Storage and disposal of reprocessed high-level (radioactive) waste: economic optimization

by

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HLW - High-level (radioactive) waste

SF - Spent (nuclear) fuel

PWR - Pressurized water reactor

BWR - Boiling water reactor

LWR - Light water reactor

HTGR - High temperature gas reactor

LMFBR - Liquid metal fast breeder reactor

LL-TRU - Low-level - Transuranic waste

IL-TRU - Intermediate-level - Transuranic waste

TRU - Transuranic waste

MWe - Megawatt electric

MWD - Megawatt-day

MT - Metric ton

MTHM - Metric ton of heavy metal

KHM - Kilogram of heavy metal

AR - At reactor

AFR - Away-from-reactor

F.P. - Fission Products

DR - Discount rate

VNF - Very-near-field (thermal loading)

NF - Near-field (thermal loading)

BU - Burnup

I. INTRODUCTION

A. Statement of the Problem

The present study is the development of an economic model of the back end of the nuclear fuel cycle. Within political and social constraints, a feasible pathway leading to optimal solutions will be sought.

In recent years, the nuclear industry has generated considerable amounts of highly radioactive nuclear spent fuel (SF). Part of this SF, primarily generated in Europe, has already been reprocessed to recover fissile and fertile materials, giving rise to so called "high-level (radioactive) waste" (HLW). The quantities of SF and HLW are expected to be greatly increased in the next few decades, for the amount of nuclear electricity being generated is growing rapidly.

Because high-level radioactive wastes are hazardous materials, final disposal has become a matter of special concern. To deal with fears that this aspect of the nuclear industry is not being adequately managed, a determination about isolation of HLW from the environment must be taken in the inmediate future. Many factors will come up in deciding the final procedure to be used in the different steps involved in the management of SF and HLW. Some considerations are likely to exert a strong influence in the final decision, such as safety factors, public acceptance, political constraints and economic impact.

The goal of the present work is to obtain some conclusions about the two final steps of HLW management (temporary storage and permanent disposal) based on an economic optimization of a parametric model. These conclusions can help in decision-making about the final steps of the back end of the nuclear fuel cycle.

B. The Back End of The Nuclear Fuel Cycle: Model and Parameters

The back end of the nuclear fuel cycle starts when the SF is discharged from the reactor and concludes with the burial of HLW in an underground repository. In the model assumed in this study, which is presented in Chapter III, four main steps are identified, i.e., cooling down of SF at the reactor site, reprocessing of SF and solidification of HLW, temporary storage of HLW and permanent disposal of HLW.

It is a common practice to store the discharged spent fuel at the reactor site for a certain period of time. This allows the radioactivity to decay to a more suitable level for transportation and reprocessing. This cooling time period for SF (delay of reprocessing) turns out to be an important parameter. From an economic standpoint, the determination of the cooling down period is strongly linked to the costs associated with the subsequent stages, especially with transportation and reprocessing. If the value of the recovered fuel in this last process is found to be higher than the cost of transportation and reprocessing, the time of cooling down the SF should be minimized. Otherwise, reprocessing should be delayed as long as possible. However, the HLW temporary storage, disposal and transportation costs are increased by reducing the time of SF cooling down, because of the higher heat generation rates and radioactivity levels. Therefore, the delay of reprocessing should be determined from an optimization of the whole fuel cycle, leading to a minimum feasible cost. Nevertheless, it is probable that the time of cooling down the SF at the reactor site will be limited for political and safety reasons rather than on economic grounds.

The spent fuel still contains considerable amounts of fissile and fertile nuclides that can be reused as nuclear fuels. The principal objective of reprocessing is to recover these isotopes. The radioactive constituents of SF after most of the fissile and fertile materials have been separated, form the high-level wastes. The United Kingdom and France have already incorporated reprocessing as a part of their fuel cycle and it is assumed to take place in the present model.

The HLW so generated is in a liquid form as a solution of fission product nitrates in nitric acid, which is not considered safe enough for long-term isolation from the environment. The liquid HLW is therefore converted into a solid form, more suitable for permanent disposal. Two main goals are reached with the solidification process: reduction in volume and safer immobilization of the radioactive nuclides. Among several alternatives for the solidification product, glass matrices seem to be the preferred choice, with borosilicate glasses promising the best performances in long-term stability and immobilization of radionuclides.

The purposes of the temporary storage of HLW are to allow monitoring of the canisters for possible leakages or thermal instabilities, and to let them cool down enough to achieve better densities of disposal. As with the spent fuel cooling down, the period of HLW storage is a very important parameter for all considerations. Particularly, in the economic sense, this time becomes a key variable for the optimization of the back end of the nuclear fuel cycle. As the cooling down time of HLW increases, the heat generation rate decreases. For given thermal properties of the mined repository materials, higher disposal densities (units of mass of HLW disposed per unit volume excavated) can be reached with lower heat generation rates. Since the repository will be a very expensive facility, long periods of cooling down might reduce significantly the excavation costs per unit mass of HLW buried and, more important, the costs of the repository will be deferred. But the cost of the temporary storage would increase proportionally to the time of storage, especially because of the need for a larger capacity facility. This time of cooling down the HLW should be determined, therefore, by minimizing the combined costs associated with both stages. Political limitations on the period of HLW storage can also be expected, although the maximum permissible time is likely to be much longer than the limiting time for storage of SF at the power plant site.

The final disposal of HLW will be performed in a deep underground repository, excavated in a very stable geologic formation. This is nowadays the worldwide accepted method, and research on that concept is being done in all countries having a developed nuclear industry. Several geologic formations are being studied as possible locations for a repository, such as salt, tuff, granite and basalt, both because of their national interest and availability and for the impact of their properties on repository design. Many factors will play their roles in the repository economics. These factors can be grouped into two principal sets of data and parameters, i.e., those related to the HLW properties and those connected with the repository characteristics.

C. Economic Optimization of the Back End of the Nuclear Fuel Cycle

A complete optimization of the back end of the nuclear fuel cycle would require dealing with all the variables and parameters involved in each stage. Moreover, the results of the optimization of the back end of the cycle could be incorporated into the complete reactor fuel cycle, for possible alterations of burnup rates or power levels leading to lower total costs. This kind of study would involve many uncertainties. It is not decided yet if reprocessing must be done, and, in the affirmative case, when it should be carried out. The reprocessing and solidification methods, which can alter the composition and properties of the HLW, are other unresolved questions in the process. A suitable geologic formation and a final configuration for the repository have not been selected. Decisions about all these subjects will probably be taken for political, social and safety reasons in addition to economic ones.

The analysis of the whole back end of the nuclear fuel cycle, involving all those uncertainties, is beyond the scope of the present work. However, the linkages required to undertake such an analysis will be specified. The part analyzed in this study relates to the last two stages of the model described; the temporary storage and the permanent disposal of the HLW.

Several assumptions must be made, within the proposed model, for characterization of the remaining steps of the back end of the fuel cycle, as well as for defining the repository data. First of all, a certain period of cooling down the SF at the reactor site is to be specified. This time sets the radiation and thermal properties of the HLW after the SF has been reprocessed. The physical characteristics of the HLW glasses are inferred from the assumed methods of reprocessing and solidification. A standard HLW canister is also assumed, according to the prototypes that have already been developed. The properties of the waste to be disposed of provide the first set of input data for the economic model. A second set of data comes from assuming some design characteristics for the temporary storage and repository facilities. A generic site is selected and the capacity, geometry and auxiliary systems for both stages are defined. Selection of the material excavated includes the determination of its thermal properties, which are very important in setting the allowable densities of disposal. The design characteristics and their relation with the costs incurred in the last two steps of the fuel cycle, are analyzed in Chapter IV. Finally, the model is provided with data concerning volumes, capacities and schedules for the process. These data are derived from the scenario that is developed for the first repository (Chapter III), which is the object of the optimization analysis.

In defining all the input data, state of development, requirements and political constraints expected at the present time are considered. These sets of information are linked to the economic model, presented in Chapter V, where the costs for the basic operations are estimated and introduced as parameters. The economic model is used to search for a least cost situation for the storage and disposal of HLW under the assumed situations and characteristics. The principal parameter to vary in the optimization process is the time of temporary storage.

For the input parameters supplied, the results of the optimization are, principally, the optimum time of temporary storage, the estimated cost of storage and disposal per unit mass of HLW, and per unit mass of SF and the total cost of the operations for the entire scenario (Chapter VI). The accuracy of the results depends on the quality of the information available to estimate the costs of the different processes involved. The analysis so developed is based on a parametric model and the input data can be easily modified. The purpose of this methodology is to validate the model under different circumstances than those assumed. As input information improves, the model can still be used to generate finer results, in accordance to the new situations considered. The model developed is used to analyze different alternatives and its sensitivity to several varying parameters is also studied.

This economic model can be used as a method of comparison between different hypothesis or situations. Different excavated materials or repository concepts can be compared on the basis of costs of temporary storage and permanent disposal that they would generate.

II. LITERATURE REVIEW

The commercial nuclear power industry has been successfully operating for about 30 years. However, in order to achieve full credibility and public acceptance, the nuclear industry must find a permanent solution to the problems involved in radioactive waste management [1], which would complete the nuclear fuel cycle. Consequently, a lot of research has been done in the field of nuclear waste management. To complete the fuel cycle, two groups of options have been proposed, the once-through cycles and the recycle (closed) cycles [2]. A closed fuel cycle is already being commercially used in several countries, such as France [3, 4], Japan and United Kingdom [3, 5]. The U.S. has not decided yet whether to apply a closed cycle or a once-through one. Although the decision might be taken for political or social reasons, research on reprocessing (and closed fuel cycles) is being done [6, 7]. Independently of what the decision will turn out to be, the U.S., as established in the Nuclear Waste Policy Act of 1982, is committed to completing the back end of the nuclear fuel cycle, by disposing SF or HLW in an underground repository, no later than 1998 [8, 9, 10].

A closed cycle, whose back end comprises storage and reprocessing of SF, solidification of HLW, temporary storage and final underground disposal of HLW is the most common design proposed for LWR fuels [3, 11, 12]. This is the concept of back end of nuclear fuel cycle that is adopted in this work. Adequate technology is currently available to perform all the steps involved in this model for the back end of the fuel cycle [4, 11, 12].

Many publications exist analyzing some of the technical aspects involved in the back end of the nuclear fuel cycle. The storage of SF is currently being carried out and much experience has been gained during the last decades [3, 13-16]. Reprocessing is also a known technology and was commercially performed in the U.S. from 1966 to 1972 [3]. Currently, spent fuel reprocessing plants are operating in France, Japan, West Germany, USSR, and the United Kingdom [3, 17, 18].

The solidification of HLW after reprocessing of the SF is a relatively new process and it is only taking place at a commercial scale in France [4, 19]. However, extensive research is being done in this field in several different countries, especially the United States and the Federal Republic of Germany [20, 21, 22]. Different alternatives (mainly ceramic and glass matrices) have been developed for the solidification HLW product [21, 23, 24] and the characteristics of the most promising solid matrix (borosilicate glasses) are well-defined [21].

Temporary storage of HLW is also the object of research and development. Different options are already open to perform this operation [3, 25, 26]. Many of the technical concepts that are being used or have been proposed for storage of SF are also acceptable for the storage of the HLW, because of the similarity of the processes. The disposal of HLW (or alternatively, SF) in an underground repository is probably the step in the back end of the fuel cycle that has stimulated the highest number of analyses and conceptual designs. The underground disposal of HLW/SF has been studied in the U.S. since the late 1950s [8, 25] and later in other countries, too, particularly in West Germany [3, 27]. Many different aspects of an underground repository for HLW/SF, such as geometry, thermal loadings, geologic feasibility and stability, and environmental impact, have been studied for different rock types [25, 27-39]. Also, some pilot repositories have already been developed to conduct research and on-site tests [3, 25].

Since high cost processes are involved in the back end of the nuclear fuel cycle, a lot of attention is also being paid to the economic aspects involved in all the steps. Generally, the economic studies developed so far, analyze one of the processes or operations of the back end of the fuel cycle. Such is the case in several economic analyses of spent fuel storage [13, 40-42]. The U.S. Department of Energy recently published a comparative study [43] for comparison of the different options available to carry out the SF storage. This study is based on previous cost analyses performed by DuPont, AGNS, IAEA, GE, TVA, Sweden, Bechtel, and Stone and Webster. A relationship between the cost of storage and the maximum capacity of the facility is presented and confirmed in this document. This relationship, modified for HLW, is used in the present work.

The cost of disposal (or the cost of an underground repository) has also been studied by different authors [30,44] and the analyses are usually based on disposal of SF. A particularly interesting analysis was developed by Forster [37]. Forster compared the costs of disposal predicted by 6 different previous analysis, involving many different situations. He performed a sensitivity analysis of the costs of disposal with respect to different parameters, finding that the discount rate was the most important of them.

Some studies include the entire back end of the nuclear fuel cycle. Frank [45], gives some rough estimates of the cost of the different processes and operations. A more detailed analysis of the different costs involved in the back end of the fuel cycle, comparing different options for most of the operations, is found in a document released by the Department of Energy [25].

Other authors have studied a particular aspect of the economics of SF/HLW disposal or have analyzed the influence of certain parameters on the final cost. Recent studies have been performed to study the impact of the HLW canister length on the final cost of the repository [46], variations in cost due to changes in repository thermal design limits [47], and the influence of TRU waste on the repository cost [48].

Some computer models have been also developed for analyzing the costs of an underground repository. The most recent computer codes were developed in 1983; a simplified model was created by Henry [49], and a more sophisticated model, which includes many details, was prepared by Clark et. al. [50]. In this later model, the costs of the repository are split into many different items, and very complete information must be supplied by the user in describing the specifications.

In the document published by the Department of Energy [25] concerning the back end of the fuel cycle, it is pointed out that the period of storage of HLW before disposal takes place could be varied in order to achieve a least cost situation for the storage and disposal operations. Becker and Varadarajan [51] have formulated a semianalytical formulation of the waste aging problem. They state the problem, pointing out the advantages or disadvantages of aging the HLW before disposal, and propose a criterion for the optimization of the costs of storage and disposal. Their conception of the aging problem is followed in this work, in trying to couple together a model for the disposal costs with the effects produced by aging the HLW on the disposal system costs. A similar criterion for the optimization process is used in the program developed in this work.

