5
Phase ratio in settlers, A/O	1.0
Number of stages	4
Retention time in mixers, min	0.5
— Settler unit area, as referred to the organic phase, $L \cdot min^{-1} \cdot m^2$	25
— Retention time of the organic phase in settlers, min	20

A-6. STRIPPING

Concentration of aqueous extract, g U_3O_8/L	20
Uranium concentration in stripped organic phase, g U_3O_8/L	0.120
Stripping agent	
— Ammonium sulphate, mol/L	2
— Ammonia gas, kg NH_3/kg U_3O_8	0.45
Number of stages	4
Phase ratio in mixers, A/O	1.2

[a] A/O: aqueous/organic.

Phase ratio in settlers, A/O	1
Retention time in mixers, min	5
Retention time of the organic phase in settlers, min	20
Settling unit area, as referred to the organic phase, $L \cdot min^{-1} \cdot m^2$	25

A-7. PRECIPITATION

Temperature, °C	35
Ammonia dose, kg NH_3/kg U_3O_8	0.2
Tanks in series	3
Total retention time, h	1.5
pH distribution in tanks	
— Tank 1	5.0
— Tank 2	6.5
— Tank 3	7.5
Ammonia distribution in tanks, %	
— Tank 1	75
— Tank 2	20
— Tank 3	5
Grade of concentrate, % U_3O_8	85
Specific gravity of concentrate	4.5
Uranium concentration in mother liquors, g U_3O_8/L	0.004

A-8. THICKENING

Number of stages (thickening and washing)	2
Flocculant dose in thickening, g/m^3	10
Flocculant dose in washing, g/m^3	5
Flocculant concentration, g/L	1
Solids in thickeners underflow, wt%	25
Washing ratio, m^3/t	20
Unit area, $m^2 \cdot t^{-1} \cdot d$	0.3

A-9. EFFLUENT TREATMENT

Neutralization reagent	Milk of lime
Milk of lime concentration, wt%	20
Specific gravity of milk of lime	1.18
Grade of lime, % CaO	70
Lime dose, kg CaO/kg H_2SO_4	0.6
Solids increase, kg solids/kg H_2SO_4	1.75

A–9.1. Pulps

Equivalent acidity in the pulp, kg H_2SO_4/t	0.2
Specific gravity of generated solids	2.7
Tanks in series	2
Retention time, h	2

A–9.2. Liquids

Equivalent acidity in the liquids, kg H_2SO_4/m^3	12
Barium chloride dose, g $BaCl_2/m^3$	20
Barium chloride concentration, g/L	100
Tanks in series	2
Retention time, h	2

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