III. THE BACK END OF THE NUCLEAR FUEL CYCLE

Before analyzing any cost issue involved in the back end of the nuclear fuel cycle, it is necessary to describe the model adopted for such an analysis. The characteristics of the different stages and operations undergone by the SF or HLW are defined and justified in the present chapter. Once the model is defined, the expected scenario for the first repository is described.

Both the model and the scenario are presented for commercially generated SF and HLW. Moreover, all the SF is considered as being produced in light-water reactors. (In September, 1983, there were 74 commercial power reactors in the U.S.A.: 48 PWRs, 24 BWRs, 1 HTGR and 1 graphite-water reactor [52].)

A. Model for the Back End of the Fuel Cycle

Several changes in the composition of the fuel occur as it is irradiated in a nuclear reactor. The most important changes concern the consumption of fissile material, the build-up of neutron absorber fission products and the formation of some new actinides (Uranium and Plutonium isotopes, primarily). These changes in composition bring about changes in reactivity, which eventually decreases [2]. Radiation effects on the fuel element structural material together with the changes in fuel composition, limit the utilization of the nuclear fuel to a certain burnup. When this limit is reached, the fuel elements are discharged from the reactor and become (nuclear) spent fuel. This is the starting point of the "back end" of the nuclear fuel cycle.

Two main alternatives has been proposed for the fuel cycle regarding its back end. The simplest treatment is the so-called once-through cycle, in which the SF discharged from the reactor is not recycled at all. This handling was considered appropiate for natural Uranium fuels (Candu and Magnox reactor types), with low fuel burnup and low formation of new fissile materials. It has been argued that the recovery of fissile and fertile materials is economically disadvantageous in this type of fuel [2]. Therefore, the back end is designed to dispose of the SF, after consolidation of the fuel assemblies (for volume reduction) and appropiate cooling down.

The other proposed alternative, the "closed" cycle, was originally suggested for LWR reactor fuels. The LWR fuel is slightly enriched (3%) and can reach higher burnup rates. The fertile and fissile materials contained in the SF are both at a significant concentration. These can be recovered by reprocessing and reused as fuel in either fast or thermal reactors. The value of the recovered fuel will pay for at least part of the cost of reprocessing and F.P. separation, and also, the cost of disposal of the waste can be decreased. This cycle permits a much better utilization of the original uranium that is mined. When this cycle is adopted, the HLW is formed as a byproduct of the reprocessing operations [53].

In the present study, the closed cycle has been adopted as the most reasonable to take place in the U.S.A., where almost all the reactors are LWR. Figure 1 diagrams the closed LWR fuel cycle. The different steps considered in the back end of this process are shown in Figure 2. This diagram is based in the present French system, which has already been developed up to the stage of solidification of the HLW [4,19]. According to this system, the cooling down of the SF, after it is discharged from the power reactor, is done at the reactor sites. The rest of the operations are assumed to take place in two different areas, namely, the reprocessing plant site and the disposal site. The operations that take place in the first site are the AFR (Away-From-Reactor) storage of SF, if necessary, the reprocessing of SF and the solidification of HLW. The facilities located at the second site are the temporary storage facility for HLW and the repository. In the U.S.A., this "two-site" concept might be converted into a single site, so that the facilities at the reprocessing plant site would be located at the disposal site. The purposes of this single site scheme would be to minimize the transportation risks and costs.

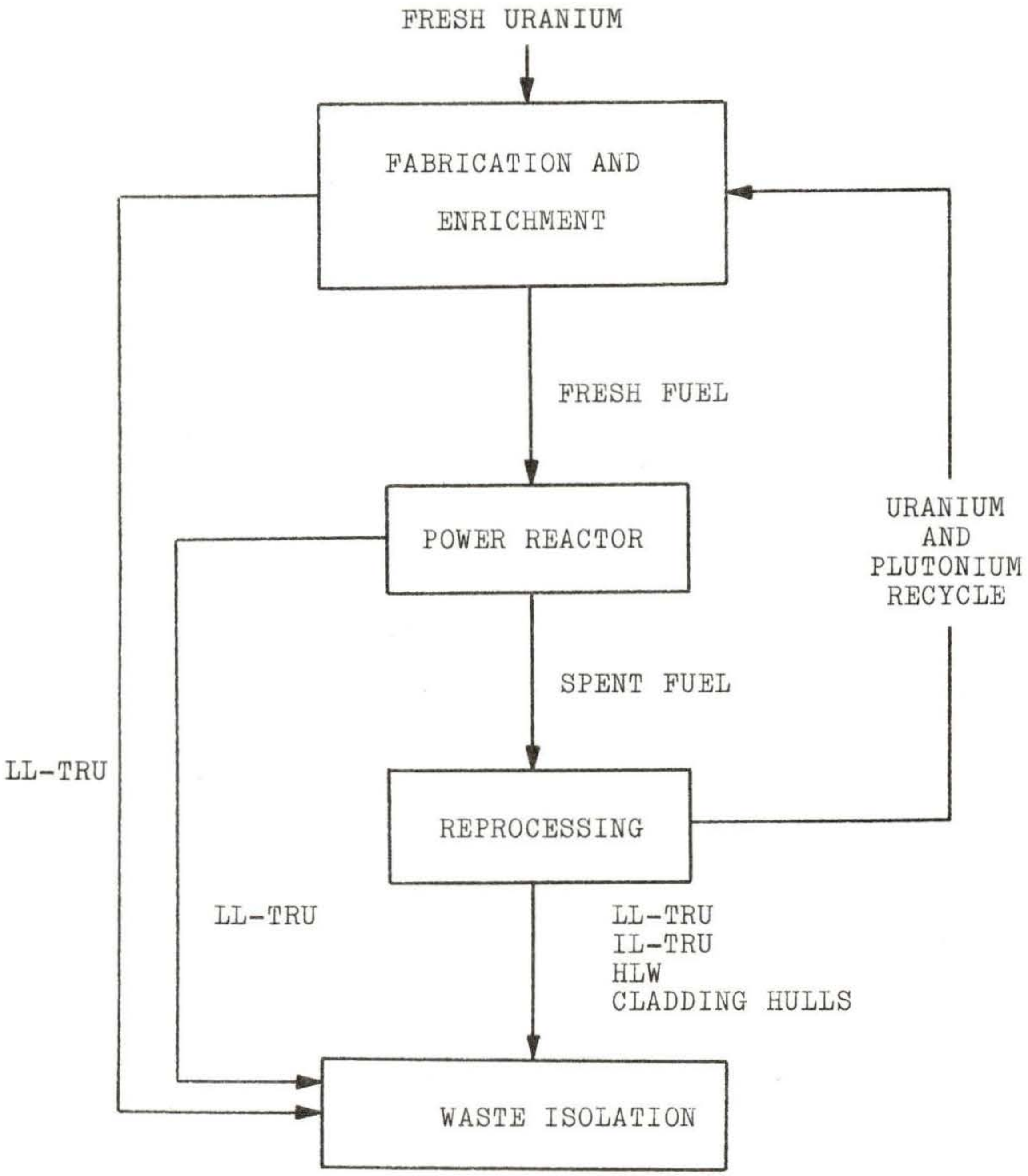

Figure 1. LWR closed nuclear fuel cycle

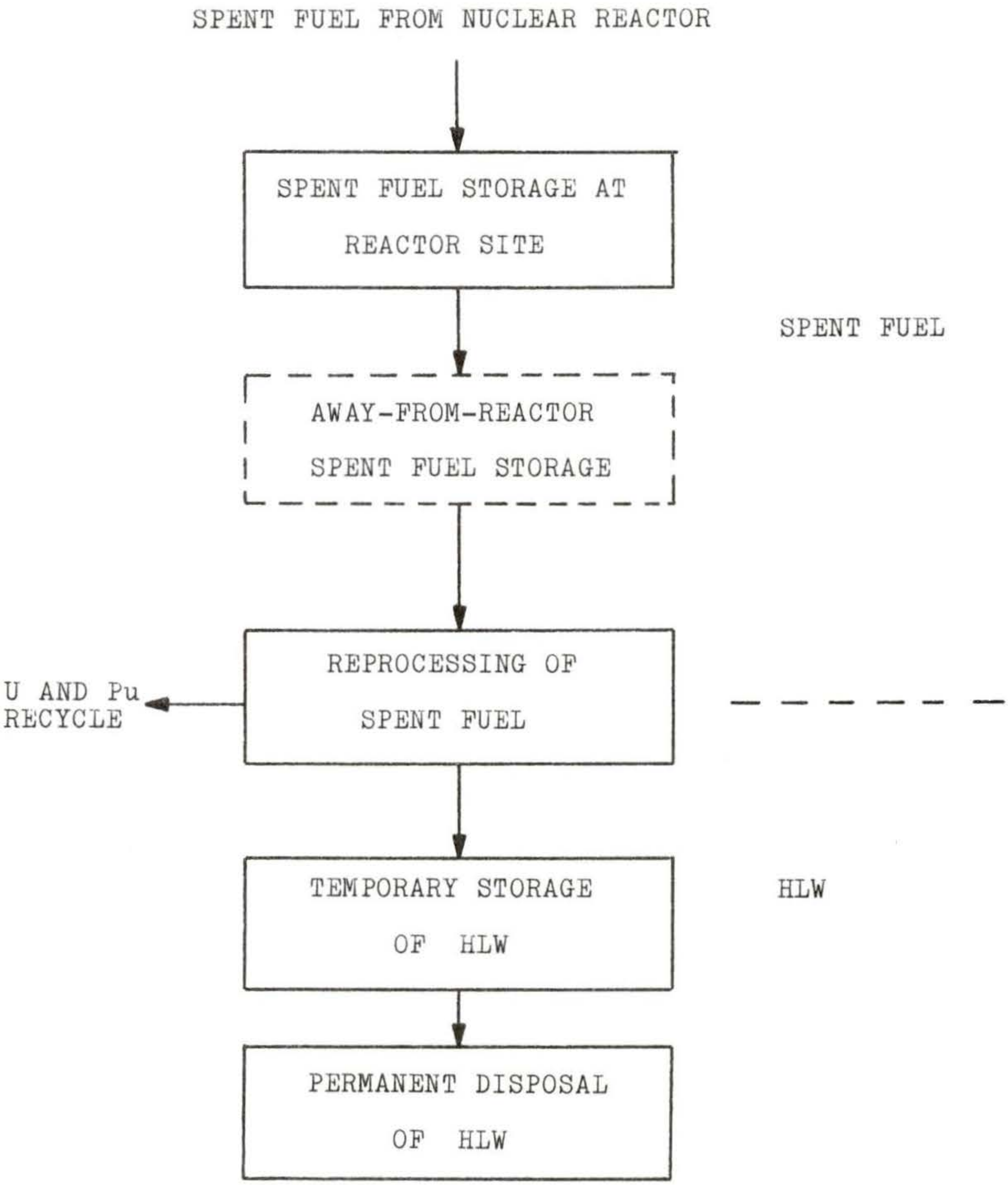

Figure 2. Back end of the closed nuclear fuel cycle for LWR

Transportation of SF or HLW is an expensive process, because of the safety (cooling, shielding and security) measures that must be taken [54]. Therefore, once the disposal site is chosen, the location of the other facilities should be decided in order to minimize transportation requirements. However, other factors must also be taken into account, such as the distance to the power plants, population in the area and situation of the fuel fabrication facilities. It is accepted that a low population area is mandatory for the repository site and it is preferable for the reprocessing facilities location.

B. Cooling Down of Spent Fuel

When the SF is discharged from the power reactor, the radioactivity level and the decay power are still very large. For example, one month after shutdown, the decay power amounts about 0.1 % of the rated reactor operating power [55], which for a 1000 Mwe LWR reactor, turns out to be about 30 Kw per MTHM. If adequate cooling is not provided, this large decay heat can cause overheating and, ultimately, melting of the fuel elements. It is the current practice to store the discharged SF in water pools located at the power plant site. The SF is cooled down in those pools, while awaiting reprocessing. The time of cooling down the SF becomes a key parameter for the economic analysis of reprocessing, and, in turn, for the economic optimization of the entire back end of the fuel cycle.

Countries such as United Kingdom and France, with reprocessing already incorporated in the back end of the cycle, are currently using cooling periods of 150 days and 1 year before reprocessing for metal and oxide uranium fuels respectively [3, 17]. The Soviet Union is reprocessing LWR SF after a delay of 3 years [17]. By aging the SF before reprocessing, some gains are obtained, because of the decrease in radioactivity and heat generation rates. First of all, the transportation, when the SF is taken to the reprocessing plant after the cooling period, will be safer and cheaper, requiring less shielding and cooling. For the same reason, the reprocessing costs are also likely to be lower. For lower radiation and heat generation levels, the extraction ratios of uranium and plutonium will presumably be higher, adding a new incentive to cool down the SF for longer periods than those currently practiced.

In deciding an optimal period for cooling the SF before reprocessing, its economic effect on all next stages of the back end of the nuclear fuel cycle should be considered. However, as a first approach, it could be decided in accordance to the current situation of reprocessing and demand of fuel. If the demand for mixed oxides or LMFBR fuels were very strong, the value of the recovered actinides during reprocessing could be higher than the cost of reprocessing and this situation would recomend reprocessing as soon as possible, thus reducing the cooling down period. Otherwise, in the case of reprocessing costs exceeding the value of the plutonium and uranium recovered, long periods of cooling down the spent fuel would be advisable. Other reasons, such as political limits for minimum and maximum cooling periods, or limited storage capacity, can also affect the decision about the delay of reprocessing.

The decay power decreases at a relatively fast rate during the first ten years after discharge and decreases at a slower pace after this time [56]. Therefore, the advantages obtained by aging the SF before reprocessing, will be very sensitive to the time of cooling during the first 10 years, and its dependence will be reduced for times longer than 10 years. In other words, the gain obtained by delaying reprocessing for one more year will be relatively small when the SF is already older than 10 years. The SF storage capacity provided in most of the current power plants is sufficient to accumulate SF for 10 years delay of reprocessing [57]. The storage capacity can be considerably increased by adopting the already developed reracking techniques [40]. For these reasons, 10 years turns out to be a very reasonable time for cooling down the SF before reprocessing and in this work it is assumed as a standard when postulating scenarios and estimating the required reprocessing capacities to be installed.

In the United States, because of the large backlog of SF awaiting reprocessing [13], the cooling down period will be even larger than 10 years for all the currently existing SF and for that generated in the immediate future. In particular, according to the scenario proposed in the present work (Section G), the age of the SF reprocessed for the first disposal site will range between 25 and 12 years, assuming that reprocessing starts at year 2000. With such a long period of cooling down (25 years) some of the SF, a shortage in storage capacity can be expected. Even though reracking techniques are being used, some additional facilities may be required for storing ths SF. These facilities are commonly called AFR storage facilities and they, too, could be located at the reprocessing plant site, to avoid additional transportation of the SF. According to the Nuclear Waste Policy Act of 1982, the United States Government may provide up to 1,900 MT capacity for storage of SF in AFR facilities [10].

C. Reprocessing of Spent Fuel

Most of the U-238 and 35 to 40 % of the U-235 loaded into a LWR reactor is still in the discharged SF. In addition, the SF contains considerable amounts of Pu isotopes that were built up during the life of the fuel. These fertile and fissile materials in the SF can be recovered, by reprocessing of SF, and reused as reactor fuels [2, 3].

Reprocessing is considered a known technology. The United Kingdom, France and the Soviet Union have incorporated full-scale reprocessing as a standard operation in their fuel cycle [3, 17, 18]. Other countries, such as Japan and the Federal Republic of Germany are currently operating relatively small plants, preparatory to initiating full-scale reprocessing [3, 17].

Commercial reprocessing was done in the U.S. from 1966 until 1972, when the West Valley facility was shut down [3]. Currently, the back end of the fuel cycle in the U.S. consists only of the first stage, that is, the cooling down of SF.

By incorporating the reprocessing of SF as a normal step in the fuel cycle, significant advantages are obtained. First of all, the fertile and fissile materials from the SF are recovered, which permits a much better utilization of scarce supplies of uranium. Moreover, new options are created for the nuclear industry, such as the use of mixed U-Pu oxide fuels in LWR or combined cycles with fast breeder reactors [53]. By adopting the once-through cycle and disposing of the SF directly, a valuable energy source is definitely lost and the period of availability of relatively low cost uranium is considerable shortened.

Other advantages provided by reprocessing concern the safety and economics of waste disposal. Solidified HLW glass is a safer form than SF for long term disposal of radioactive materials, because it is less leachable by water and because it has a higher maximum allowable temperature [33]. The maximum permissible temperatures in SF are about 200 C, whereas temperatures up to 500 C can be tolerated in HLW glass. Also, the disposal of HLW can yield considerably lower costs then the disposal of SF, because it would require smaller excavated volumes per unit of power installed. The reasons for this, are:

1. There is a reduction about 70 % in mass, and even more in volume.
2. The canisters of HLW can be stored closer to each other than the canisters of SF, because of the higher maximum temperatures allowable in HLW. The area of the waste repository is therefore reduced.
3. The canisters of HLW are about 1 meter high [26], whereas the SF canisters are longer than 4 meters, requiring higher disposal rooms in the repository.

The savings in disposal costs obtained by disposing of HLW instead of SF might even compensate for the costs of reprocessing the SF, adding a new incentive for reprocessing. Because of the advantages just noted, reprocessing is assumed, in the present work, as a logical step in the back end of the fuel cycle.

Several reprocessing methods for SF have been developed since the 1940s. By now, the most successful method is a solvent extraction process, called Purex, that was first put into operation in the U.S. [3]. The Purex process is being used at reprocessing plants currently operating in France, United Kingdom, the Soviet Union, West Germany and Japan [3], as well as at military production facilities in the U.S.

With the Purex process, efficient extraction of U and Pu from the SF is achieved. For long periods of cooling down the SF before reprocessing, the recovery of U and Pu could be as high as 99.5 % of the total mass of these materials, and this will be the figure assumed in the present model. Essentially, 100 % of the noble gases and about 99.9 % of the bromine and iodine are released from the bulk of the waste during reprocessing [3, 56]. The remainder of the SF, composed mostly of the fission products, but including some structural materials and the unrecovered actinides, form the high-level radioactive waste.

D. Solidification of the HLW

1. The solidification process

The HLW generated in the reprocessing plant is in the form of fission product (and actinide) nitrates dissolved in nitric acid [3, 21]. Immediately after reprocessing, this acidic solution is stored in stainless steel tanks that require corrosion (or leaking) monitoring and cooling. This storage form of HLW is not suitable at all for transportation and long term isolation of the radioactive materials from the environment [21]. A safer form for the HLW is required for the inmobilization of those hazardous materials. The universal choice is to solidify the HLW into a product that ensures the long term fixation of the waste, especially of the long-lived radionuclides [21]. Different alternatives have been studied for the solidification product and special attention has been given to calcine and glass forms, the latter being considered as the more reliable one to provide an effective barrier to the release of radioactive products [21, 22].

For short periods after the SF is discharged from the reactor (less than 5 years), some problems could arise in the solidification of HLW into a matrix form. For the usual concentrations of waste in the glass and the usual expected sizes of the glass blocks, because of the large heat generation rates for short periods after discharge, the solidified product could suffer overheating, leading to some devitrification of the internal parts [3]. For HLW generated from SF reprocessed at short times after discharge, a period of storage in solution in steel tanks before solidification takes place would be in order, until the heat rates reach more suitable levels for solidification.

If the SF reprocessed is already older than 10 years, as was suggested in Section B, the solidification of the HLW can take place immediately, thus suppressing the storage in steel tanks. This gives an advantage from the safety standpoint, since the risk of releasing radioactivity materials to the environment is much lower for a solidified product than for the acidic solution.

The process for immobilizing the waste in a glass form is carried out by melting the waste oxides together with the components of the glass. The waste oxides are obtained by calcining the acidic waste solution, releasing water, nitric acid and nitric oxides, and leaving the fission products and actinides in oxide form [3].

2. Characteristics of the HLW glass

Different types of glass have been studied as matrices for the solidification product, and borosilicate glass is the one that is currently accepted worldwide as the best choice [21, 58]. Borosilicate glasses are preferred, because of their high resistance to dissolving by water. The drawback of the glasses is the possibility of devitrification, which leads to products that can behave quite differently from the initial glass. However, for small diameter glass blocks, (less than 50 cms.), proper cooling is easily achieved, so that devitrification does not represent a major risk. Borosilicate glass presents the desirable characteristics of chemical, mechanical and radiological stability for long term immobilization of the radioactive waste [21]. Thermal stability is also obtained for temperatures not exceeding a temperature limit set to avoid devitrification. For a typical borosilicate glass, this temperature limit is found to be around 500 C [21].

Commercial solidification of HLW is currently being performed in France, using a borosilicate glass. A typical composition of this borosilicate glass, as used in Marcoule (France), is given in Table 1.

Table 1. Composition of the HLW borosilicate glass used in Marcoule (France) [21]

Component	Percentage (by weight)
Silica	49.
Boron oxide	13.
Sodium oxide	8.
Aluminum oxide	5.
Waste oxides	25.

The maximum concentration in waste oxides that a glass can have is limited for chemical reasons (phase separations) [3]. The upper limit in most of the studies is around 25 to 30 % by weight [21]. Since the HLW is formed by F.P. oxides, actinide oxides and structural (and corrosion product) materials, the composition assumed in the present work is of 25 % by weight of waste (F.P. and actinides) oxides and up to 5 % by weight of corrosion and structural material oxides. 25 % of waste oxides corresponds to approximately 13 % by weight of fission products (slightly dependent on BU). The corrosion materials are not set at an exact concentration because their contribution to the decay heat is negligible [56], and they are not important for the purposes of the present work.

The solidification product is obtained in the form of cylindrical glass blocks. The dimensions of the glass block vary from one experiment to another. The diameter is usually taken around 30 cms. [36, 46] to avoid very high temperatures in the centerline that could lead to devitrification. It is assumed here that the dimensions are 35 cms. in diameter and 1 m. in length, to facilitate the operations in the repository. The volume, under this assumption, would be 0.0962 cubic meters per block. The glass blocks are canistered in a stainless steel container, 1 cm. thick and 1.3 m. long.

The typical densities for borosilicate glasses with a concentration of 25-30 % by weight in waste oxides, is 2.6 gr/cm . The thermal conductivity of the borosilicate glasses ranges from 1.0 to 1.5 w/m C for the range of temperatures of interest. The thermal conductivity of the canister (usually stainless steel 304 L) is about 43 w/m C [21, 58].

3. Decay heat in HLW glasses

For an economic analysis of the disposal of HLW, the most important characteristics of the HLW glass are the maximum centerline temperature (already mentioned) and the heat generation rate. These two parameters will exert a strong influence on the achievable density of disposal in the repository.

The heat generation in the HLW is produced by the decay of the radioactive nuclides present in the waste, especially the fission products. The decay power decreases with time. At times of interest for the storage and disposal of HLW (more than 10 years after SF is discharged from the reactor), the decay heat is dominated by a few long-lived fission products, Cs-137 (half-life of 30 years) and Sr-90 (half-life of 29 years) being the most important of them. The dominance of these few fission products extends up to 500 years. For longer times, most of the decay power is due to the radioactive decay of the actinides, since most of them have an extremely long half-live. However, by that time, the decay heat is no longer an important consideration for HLW, because most of the actinides were removed from the waste during reprocessing. (In the case of SF disposal, 500 years after discharge of the SF, the decay heat is still important.)

To evaluate the decay power in SF/HLW, summation methods are normally used. The summation methods currently being used account for the decay of a few hundred nuclides. These methods were developed for evaluations of the decay power at short times after reactor shutdown, when many fission products are still present. To estimate the decay power in HLW, assuming that reprocessing takes place about 10 years after discharge, a simplified summation method could be used. For such periods after discharge, most of the F.P. have decayed away. A summation method accounting for as many as 50 fission products would give very accurate results. To preserve accuracy, the model should consider the contribution of Pu-239, Pu-241 and U-238 to the heat production as well as the power history that the fuel underwent. Without adding too much complication, the model could also consider the effect of neutron capture in fission products, which, on the average, increases the decay power at the times of interest.

A summation method especially intended for evaluation of the decay power in HLW has not been developed. However, several standard methods, mainly developed for short time evaluations, can provide results accurate enough for the purposes of this work.

In the economic model, the heat generation rate of the HLW is evaluated for 9 different ages of the waste (see Section G). Moreover, these evaluations are repeated for each period of temporary storage being considered. In order to maintain a fairly short running time of the optimization program, we have simplified the estimation of the decay power, by using a double exponential model, in the form:

$$D.H. = A \exp(r\ t) + B \exp(s\ t) + C$$

where D.H. is the decay power (in w), t is the time after discharge (in years) and A, B, C, r, and s are constants to be determined. These five constants were determined by using a least-squares fit to the data on decay heat provided by one of the standard summation models. The data used were obtained from an Oak Ridge National Laboratory analysis [56] of decay power in HLW using the ORIGEN computer code. The data from this source are based on a BU at the discharge of 33,000 MWD/MTHM. Decay powers evaluated at 5, 10, 30, 100 and 300 years after discharge were used in the least-square fit. The fit was carried out by using the NLIN subroutine from the SAS library of programs. The double exponential model found, is:

$$D.H. = 2{,}831.\ \exp(-0.321\ t) + 1{,}038.\ \exp(-0.02345\ t) + 7.$$

for the reference BU of 33,000 MWD/MTHM.

However, in the scenario proposed in this work (see Section G), we deal with BU different than 33,000 MWD/MTHM. To adjust the model to our BUs, two correction factors were derived. The first of them accounts for the different total number of fissions per unit mass undergone by spent fuels with different BU rates. The second factor corrects for the different irradiation periods of the different spent fuels. The correction factors for the different BU rates used in the present model, are listed in Table 2. The simplified model for evaluating the decay power to be used in the economic model has the form:

$$D.H. = Q \left[2{,}831 \exp(-0.321\ t1) + 1{,}038 \exp(-0{,}02345\ t1) + 7. \right]$$

where t1 is the corrected time after discharge and Q is the normalization factor accounting for the total number of fissions.

The results predicted by the exponential model are expressed in watts generated in the HLW corresponding to 1 MT of SF. With the data of content of waste in the HLW glass and the waste generated per MT of SF (function of the BU rate), the heat generated in a canister of solidified HLW is then calculated.

The decay power estimates predicted by the simplified model so developed, are in acceptable agreement with evaluations performed with other summation methods [30]. The differences observed are due to different rates of extraction of actinides or other products during reprocessing, as well as to the differences in BU rates considered.

Table 2. Correction factors for evaluating the decay heat in HLW as a function of the BU of the SF at discharge

Burnup rate MWD/MTHM	%	Correction factors t1 (years)	Q
33,000	3.4	t	1.
21,300	2.2	t - 0.74	0.6471
27,300	2.8	t - 0.37	0.8235
31,500	3.24	t - 0.10	0.9529

E. Temporary Storage of HLW

As a penultimate step to final disposal, the canisters of solidified HLW are to be placed in a retrievable storage facility. This temporary storage of HLW has a twofold purpose [3]:

1. To monitor the canisters for possible thermal instabilities, deterioration or leakage of radioactive materials.
2. To let the decay power decrease to lower levels in order to achieve better densities of disposal.

During temporary storage, proper cooling must be provided to the HLW canisters, assuring that the temperature limits of the glass and the steel cask are not exceeded. A cooling system for HLW can be simpler than a system for spent fuel, because of the lower heat generation rate and the higher allowable temperatures in the HLW canisters. Therefore, a dry storage system, where the canisters are cooled by circulating air, is preferred instead of a wet (or water pool) method. The advantages of a dry system are its lack of corrosion problems and, especially, its lower cost with respect to the water pool systems [13].

The conceptual designs for retrievable storage are normally based on an aboveground or a near-surface facility. The HLW canisters are arranged in rooms where they are cooled by forced circulating air. The canisters and the air are monitored for temperature increases and for radioactivity detection. The arrangement of the HLW canisters is less restrictive than in the case of SF assemblies, since the risk of criticality no longer exists.

The period of temporary storage is a very important parameter. First of all, the time of storage has to be long enough to assure that no failures exist in the HLW canisters, and this can set a constraint on the minimum time of retrievable storage. Moreover, by aging the HLW before permanent disposal, the heat generation rate is decreased and higher densities of disposal can be achieved, thus reducing the cost of disposal (principally, by deferring the costs of the repository and reducing the excavation costs) [51]. However, the costs incurred in HLW storage will increase for longer storage times, because this requires a facility of larger capacity [51]. An optimal period of temporary storage should be set up as the time leading to a least cost situation for the storage and disposal of HLW. Nevertheless, political constraints are likely to exist for both a minimum and a maximum time of temporary storage. Several countries have set recommendations for the period of temporary storage, taking into consideration the gains obtained by aging the HLW. In the U.K., the SF/HLW is to be stored for at least 50 years; in Sweden, about 40 years and in Japan, between 30 and 50 years. India and Argentina are considering a minimum time of 20 years of storage before disposal [59]. All these times are understood as years after discharge of SF from the reactor.

In the U.S., although no limits have been established, it is currently considered that the minimum time of retrievability should be about 5 years and times of storage of HLW longer than 100 years would not be acceptable, for political and safety reasons [12]. Therefore, the search for an optimum time of temporary storage has to be constrained by these lower and upper limits.

F. Disposal of HLW

The last step in the nuclear fuel cycle is the final disposal of the HLW. The objective of the permanent disposal is the isolation of these hazardous materials from the biosphere. Because of the long-lived nuclides contained in the HLW, the isolation must be effective for quite long periods of time. Between 300 and 500 years after reprocessing of SF, the radioactivity level of the waste reduces to that of the naturally occurring uranium ores. However, the ingestion hazard of HLW does not become smaller than that of the naturally occurring uranium until several thousands or several hundred of thousands of years after reprocessing [3, 11, 12]. Although the ingestion hazard is a very poor measure of safety, and the isolation need not be absolute, the HLW must be kept from the environment for periods of time in the order of 1 million years to reach public accepted hazard indexes. At those times, the toxicity of the HLW is much smaller than that of other natural ores, such as Cr, Ag, Hg or Pb [3, 11].

Several disposal techniques have been proposed for the HLW, such as deep-sea, space or icesheet disposal, transmutation of the long-lived nuclides and geologic (shallow, deep or deep well) disposal [11]. Disposal in a deep geologic formation is the most developed concept in all the countries with advanced nuclear programs, and it is currently accepted as the safest and the most reliable of the different methods mentioned above. Many research programs have already been carried out in the field of geologic disposal, especially in the U.S., Canada and West Germany.

In a deep geologic repository, water is considered the only pathway for the radionuclides to be released to the biosphere. By corroding the HLW canister and dissolving part of the HLW, the underground water can become contaminated. This contaminated water can enter an aquifer or reach the surface, eventually contaminating the drinking water. In order to prevent such an event, the HLW must be protected by a multibarrier system. The first barriers are the glass itself (it has very low solubility) and the canister (corrosion resistant). The ultimate barriers are the backfilling materials of the repository (water retainers) and the geologic formation itself.

In selecting a geologic site for a repository, the characteristics desired are:

1. The geologic formation must be located at a sufficient depth to avoid accidental access from the surface or erosion problems, but not impose major problems for the excavation. Many of the formations investigated are located between 700 and 1000 m. underground [37].
2. Geologic stability, since the occurrence of earthquakes can develop fissures, creating pathways

for the water.

3. Absence of near aquifers or circulating groundwater.
4. Good thermal conductivity, allowing good dissipation of the heat generated in the HLW.
5. Radiation, mechanical and thermal stability of the excavated rock.
6. The formation should be located in a low populated area.

Several types of geologic formations are being considered in the U.S., for their availability, to meet these requirements, namely salt (bedded or domed), granite, basalt and tuff [25, 30]. Salt has been the object of most of the studies in the U.S. and West Germany [3]. The most attractive property of salt is its plasticity, since the fissures that can appear would be self-sealing [35]. Moreover, the existence of a large salt formation guarantees the absence of water. The thermal conductivity of salt is the largest among the four types of rock considered, although the maximum allowable temperature is rather low, because of the risk of dehydration [38]. The most important drawback of salt is its ease of dissolution, and the corrosive nature of salt water, in case water penetrates the repository. Since salt is a soft material, the cost of excavation is likely to be low, but the self-sealing property can create some complications.

Tuff is another soft material considered for a repository. This is a porous material. Earlier, porosity was thought to be an undesirable property in the host rock, because high porosity materials are not a reliable barrier against water entering the repository. But, on the other hand, porous materials can retain the water and slow down the release of redionuclides to the surface, because of their high ion-exchange capacity. In this sense, tuff could behave better than the hard rocks, which can develop large fractures, creating easy pathways for circulating water. Tuff's thermal conductivity is not as good as that of salt, but is still adequate for the purposes of a repository, and tuff can tolerate higher temperatures than salt.

Granite and basalt are hard rocks. Their characteristics from the point of view of host rock in a repository are similar. The excavation costs can be expected to be higher than those for tuff and salt, although with the hard rocks there is no longer the problem of self-sealing. Their thermal stability is excellent and the conductivity is quite large [48].

The final selection of a repository will be made on the basis of balancing the costs of excavation, the safety issues and political constraints, particularly public acceptance.

For disposing HLW, the best option for the excavation of the repository is the room and pillar technique [30]. In the rooms, single boreholes are drilled in the floor, to

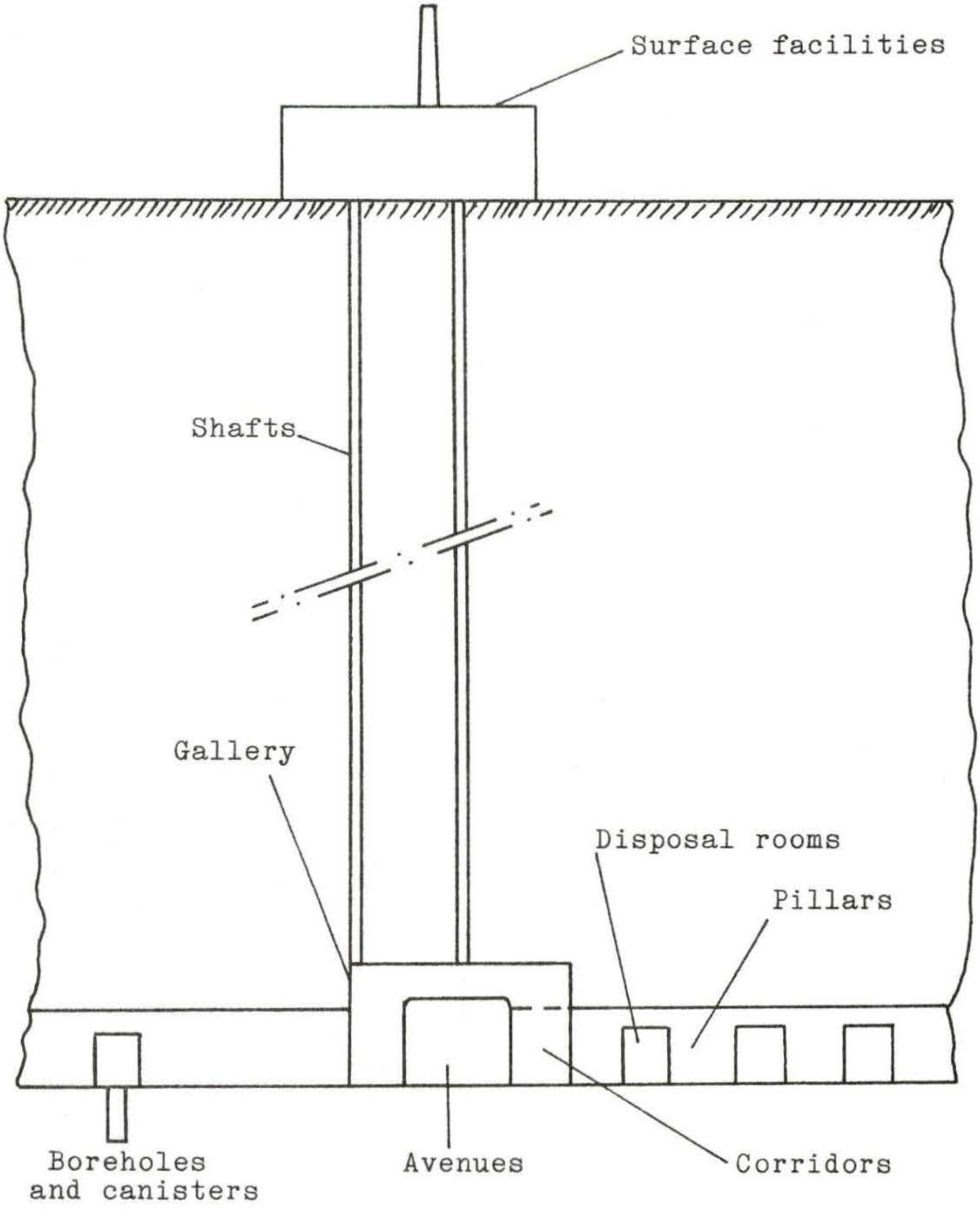

Figure 3. Artist's view of an underground repository for HLW

accommodate the canisters of HLW. An artist's representation of the general layout of a repository is shown in Figure 3. The different excavation parameters (such as room and pillar width, room height, canister pitch, etc.), will depend on the heat generation in the canisters and the thermal and mechanical properties of the host rock. These parameters will be different for the different types of rock considered. The general geometry of the repository is to be defined in order to minimize the excavation volumes.

G. Description of the Scenario

For the first repository, the scenario is likely to be different than for the successive repositories. Spent fuel has been accumulated for several years and the stored amount will increase until the reprocessing operations begin. Therefore, effective reprocessing capacity in excess of the annual production of SF will have to be provided until all the SF more than 10 years old has been reprocessed. At that time, the reprocessing capacity needed will equal the annual production of SF. The initial disagreement between spent fuel produced and reprocessed, as well as the schedule for starting up the reprocessing plants, will affect the utilization and maximum capacity of the temporary storage facility of HLW. For this reason, the scenario that seems more realistic today, must be described, for the influence it will exert on the economics of temporary storage and disposal of HLW.

1. Disposal site capacity

The total capacity of the disposal site, although it is linked to the total amount of SF reprocessed during the lifetime of the first generation of reprocessing plants, depends also on the size of the geologic formations being considered as possible repository sites. Most of the latest studies on repository economics consider a value around 70,000 MT of SF equivalent in HLW for the total disposal site capacity. A comparison of different proposed repository models can be found in reference 45. The different capacities considered in this comparative study are shown in Table 3.

Other economic analysis have been performed on the bases of a total repository capacity of 72,000 MT [46-48]. According to these studies, the total capacity of the disposal site has been set up at 72,000 MT SF equivalent of HLW in the present work. This value will match up with the expected schedule of reprocessing and SF production.

The high-level wastes to be disposed of in the first repository, will come from the SF that has been accumulated since the earliest days of the nuclear industry. We assume this SF for the first disposal site will be the oldest (and coolest) available, so that the first repository will absorb most of the backlog of SF, once it is reprocessed. The schedule for burial of the HLW into the repository will be influenced by the fact that the SF is the oldest available. The period of cooling down the HLW in the temporary storage facility can be shorter for the first disposal site than for the successive ones.

Table 3. Capacities studied for a repository [45]

Case studied	Capacity (mt of SF)
Baseline repository	68,500
Variation 1	51,100
Variation 2	39,500
Variation 3	76,500
Variation 4	62,170
Variation 5	121,600
Variation 6, 7 & 8	69,000

Constraints of different nature are also likely to exert influence on the schedule of this first disposal site, including both the temporary storage facility and the repository. Technical reasons, such as delays in the site characterization tests, delays during the construction and excavation, preference for a certain long-term temporary storage for safety and economic reasons, might come up in setting up the disposal site schedule. Other kind of constraints can include social reasons (public acceptance of the selected disposal site, for example), and political constraints imposing limits on the period of temporary storage or latest dates for the availability of operational facilities. Under the last category, there already exists some limitations in different countries (Section E). The United States has determined that a first disposal site should be operational by the end of the century [10]. This constraint set up the year 2000 as the latest schedule date that could be acceptable for, at least, the retrievable storage facility of HLW, and therefore for the start of reprocessing operations.

2. History and projections of SF generation

For a better utilization of both nuclear plants themselves and fuel as well, the utilities are interested in reaching high burnup rates. This implies a better use of the fuel in the reactor and longer periods between two consecutive refueling shutdowns. A theoretical target for the burnup rate is 4 %, but for practical reasons, a 3 % average burnup is considered a good achievement [60]. The amount of SF generated annually in a power plant depends on the maximum burnup that is reached before discharge, and on the average load factor that the plant has undergone. In accounting for the annual production of SF per unit plant capacity, both the BU rate at discharge and the average load factor have to be estimated.

The average burnup rate obtained in the U.S. power plants has changed since the beginning of the nuclear industry and, for different periods, a good estimate is listed in Table 4.

Table 4. Average annual production of SF in the U.S.[a]

Period	Average burnup [57, 60]		Load factor [52]	Annual SF production
	%	MWD/MTHM	%	MT
Prior to 1978	2.2	21,300	55.0	28.6
1978 to 1982	2.8	27,300	60.0	24.3
Since 1982	3.24	31,500	60.0	21.0

[a] Normalized to 1,000 MWe power plant capacity with a thermal efficiency of 33 %.

The average load factor for LWR reactors (PWR and BWR), has been fairly constant for many years, not only in the U.S., but also in foreign countries, and it turns out to be a value around 60 % during the last years [52]. The cumulative load factor for the complete history of LWR reactors is about 55.5 % [52]. Using the estimated data, tha annual production of SF, normalized to 1,000 MWe power plant capacity with a thermal efficiency of 33 %, and a load factor L, can be evaluated in the following way

$$\frac{1,000\ /\ 0.33}{\text{BU (MWD/MTHM)}} \times L \times 365 = \text{MT of SF per year}$$

The estimated annual production of SF for the different periods of average burnup are shown in Table 4. With these estimated values a rough calculation of the production and accumulation of SF (in equivalent MTHM) can be carried out, for the installed nuclear capacity throughout the years. The nuclear capacity and the estimated annual production of SF are displayed in Table 5, starting at the year 1970.

It must be pointed out that the values calculated are an approximation, accurate enough for the purposes of this work; it has been considered that all the power plants started up at July 1st., turning out a half-year production of SF during the first year of operation. This partially compensates for the relatively low burnups that characterize initial loads, since a more realistic average date would be September 1st. The estimated amount already reprocessed has been discounted and the results of SF accumulation up-to-date are in acceptable agreement with other estimations [57, 61].

For the year 1984 and subsequently, the installed nuclear capacity has been estimated in accordance to the expected start up schedules of the power plants currently in

Table 5. Estimated SF production and accumulation

Year	Nuclear installed capacity MWe	SF production Annual MT	Cumulative MT
1970	6,107	140	--
1971	8,842	214	--
1972	14,367	333	--
1973	18,714	474	--
1974	29,550	692	150
1975	36,742	951	1,101
1976	39,614	1,095	2,196
1977	46,793	1,240	3,436
1978	49,632	1,171	4,607
1979	50,768	1,219	5,826
1980	52,516	1,255	7,081
1981	56,779	1,328	8,409
1982	59,005	1,406	9,815
1983	65,112	1,303	11,118
1984	71,100	1,430	12,548
1985	77,100	1,556	14,104
1986	83,100	1,682	15,786
1987	87,100	1,787	17,573
1988	90,000	1,859	19,432
1989	90,000	1,896	21,328

Table 5. (Continued)

Year	Nuclear installed capacity MWe	SF production Annual MT	SF production Cumulative MT
1990	90,000	1,896	23,224
1995	90,000	1,896	32,704
1999	90,000	1,896	40,288
2000	90,000	1,896	42,184
2005	90,000	1,896	51,664
2010	90,000	1,896	61,144
2015	90,000	1,896	70,624
2016	90,000	1,896	72,520

construction [62]. It has been considered that the capacity at the end of the '80s, will be the about 90,000 MWe and it will remain stable until the beginning of the new century, when a new increase of the installed nuclear power is likely to take place. However, to build up the scenario for the first repository, a constant capacity of 90,000 MWe will be considered after the year 2000 in order to estimate the storage and reprocessing needs. Additional installed power capacity, which cannot be predicted with accuracy, would belong to another system of storage-reprocessing-storage-disposal, and it is considered here that it will not affect the operations or capacities of the system for the first disposal site. The HLW to be disposed of in the first repository will be, as can be seen in Table 5, that produced from reprocessing of all the SF generated until the year 2016 (for the installed power assumed), amounting to about 72,000 MT of SF.

3. Reprocessing plant capacity and schedule

In setting up the annual reprocessing requirements for this scenario, the main objective is to avoid further accumulation of SF and, indeed, achieve a gradual reduction of the stored SF previous to beginning reprocessing operations. From Table 5, the estimated SF production for a 90,000 Mwe system is about 1,900 MT/year. An excess of 25 % over this value is chosen for the annual reprocessing amount of SF, which turns into 2,400 MT/year of SF reprocessed. To determine this quantity, several factors have been accounted for.

The first factor is the date for starting up the commercial reprocessing. To fulfil the constraint that the latest acceptable schedule for setting the HLW storage facility is the year 2000, commercial reprocessing should start no later than this date. The operational life of the reprocessing plants is taken to be 30 years, which is a reasonable lifetime for chemical industries with similar processes. Therefore, by the end of the lifetime of the first generation of reprocessing plants, at the rated capacity of 2,400 MT/year most of the backlog of SF would have been reprocessed, since the SF reprocessed during the last year of operation would be 12 year old SF. The expected limitation that the SF should be reprocessed no later than 10 years after the discharge from the reactor, would almost be met by the end of the first reprocessing-disposal site system.

Another reason for setting the annual reprocessing at 2400 MT/year is that the total amount reprocessed during the lifetime of the first generation of reprocessing plants will equal exactly the total capacity determined for the first disposal site (72,000 MT of SF). In other words, the capacities of the different facilities of the scenario considered will match up: at the end, the wastes generated when decommissioning the reprocessing plants, could be disposed of in its dedicated repository.

The last factor considered has its foundations in the French policy for reprocessing LWR spent fuel. The reprocessing units in France are being constructed for an individual capacity of 800 MT/year [5, 21], this size being considered as a technical and economical best choice. The 2,400 MT/year needed in the U.S. according to the scenario that is presented, could be obtained with 4-800 MT/year units like those operating at La Hague, France, working at 75 % capacity factor.

The starting point for reprocessing operations is taken as the year 2000, in this scenario. (Detailed schedules, cumulative amounts and age of SF being reprocessed are shown in Table 6.) Further delay of reprocessing, although it would reduce the need for HLW temporary storage, would require larger SF storage capacity, which is likely to be limited. The A.F.R. maximum capacity might be restricted to 1,900 MT of SF, according to the Nuclear Waste policy Act of 1982 [10], and the longer the delay of reprocessing, the more difficult will be this limitation to fulfill.

4. HLW storage facility requirements

The scenario adopted has impact on the requirements for HLW storage and, as a result, it influences its economic analysis. Under this scenario, the retrievable storage facility will be receiving 2,400 MT/year SF equivalent of solidified HLW from the years 2000 to 2029. The age of the wastes shipped will range from more than 23 years to 12 years for the last shipment. This would mean that the last HLW arriving to the facility will stay longer than the HLW received at the beginning of its operational life, if a longer age than 12 years is required before permanent disposal. Depending on how long the disposal of HLW into the underground repository is delayed, the maximum capacity and utilization of the temporary storage facility will vary. For example, if the minimum age of permanently disposed HLW is to be 20 years, the maximum capacity needed would be the equivalent to 16,800 MT of SF; for disposal of 30 years old HLW, 33,600 MT and for 50 years old HLW, the maximum capacity would increase up to 67,200 MT. A comparison of the retrievable storage needs, for these three different ages of HLW disposed, is shown in Figure 4.

Since the capacity required for the storage facility depends on the age of the HLW at disposal, it will be a key parameter when performing the economic optimization. The schedule for HLW temporary storage will thus be determined in the economic analysis, as a result of the chosen age of the HLW disposed.

5. Suggested second-site, second-plant schedule

The schedule for the second generation of reprocessing plants (and its dedicated second disposal site) will depend on the increase in nuclear installed capacity after the year 2000. To meet the assumption that the final objective is to reprocess 10-year old spent fuel, if the growth of installed capacity in the first years of the next century is very large, the second-site system should be ready for operation in the early 2010s. If the installed capacity remains stable at 90,000 MWe or increases slowly, the reprocessing (and HLW retrievable storage) could be delayed until the year 2027.

Table 6. Reprocessing schedule and projections

Year	SF reprocessed Annual MT	 Cumulative MT	Accumulated SF MT	Age of SF reprocessed years
2000	2,400	2,400	39,784	23
2001	2,400	4,800	39,270	23
2002	2,400	7,200	38,767	21
2003	2,400	9,600	38,263	20
2004	2,400	12,000	37,759	19
2005	2,400	14,400	37,255	19
2006	2,400	16,800	36,751	19
2007	2,400	19,200	36,247	18
2008	2,400	21,600	35,743	18
2009	2,400	24,000	35,239	18
2010	2,400	26,400	34,735	17
2011	2,400	28,800	34,232	17
2012	2,400	31,200	33,728	17
2013	2,400	33,600	33,224	17
2014	2,400	36,000	32,720	16
2015	2,400	38,400	32,216	16
2016	2,400	40,800	31,712	16
2017	2,400	43,200	31,208	15
2018	2,400	45,600	30,704	15
2019	2,400	48,000	30,200	15

Table 6. (Continued)

Year	SF reprocessed Annual MT	SF reprocessed Cumulative MT	Accumulated SF MT	Age of SF reprocessed years
2020	2,400	50,400	29,697	15
2021	2,400	52,800	29,193	14
2022	2,400	55,200	28,689	14
2023	2,400	57,600	28,185	14
2024	2,400	60,000	27,681	14
2025	2,400	62,400	27,177	13
2026	2,400	64,800	26,673	13
2027	2,400	67,200	26,169	13
2028	2,400	69,600	25,665	13
2029	2,400	72,000	25,161	12

In this year, the SF generated in 2017, 10 years old, would be reprocessed. If the reprocessing capacity for this second generation is mantained at 2,400 MT/year, this second system would be able to support an additional installed capacity of about 20,000 MWe, without causing an increase in the accumulation of SF, if the starting of operations were adjusted to the schedule of the power growth. For a constant installed capacity of 90,000 MWe, the reprocessing capacity could be reduced to 1,900 MT/year (the annual production of

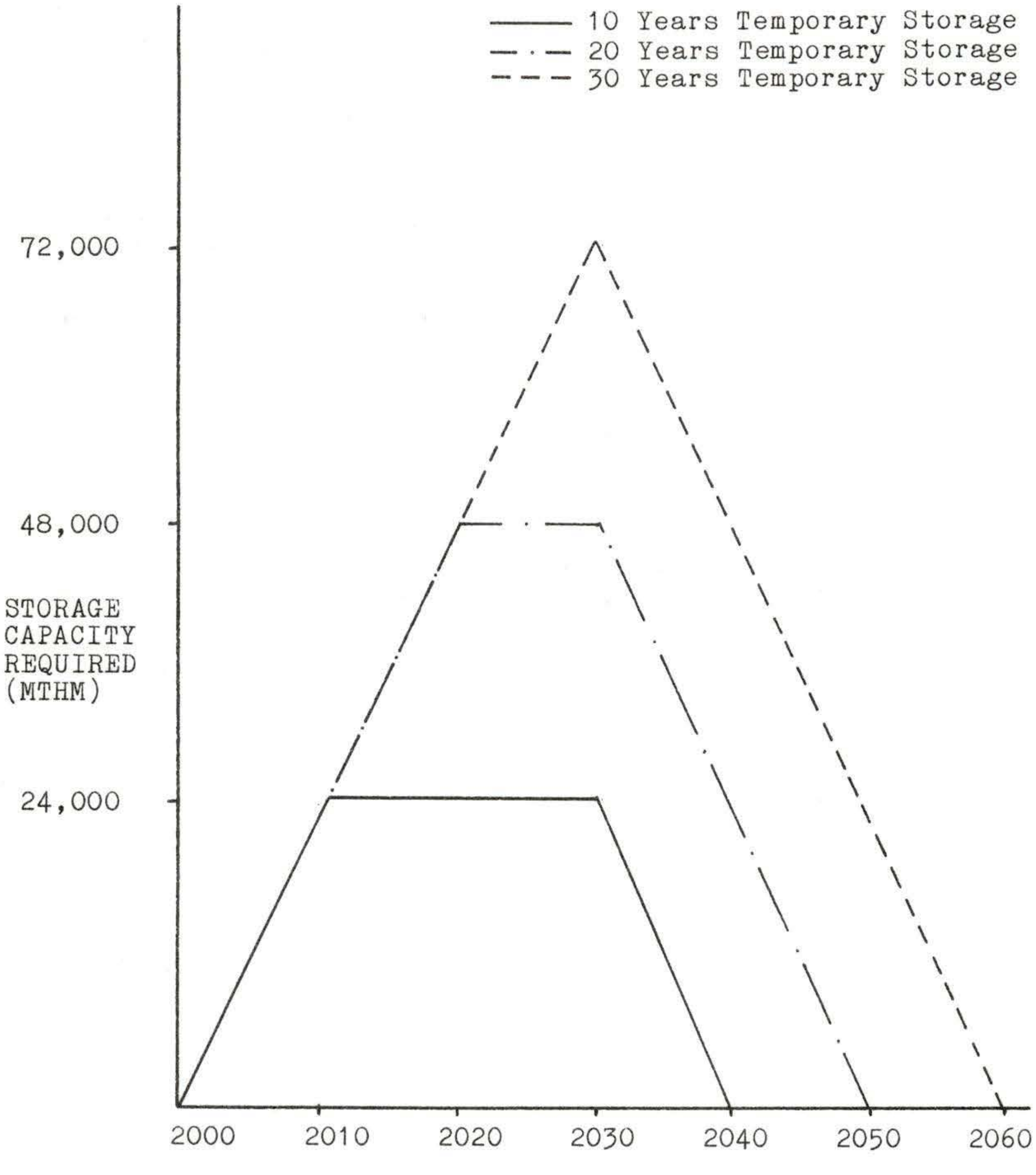

Figure 4. Storage capacity requirements for different periods of temporary storage

SF) and the best schedule for starting reprocessing would be the year 2027. Under this schedule, there would be no need for AFR storage capacity and the SF being reprocessed would be 10 years old during the entire life of the reprocessing plants.

The retrievable storage facility of HLW should also start in the year 2027. For different delays of disposal, the maximum capacities and operational lives of the retrievable storage facilities would be different. Assuming the same life for the reprocessing facilities of 30 years, the total capacity of this second disposal site system, would be about 57,000 MT of SF.

6. Scenario summary

The summary of the main issues and parameters adopted as the scenario for the first repository, are shown in Table 7. These are the information and values that are used in the economic analysis.

Table 7. Scenario summary

FIRST DISPOSAL SITE	
Total capacity of the repository	72,000 MT SF
Schedule for the repository	Dependent on disposal delay
SF received	From year 1970 to 2016
SF PRODUCTION	
Cumulative (end of 1988)	17,525 MT
Annual production after 1988	1,896 MT
Average BU	3.2 %
Average load factor	60 %
Inst. nuclear capacity	90,000 MWe
Cumulative (end of 2000)	42,184 MT
Cumulative (end of 2016)	72,520 MT
SF STORAGE NEEDS	
Total (at reactor and A.F.R.) capacities	
End of 1988	17,525 MT
End of 1999 (maximum)	40,288 MT
End of 2000	39,784 MT
End of 2029	25,161 MT

Table 7. (Continued)

REPROCESSING	
Starting operations	Year 2000
Life of the reprocessing plants	30 years
Annual SF reprocessed	2,400 MT
Total SF reprocessed during lifetime	72,000 MT
Age of SF reprocessed during:	
year 2000	23 years
year 2029	12 years

HLW RETRIEVABLE STORAGE	
Starting operations	year 2000
Lifetime and maximum capacity	Dependent on disposal delay

IV. COSTS ASSOCIATED WITH THE BACK END OF THE FUEL CYCLE

A. Discussion of the Costs

Costs are incurred in all the steps of the back end of the fuel cycle. Many of the different costs will depend on the heat generation rate in the HLW, and, in turn, on the two different times of storage (SF and HLW). A least cost situation for the management of the SF/HLW should be predictable as a function of a set of parameters, in particular the two different periods of storage.

Cooling down the spent fuel, either at the reactor site or at an A.F.R. facility, produces two principal costs: the cost of the facility and the running cost (monitoring, loading and other operations) [42]. Both costs are strongly dependent on the time of cooling down (delay of reprocessing), since longer periods of storage of SF, would require larger capacity facilities and longer periods of monitoring and operations. Thus, in general, the cost of cooling down the SF will increase for increases in the delay of reprocessing.

Reprocessing of the SF is a relatively high-cost process, because of the safety and protective measures that are involved. For this step, the cost will also depend on the delay of reprocessing; the costs of the process should be lowered by increasing the time of storage of SF. Furthermore, for longer delays of reprocessing, the extraction yield of U and Pu can be higher, thus increasing the reprocessing benefits.

The cost of the solidification of the HLW can be considered essentially independent of the time of cooling down the SF. As was pointed out in Chapter III, Section D, the solidification of HLW is carried out at times longer than 5 years after the discharge of the SF from the reactor. For short-cooled SF reprocessing, liquid storage of the HLW is required before the solidification can take place. Therefore, the solidification process is performed after some minimum time following the discharge of the SF, and the delay of reprocessing will not affect the cost of the operation. However, for long times of cooling down the SF, the cost of the tank storage can be reduced or even eliminated.

In the temporary storage of HLW, both the cost of the facility and the operating cost are dependent on the time of storage, increasing as this time is enlarged. The total delay of disposal can be understood as the time elapsed from the discharge of SF from the reactor until the burial of the HLW in the repository. If a certain age of the HLW disposed is to be achieved, the period of temporary storage of HLW will depend on the time that the SF was cooled down. In summary, the cost of the temporary storage of HLW is a function both of the period of storage of HLW , and of the period of SF cooling down. Longer periods of SF cooling down will permit shorter times of HLW temporary storage, thus reducing the cost of this operation.

In the disposal stage, the costs depend on many parameters, such as the thermal and mechanical characteristics of the host rock, the heat generation rate of the waste, the geometry of the repository, etc. The heat generation rate of the HLW at the time of disposal is a function of the age of the HLW disposed. The older the HLW at disposal, the smaller the decay power, and the higher the densities of disposal that can be achieved [51]. With the other parameters maintained constant, the excavation costs will decrease for longer delays of disposal. Moreover, another benefit is obtained by aging the HLW before disposal, and that is the deferral of the costs incurred in the repository [51].

Finally, there are the costs of transportation from one facility to another. This cost is obviously dependent on the distance between facilities, but the period of SF/HLW cooling down is also an important issue for transportation requirements. Cooler SF/HLW will need less shielding and cooling during transportation, thus reducing the costs [25].

A complete optimization of the back end of the fuel cycle would require adjusting all the parameters that the costs depend on, to produce a least cost situation. In setting up the time of cooling down of SF, many factors should be taken into consideration, such as the reprocessing fees, the price of uranium, the reprocessing benefits, the excess cost of fabricating mixed-oxide fuel over uranium-oxide fuel and the influence of this period on the transportation and temporary storage of HLW. Many uncertainties are still involved in all these factors, especially in those concerning reprocessing. In the case of the first disposal site, there are more restrictions, such as the schedules and the varying age of the SF that is being reprocessed. The delay of reprocessing may be fixed by the constraints instead of being decided on economic grounds. Such is the case assumed in the present work, where an optimal situation is sought for the HLW temporary storage and disposal costs, by adjusting the time of temporary storage for the SF cooling times estimated in the scenario for the first repository.

B. Cost of Temporary Storage

The cost of the temporary storage will increase with the period of storage. The two principal costs in this operation are the construction of the facility and the operating costs, which include the maintenance, monitoring, air filtering and circulation, and other auxiliary systems [42]. The cost of the facility will increase as capacity increases, and the required capacity turns out to be proportional to the age of the HLW at disposal. The operating costs will be proportional to the period of operation, which increases if the age of the

HLW disposed is to be increased. Some of the operating costs, such as the cooling system running expenses, will also be dependent on the factor of the total capacity that is being used at a certain time, and this can change throughout the operational life of the facility. However, some other operating charges, such as the monitoring, are likely to be almost independent on the load factor. Cost of surveillance is also considered in the temporary storage facility and is expected to apply during its operational life.

A final cost must also be considered: the cost of decommissioning of the facility at the end of its life. The older the HLW is to be at disposal, the later will be the decommissioning time and the lower its present worth cost. For this reason, this cost can be considered as dependent on the period of temporary storage.

Because of the varying age of the SF reprocessed, according to the scenario proposed, the period of storage of the HLW to achieve a certain age at disposal, would not be constant for the SF reprocessed at different years. This would require interrupting the disposal several times during the life of the repository, to let the HLW reach the appropiate age. These discontinuities in the disposal would have a negative effect in the cost. In order to operate the repository in a continuous fashion, some waste will be disposed some time before it reaches the desired age. This will slightly affect the costs of both the temporary storage and the disposal. The densities of disposal of the HLW inside the repository will not be constant.

C. Cost of Disposal of HLW

The disposal of the HLW is expected to be a high-cost operation, because of the many systems involved in the construction of a deep underground facility [25, 37, 44, 45]. Many different components will build up the total cost of disposal [50]. The geometry of the repository is important to reduce the total length of the avenues and corridors, which are only used for access to the disposal rooms. The geometry adopted in this study is shown in Figure 5. It has been assumed that any room must be reached from two different sides, to maintain access to the disposal rooms, should a corridor collapse in a particular location.

Some of the partial costs are dependent on the heat generation rate in the HLW canisters (and therefore dependent on the age of the HLW disposed), whereas some other costs can be considered essentially not governed by the age of the waste. Among the first group, the most important costs are:

1. Excavation of the avenues and corridors.
2. Excavation of the disposal rooms.
3. Backfilling of rooms and corridors.
4. Operating costs: electricity, air conditioning, and

other auxiliary systems proportional to the area excavated.

5. Disposal of the remaining excavated rock, not used in the backfilling.

Among the second set of costs, the following are the most important:

1. Receiving and other above and underground facilities.
2. Internal transportation.
3. Excavation of the shafts.
4. Drilling of the holes for the HLW canisters.
5. Aboveground site preparation and licensing.
6. Operating costs: emplacement of the canisters, overpacking of the canisters, and maintenance.
7. Surveillance cost, which also includes monitoring for water flow, geologic stability, temperatures and radioactivity levels.
8. Backfilling and sealing of the shafts, and decommissioning of the aboveground facilities.

One of the cost components, the excavation of avenues, corridors and rooms can be minimized by reducing as much as possible the volume of excavation. By controlling several design parameters, the excavated volume can be fairly small. These design parameters are the overall geometry of the repository, the height of the rooms, the density of disposal and other excavation parameters.

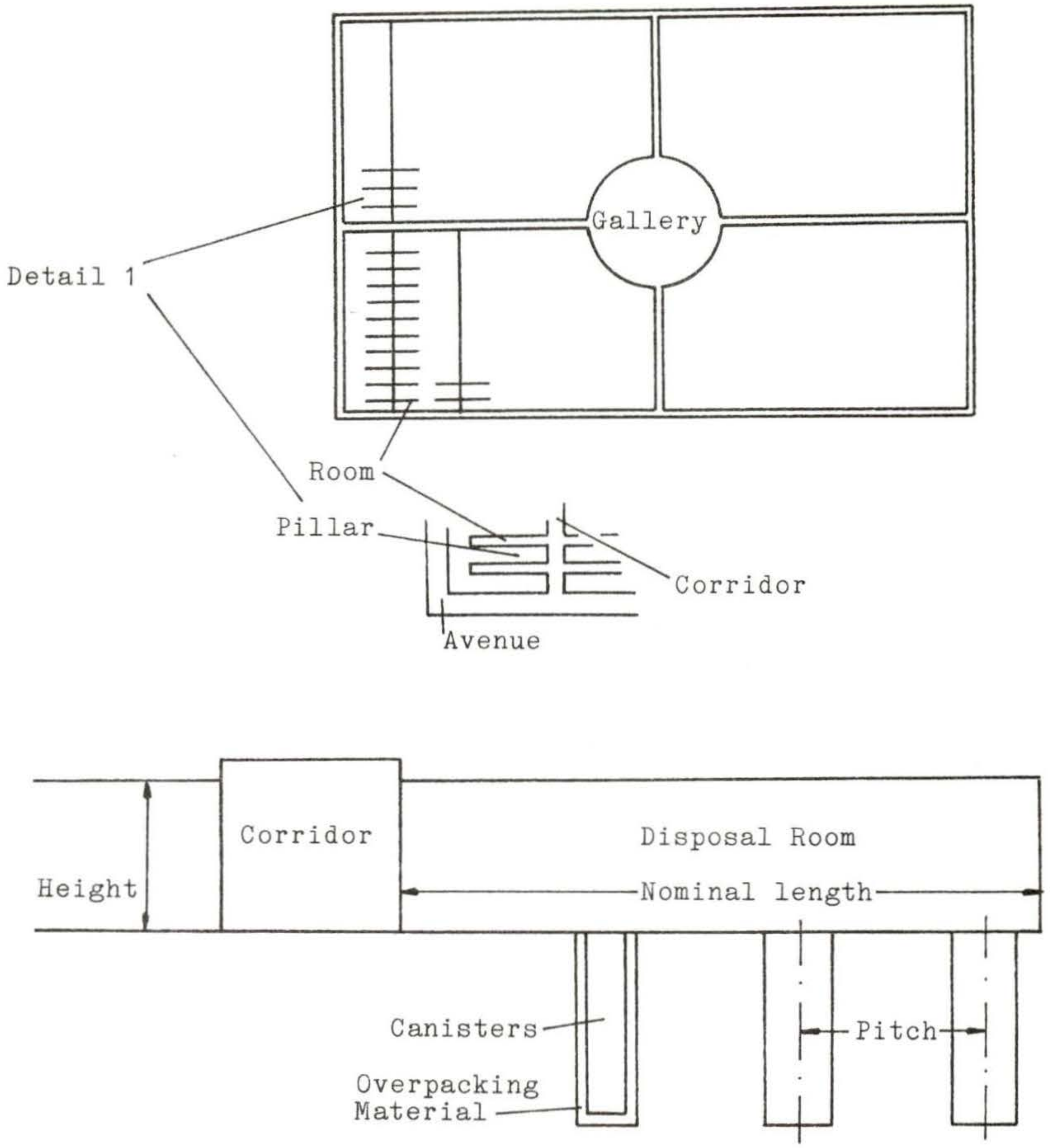

Figure 5. Plan view of the undreground area of the repository and details of rooms and boreholes

The height of the room is essentially proportional to the height of the canisters disposed. Since the canisters of HLW are about 1.3 m. high, a room height of 2.5 m. would be sufficient to place the canisters in the boreholes, and several canisters can be placed in the same borehole (assumed here 3 canisters per borehole). For longer canisters, such as the 4 m. high SF packages, rooms of at least 5 m. high would be required [30, 36, 37]. In case of SF, it might be argued that horizontal emplacement could be used, but in that case, the width of the room should be increased. The decision should be taken based on stability concepts, rather than on total volume excavated.

The density of disposal depends on the heat generation rate in the canisters at the time of disposal and the thermal properties of the host rock. The heat generation rate is reduced by enlarging the times of retrievable storage and the thermal properties of the host rock will set up the maximum thermal loadings permissible in the repository [29, 33]. The excavation parameters are understood as the rules that must be followed for assuring mechanical stability of the repository. Both the thermal loadings and the excavation parameters will be different for the different types of host rock proposed as repository media [25, 29].

1. Thermal loadings

Different thermal limits can be defined depending on the proximity to the heat source, i.e., the very near field, the near field and the far field (area loading). The very near field limit is concerned with the maximum temperatures allowable in the HLW glass, the steel canister and the host rock (restrictive only in the case of salt). The near field limit is related to the thermal loading per unit cell. The cell surface can be defined either as the surface of a single room or as the surface of a single room plus its adjacent pillar [50]. Most of the references use the latter definition and this will be used in the present work. The areal loading is defined as the total thermal loading per unit surface area of the repository, including non-storage corridors.

The evaluation of the thermal loadings for the different types of host rock, should be carefully performed for any particular location proposed as repository. For the same type of rock, the thermal properties can be sensibly different at various locations or different depths at the same site. Small variations in composition could result in variations in the thermal loadings; this is more probable if the host rock is salt.

Many different references agree fairly well in the estimation of the thermal loadings for generic host rocks: salt, basalt, granite and shale. The values proposed for shale have been accepted here for tuff, because of their similarity in thermal conductivity. The typical values for the three different thermal loadings that have been adopted in the present analysis are listed in Table 8.

2. Excavation parameters

The excavation parameters that are to be used in the economic model have been selected for minimizing the excavated volume. These parameters include the dimensions of the disposal rooms (length, width and height), the pillar width, and the dimensions of the avenues and corridors (height and width). Three factors exert influence on the design parameters: the thermal loadings, which will dictate the total underground surface area to be occupied by the repository, stability considerations (different for each host rock) and practicality of the facility.

As already mentioned, the height of the rooms is assumed to be 2.5 meters, considered high enough for the canister emplacement operation, likely to be performed by remote control. Due to the small diameter of the HLW canisters, the width of the disposal room has been similarly selected as 2.5 meters, assuming that only one row of HLW canisters is to be emplaced in a single room. With a constant thermal loading and room height, for a 2-row arrangement, the excavated volume is larger, ranging from 10 to 50 % depending on the other parameters and dimensions. More than 2 rows per room would yield very wide rooms, with consequent problems in stability.

Table 8. Thermal loadings for different types of host rock[a, b]

Thermal loading type	Salt	Tuff	Granite	Basalt
Very near field:				
Glass centerline temperature (°C)	500	500	500	500
Canister max. temperature (°C)	375	375	375	375
Rock max. temperature (°C)	250			
Max. load per canister (w)	3,600	1,600	2,300	1,900
Near field loading (w/m^2)	30	25	25	25
Areal loading (Kw/ha)	370	320	470	470

[a] From references [31-36, 46].

[b] Values for tuff are those for shale in the references.

The nominal room length has been set at 30 m. Although much longer rooms are considered in other designs [28, 30, 32], they are usually dedicated to SF disposal, which requires a larger size for the repository. By using the criterion that the smaller the rooms, the more stable they are [35], the nominal room length has been chosen rather short, 30 m.

Moreover, in the model, the final room length is adjusted to the pitch (distance between two consecutive boreholes). The pitch is calculated according to the thermal limits of the canisters and the rock, and accounts for the heat generation rate in the canisters. Since the age of the waste at disposal is variable over the lifetime of the repository, the pitches will not be equal every year. Once the pitch is calculated for each age of the HLW disposed, the room length is set by evaluating the multiple of the pitch nearest (by defect) to the nominal length (30 m.), adding 2 meters of allowance. Therefore, the final length of the rooms is not constant over the life of the repository, and depends on the pitch that is used for the waste of different ages.

The width and height of the avenues and corridors have been selected in order to provide practicality, maintaining the criterion of minimum excavation volumes. Corridors and avenues are to be wider than the rooms, since the excavation and drilling equipment must be driven in these locations, and consequently, larger allowances will be needed. Corridors and avenues will remain open for longer times than the disposal rooms and some kind of support will presumably be necessary. For these reasons, the dimensions of the avenues and corridors have been set as 6 m. of height and 7 m. of width (avenues) and 5 m. of height and 4 m. of width (corridors, for rocks other than salt). For salt, the corridors are considered to be 5 m. high and 6 m. wide, to allow for creeping. (Since the disposal rooms are to remain open for shorter periods than the corridors, no extra allowance is accounted for in room dimensions in a salt repository.)

The pillar width has been identified as a function of the room width and the pillar (and room) height [30, 35]. Also, the maximum extraction ratio allowable can determine the width of the pillar. Typical extraction ratios of 25 % are considered in salt repositories [35]. In our model, the pillar width is taken as 3 times the room width (or pillar height), as recommended or chosen by several authors [28, 35]. For granite and basalt, the pillar width is selected as a value larger than 20 ft. [30], whereas for tuff the width of the pillar is taken as more than 3 times the room width, for the more restrictive excavation recommendations given for shale in the literature [30]. (As in the case of the thermal loadings, the characteristics assumed for tuff are those given for shale in the references.)

The excavation parameters assumed in this work are listed in Table 9. It must be pointed out that, as in the case of the thermal loadings, local factors in a particular location selected for a repository site must be evaluated before deciding the dimensions of rooms, corridors, avenues and pillars. The stress and stability conditions can change from one location to another, even with the same type of host rock.

The length of corridors and avenues are calculated in the model, when the number of rooms to be filled out has been already determined. Then, using the dimensions given in Table 9 and the geometry assumed (Figure 5), the total corridor and avenue lengths are calculated.

Table 9. Room, corridor and avenue dimensions (in meters) for different types of host rock[a]

Rock Type	Avenue H	Avenue W	Corridor H	Corridor W	Room H	Room W	Room L	Pillar W	Extraction Ratio (%)
SALT	6.	7.	6.	5.	2.5	2.5	30.	7.5	25
GRANITE	6.	7.	5.	4.	2.5	2.5	30.	7.	26
BASALT	6.	7.	5.	4.	2.5	2.5	30.	7.	26
TUFF	6.	7.	5.	4.	2.5	2.5	30.	8.	24

[a] H - height; W - width; L - Nominal length.

V. ECONOMIC OPTIMIZATION OF THE STORAGE AND DISPOSAL OF HLW

A. Model for the Economic Analysis

A parametric model for seeking a minimum cost situation for the storage and disposal of HLW has been developed. The flow diagram of this economic model is shown in Figure 6.

The costs of storage and disposal are evaluated separately and then added together, yielding the final cost of the two operations. The result is given in the form of cost of the entire system (72,000 MT of SF), cost per metric ton of SF and cost per Kg. of reprocessed HLW disposed.

The cost of storage is found by estimating the cost of four different items, i.e., capital cost of the storage facilities, operating cost, surveillance cost and decommissioning cost. The model assumes that the capital expenditure for the facilities takes place during the five years previous to the beginning of operations, which, according to the proposed scenario, happens in the year 2000. The operating and surveillance costs are incurred during the entire operational life of the storage facility, whereas the cost of decommissioning is assumed to occur the year inmediately following the close of operations. The cost of the facilities is considered dependent on the maximum capacity, which in turn depends on the length of the period of storage of the HLW before disposal (delay of disposal). The

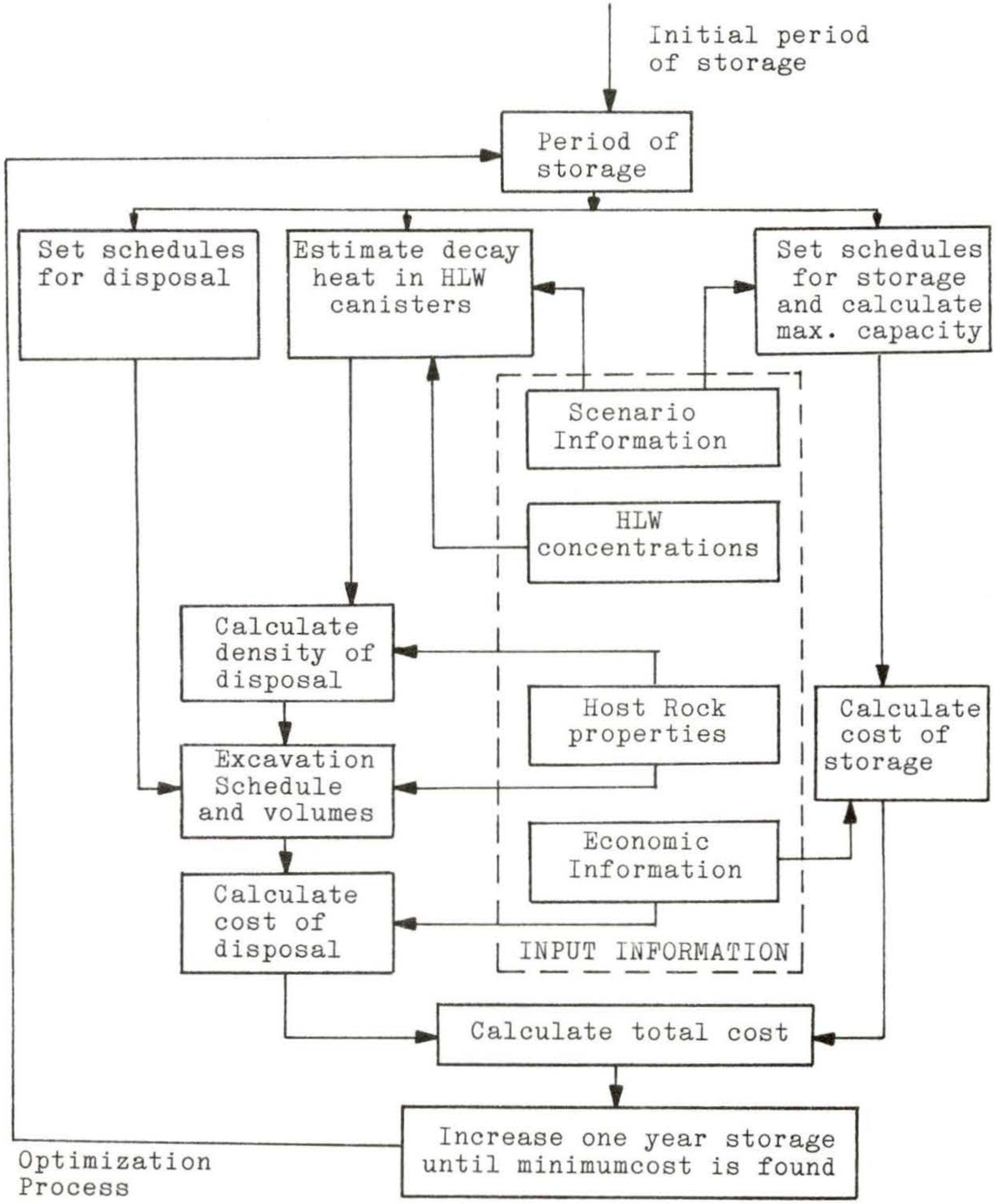

Figure 6. Model for the economic analysis

model calculates the maximum capacity and the different costs for each delay of disposal considered before the optimal situation has been reached.

To estimate the cost of disposal, the model evaluates first the mining schedule and volumes. Both the schedule and the excavation volumes depend on the period of storage, the latter because the heat generation rate decreases with the delay of disposal and, thus the density of disposal can be increased. For each length of the storage period, the heat generation rate in the HLW canisters is estimated, and the minimum pitch at disposal is calculated for each of the 30 years of operation of the repository. The pitch is not constant over the operational period because, according to the scenario for the first repository, the age of the spent fuel varies from 23 to 12 years when it is reprocessed. With the given excavation parameters and the calculated pitches, the excavation volumes are evaluated. The excavation costs are then estimated, under five different headings [50]:

1. Shaft excavation costs, not dependent on the heat source.
2. Hole drilling costs, which depend on the number of canisters disposed per year. A total of 3 canisters are assumed to be placed in the same hole.
3. Room excavation cost, dependent on the minimum pitch allowable each year.

4. Corridor excavation costs, which depends on the number of rooms excavated per year.
5. Avenue excavation costs, determined by the total size of the repository, which in turn depends also on the density of disposal.

Eight more items are added to the excavation costs in order to evaluate the total cost of disposal. These other partial costs are:

1. Cost of the above and underground facilities.
2. Preparation costs, which includes licensing of the disposal site and land preparation.
3. Architect-engineering costs.
4. Decommissioning costs of the aboveground facilities.
5. Surveillance cost.
6. Backfilling cost, dependent on the excavated volume.
7. Off-site rock disposal, if any.
8. Operations and maintenance costs, which include the maintenance of the installations and the operations of emplacement and overpacking of the canisters.

The model assumes that five years are necessary to build the facilities and they are finished by the beginning of operations (first HLW disposal). The preparation costs are incurred the year before the construction of facilities starts. Architect and engineering costs are scheduled along with the facilities and preparation costs.

The excavation of the corridors, rooms and boreholes is begun some time before the disposal operations in these locations. This time is supplied in the input information. The avenue excavation is performed during the two years previous to the first excavation of corridors and rooms, and the shafts are assumed to be excavated during the year before avenue excavation.

Rock disposal costs, if any, take place during all the years in which excavation is done. Backfilling operations are performed with a certain delay (to be given in the input information) with respect to the excavation of rooms and corridors. The backfilling of avenues and shafts takes place a certain period after the disposal operations have ended. This period is also to be given in the input data.

Maintenance and operation costs are incurred during the operational period of the repository, that is, when HLW is being disposed. Surveillance operations start at the time of the first disposal of HLW and conclude with the closure of the repository (backfilling of shafts). One year after repository closure, the surface facilities are assumed to be decommissioned.

All the costs are estimated according to the economic information that is supplied to the model. This information includes unit costs, auxiliary systems and facility costs, and the discount rate. Some of the unit costs are already incorporated in the model and the rest must be specified in the input information. A presentation and discussion of the input specifications is contained in Section C, which also includes the data assumed in the baseline case.

All the costs given to or contained in the model are in 1984 dollars. However, the costs are valued as of year 2000, which is the starting point for waste operations (storage). The disposal operations could be delayed for a long period of time after the year 2000, but discounting the costs from the first year of system operations (2000 A.D.) will provide a better basis for the optimization process, as well as for comparison of different situations.

B. Optimization of the Total Cost

The optimization of the total cost of storage and disposal is based, for a determined set of specifications, on the fact that the period of storage has a strong influence on the costs of storage and disposal. By continuing one more year the storage of HLW, three main effects are caused. First of all, the cost of storage is increased, since another year of operation is added and the maximum capacity may be increased. The maximum capacity will increase only during the first 30 years. After this period, no new shipments of HLW are to be made to this first disposal site. On the other hand, the heat generation rate in the HLW canisters at the time of disposal will decrease, and therefore, the density of disposal can be higher, thus reducing the excavation costs of the repository. Furthermore, the repository schedule is delayed one year and all the costs will be discounted one more year.

A detailed block diagram of the optimization process is shown in Figure 7. The process starts with an initial period of storage (N years). The costs of storage and disposal are calculated according to the economic model. Then, the period of storage is increased one year (to N+1) and the costs of storage and disposal are calculated again. The cost increase in the storage operation is compared with the savings in disposal. The criterion used to decide if storage should continue from year N to year N+1 can be expressed in the following way

If $CS(N+1) - CS(N) < CD(N) - CD(N+1)$, storage continues.

In this expression, CS is the cost of storage and CD the cost of disposal. Otherwise, when storage the cost increase from year N to N+1 is smaller than the disposal savings from year N to N+1, storage should end at year N [51].

The optimization process is continued until the optimum period of storage (minimum cost situation) is found. However, the process is bounded by political constraints in the form of minimum and maximum length of the time of storage. The minimum period of storage can be set in the input information,

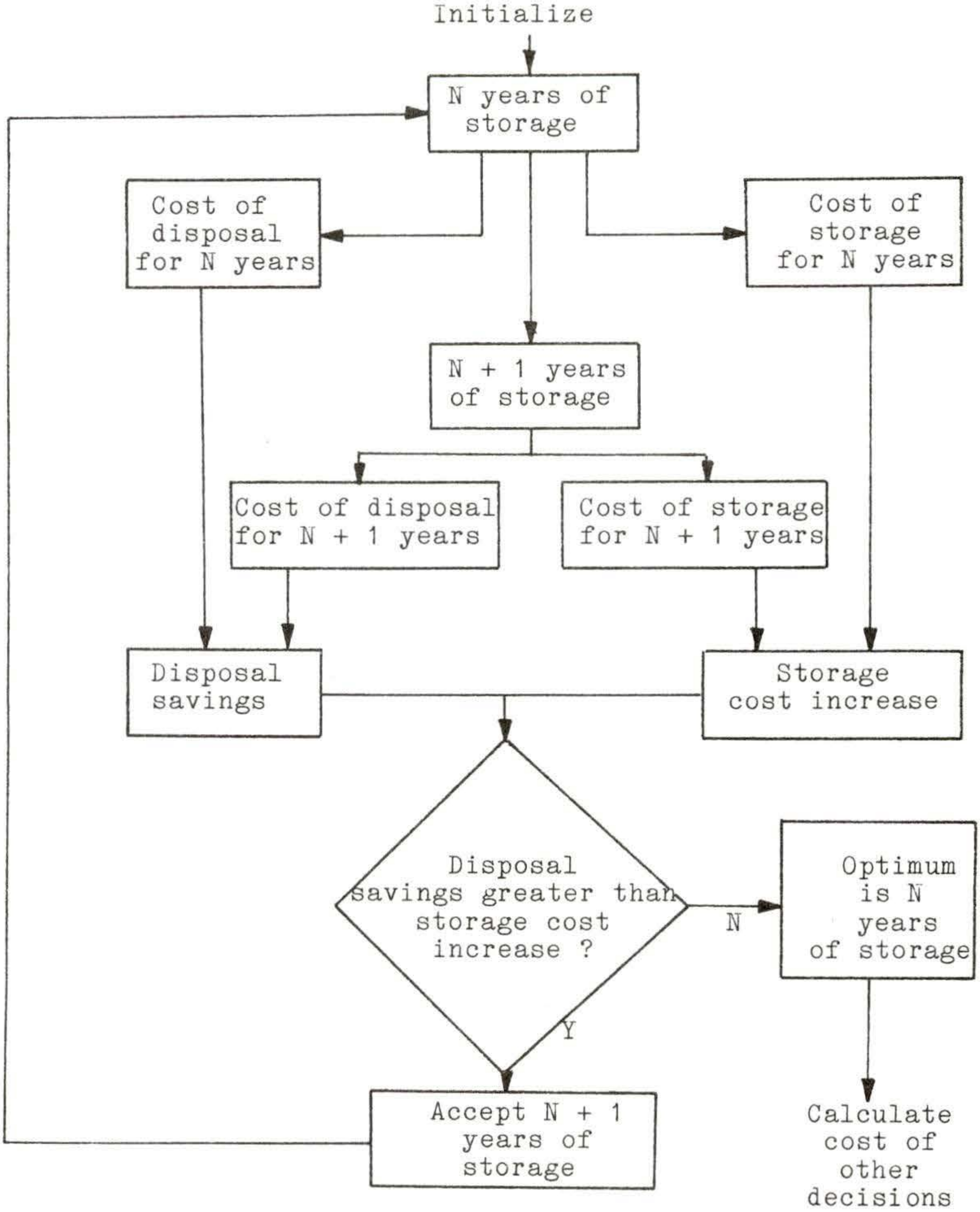

Figure 7. Block diagram of the optimization process

whereas the maximum period is assumed to be 100 years (Chapter III, Section E). If no optimization is possible within the 100 years period, the last year is taken as the minimum cost situation.

Another outcome of the optimization process is the evaluation of the cost of different political decisions on the time of storage, when they do not conform to the economic optimum. If a minimum cost situation is found within the 30 first years of the process, the differential cost of deciding to end the storage before the optimum time, is evaluated every 5 years. In case that the optimization is not possible within the 90 years period, the differential cost of ending storage before that time, is evaluated every 10 years. All these costs are converted to "present worth" in the year 2000.

C. Input Specifications: Presentation of the Baseline Case and Justification

Many variables are treated as parameters in the economic model, so that they can be easily modified by input specifications to perform the analysis under different conditions. Reference values, or specifications, for excavation parameters, scenario information, economic parameters and certain fixed schedules, are presented here.

1. Excavation parameters

The host rock type is the first information needed, and it must be selected from the four options: salt, tuff, granite and basalt. The maximum thermal loadings accepted by the selected rock type, are supplied by the program according to the values proposed in Table 8. However, there is the option of introducing new values for these loadings in the input. The next parameter is the "overall" shape of the repository, given as the ratio of total length to total width. This parameter is used to calculate the length of the avenues. In the baseline case, an overall shape with a ratio of 1.0 (a square repository) is assumed.

Information concerning the shafts (their number, diameter and depth) must be given in the input data. A total number of 4 shafts has been assumed in the baseline case. These shafts are for "men and materials" (9 m. in diameter), "supply air" (9 m. in diameter), "exhaust air" (4 m. in diameter) and "HLW" (3 m. in diameter). The number of shafts assumed, as well as their diameter, were selected from references 30 and 50, considering that the repository is not dedicated to SF, but designed for HLW. The diameter of the HLW shaft was reduced to 3 m. (from 4 m. considered in reference 30) because of the small size of the HLW canisters compared to the SF casks. The diameter of the exhaust air shaft was similarly reduced, because of the less restrictive temperature limits in case of

HLW. The depth has been assumed to be the same for all 4 shafts and, in the baseline case, is taken as 700 m.

The other excavation parameters are related to the dimensions of the rooms (nominal length, width and height), pillars (width), corridors (height and width), and avenues (height and width). These dimensions are all furnished in the program, in accordance with the values specified in Table 9. The user can also set new values for these parameters, by including them in the input information. The dimensions included in the program form the baseline case.

2. Scenario information

The information contained in the proposed scenario, concerning the annual shipments of HLW to the storage facility, must be given in the input data, in the form of canisters per year. The heat generation rate in the canisters is calculated in the program, and the different ages of the HLW disposed are taken into account. The conversion from MTHM to equivalent canisters of HLW has already been made within the program. This conversion has been made on the basis of the maximum content of waste in the HLW glass. As explained before, the content of waste in the glass is taken as 25 % by weight [21], and the dimensions of the glass blocks are 0.35 m. in diameter and 1 m. in length [36, 46]. The results of this conversion to canisters are displayed in Table 10, for the different BU rates considered. The number of canisters of glass generated for every 2,400 MT of SF reprocessed annually is the information supplied to the economic model and forms the baseline case. As can be seen from Table 10, 1,382 canisters of HLW will be shipped to the temporary storage facility for SF with a BU rate of 2.2 % at discharge. These shipments correspond to the first 2 years of operation (according to the scenario proposed). For the next 2 years, the SF reprocessed was discharged with a BU rate of 2.8 %, and the annual production of HLW amounts to 1679 canisters. The rest of the operational life (26 years), 1891 canisters will be received annually, for the SF being reprocessed will have

Table 10. Production of canisters of HLW for different BU rates[a, b]

BU rate %	F.P.+Actinide oxides/MTHM %	F.P.+Actinide oxides/MTHM Kgs.	Total waste oxides/MTHM %	Total waste oxides/MTHM Kgs.	Glass produced Kgs.	Canisters produced per 2,400 MT of SF
2.2	20.	28.8	25.	36.	144.	1,382
2.8	20.	35.	25.	43.7	175.	1,679
3.24	20.	39.5	25.	49.4	197.	1,891

[a] The glass block dimensions are 0.35 m. in diameter and 1 m. in length. The density of the HLW glass is 2.6 grams per cubic centimeter.

[b] The F.P. + Actinides oxides and the total waste oxides percentages, are over the total weight of the glass.

reached an average BU rate at discharge of 3.24 %.

3. Economic parameters and information

The economic information includes the shaft excavation costs, the unit excavation costs for the underground galleries, facilities cost, auxiliary systems and operation costs, unit backfilling cost, and off-site rock disposal cost, if any. The discount rate must also be provided in the input data.

To evaluate the cost of the shafts, the methodology proposed in the GEIS report [30] and adopted in the RECON program [50], has been used in this work. The cost of each shaft, per meter of depth, is given by the expression:

$$\text{Cost in \$ / m. of depth} = A + B \times D,$$

where D is the diameter of the shaft (in m.), and the parameters A and B are given in Table 11, for the different operations involved in the construction of the shafts and for the different types of host rock considered.

The parameters presented in Table 11 are included in the program, and the user has the option of accepting them or supplying new values in the input. The unit excavation costs are also furnished by the program, but they can be changed in the input, too. The values assumed as the baseline case, those supplied by the program, are shown in Table 12, for the different materials considered. These values are based on the

Table 11. Parameters for calculating the cost of construction of shafts in different rock types[a,b]

Rock type	Parameter	Sinking	Lining	Water Control
SALT/TUFF	A	16,570.	-4,612.	-3,028.
	B	382.	2,676.	1,795.
GRANITE	A	23,578.	1,276.	1,136.
	B	97.	0.	29.
BASALT	A	15,142.	666.	162.
	B	101.	0.	21.

[a] For tuff, with less information available than for the other materials, the parameters are assumed to be those for salt, that being the most similar material to tuff.

[b] The original data [50] was given in 1982 dollars and it has been levelized to 1984 dollars, using an annual inflation rate of 4 %.

estimations presented in the GEIS report [30] and they agree fairly well with the unit excavation costs used in RECON [50]. Two separate unit excavation costs are considered in our model: one for rooms and the other for avenues and corridors. Given the small size of the rooms proposed, and the relatively short time that they have to remain open, it is assumed that no support will be necessary in the case of disposal room openings. For avenues and corridors, the cost for support is included in the unit excavation costs of Table 12.

The hole drilling cost is evaluated according to the expression given in RECON [50], for the different types of rock:

$$\$ / \text{m. of depth} = A \times D^{**}B \quad \text{(Granite and Basalt)}$$

$$\$ / \text{m. of depth} = A \times \exp(B \times D) \quad \text{(Salt and Tuff)}$$

where D is the diameter of the borehole and the parameters A and B are displayed in Table 13. The diameter of the boreholes has been taken as 0.75 m., since the overpacking usually considered is around 15 or 20 cm. [12,33]. The depth of the boreholes is assumed to be 4 m., since 3 canisters are to be placed in each hole (each canister is 1.3 m. long).

The unit cost of backfilling (given in dollars per unit volume of gallery backfilled) is supplied by the user in the input information. Due to the lack of literature about backfilling costs, the baseline case takes this cost to be equal to the excavation cost (without support), per unit volume of material handled. Assuming a backfilling ratio of about 50 % [35], the costs of backfilling per unit volume of material will be 50 % of the unit excavation cost.

The cost of the facilities must be entirely supplied in the input specifications. For the storage facility, the cost is estimated by using the expression:

$$\text{Cost } (\$ \text{ M}) = A + B \times CAP^{**}0.75$$

where CAP is the maximum capacity of the facility and A and B are parameters given in millions of dollars. This expression

Table 12. Unit excavation costs of rooms, corridors and avenues, for different types of host rock[a,b]

Rock type	Unit excavation cost rooms	Unit excavatio cost Corridors and avenues
SALT	19.3	31.8
TUFF	25.0	37.2
GRANITE	40.5	53.0
BASALT	41.8	55.8

[a] The costs were originally given in 1978 dollars, and they have been inflated to 1984 dollars using the official annual inflation rates [63].

[b] The costs shown for tuff are those estimated for shale in the literature.

Table 13. Parameters for evaluating the cost of hole drillig in different host rocks[a,b]

Rock type	Parameter A	Parameter B
SALT/TUFF	41.5	1.16
GRANITE	1614.	1.31
BASALT	1695.	1.31

[a] Parameters A originally given in 1982 dollars [50] and inflated to 1984 dollars using an annual inflation rate of 4 %.

[b] Values for tuff have been assumed to be like those for salt.

has been proposed by DuPont, IAEA and Sweden, according to a comparative study performed by the Department of Energy [43], and it was derived for SF storage in AFR facilities. To adapt the results presented in the DOE report to the case of HLW, the fixed cost of the facilities (parameter A) is assumed to be the same as for SF. However, the capacity-dependent cost (parameter B) has been lowered. For storing HLW instead of SF, there is a volume reduction of 80 % and also a 10 % decrease in heat generation rate. Because of these significant reductions, the capacity-dependent cost of the storage facility is taken, in the baseline case, as 25 % of that for SF. However, the model will be applied to the case of a capacity-dependent cost of 50 % of that cost for SF, too. The parameters A and B, for both cases are listed in Table 14.

Less information is available for estimating the cost of the repository facilities. The existing studies refer to handling SF, which requires encapsulation facilities and a large receiving module. These facilities will not be needed in the present model, which assumes that the storage facility and the repository are located at the same site, that the HLW is encapsulated in the solidification plant, and that the canisters are taken from the storage facility to be disposed inmediately. However, an additional transportation system, from the storage facility to the HLW shaft, will be required and its cost is not included in the published cost estimates.

Table 14. Parameters for evaluating the cost of the storage facility for HLW[a, b]

Case	Fixed cost Parameter A M 1984 $	Capacity-dependent cost Parameter B M 1984 $	 % of cost for SF
Baseline	146.	15.6	25.
Option to Baseline	146.	31.2	50.

[a] Costs interpolated from data given in Reference 43 for SF storage, for different maximum capacities.
[b] Costs originally expressed in 1979 dollars and inflated to 1984 dollars, with official annual inflation rates [63].

Taking these factors into account and gathering data from reference 44 and the example shown in RECON [50], the cost estimate that will be used in the baseline case is, expressed in 1984 dollars, $ M 750., which includes both aboveground and underground facilities.

The operating cost of the facilities is also included in the input information. An annual cost estimate for operations and maintenance of the storage facility is given in the comparative study published by the Department of Energy [43]. In this study, it is considered that the cost of running a AR (at reactor) SF storage facility is about 5 % of the capital investment. Since the operating cost must be somehow proportional to the heat genration rate of the waste stored, it is assumed here that for HLW storage the operating cost would be essentially the same as that for SF, for the reduction in heat generation rate is only of 10 %, from SF to HLW. Moreover, the storage facility for HLW will not be located at the reactor site, and this can increase the cost of operations and maintenance, since an additional or larger crew can be expected. Therefore, the operations and maintenance cost for the HLW storage facility is taken in our model as 7 % of the capital investment, for the baseline case. In the repository, where there are more operations, such as internal transportation, emplacement and overpacking of the canisters, the operations and maintenance cost is assumed to be a higher percentage over the capital investment than in the case of the storage facility. The cost of operations and maintenance is one of the largest cost items in the estimates given in reference 44 and in the example shown in RECON [50]. Thus, in the baseline case, the annual operations and maintenance cost is taken as 10 % of the cost of the repository facilities.

It must be pointed out that the argument used to select the cost of the facilities as well as the costs of operations and maintenance (for both, the storage and the repository facilities) is rather weak. To obtain more accurate results with the economic model here presented, better estimates of these costs would be necessary, since (as shown in the results, Chapter VI) the final cost of storage and disposal is quite sensitive to the costs of the facilities and to the operating costs as well.

Decommissioning costs for facilities that are not likely to be contaminated is estimated as 20 % of the facility cost [43] and so is assumed in the baseline case. The decommissioning costs, as a percentage of the capital investment cost, must be supplied in the input data, for both the storage and the repository facilities.

For the disposal site, there are two additional costs: architect-engineering cost and land and site preparation cost. (For the storage facility, the architect-engineering cost is already included in the cost of the facility.) The land and site preparation cost is assumed to be about 3 % of the cost of repository facilities (and includes the area of the entire disposal site); it has been derived from data proposed in reference 44. The architect-engineerng cost is taken in the baseline case as 10 % of the cost of the facilities and the site preparation costs. This percentage is in acceptable agreement with the values used in RECON [50] and the data supplied by TRW Inc. [44].

A final cost included in the input is the cost of surveillance, for both the storage facility and the repository. It is expected that more security personnel and equipment will be needed in the storage facility, because the location of the radioactive waste (surface or near-surface) makes it more vulnerable to terrorist or sabotage actions. Monitoring of temperatures and radioactivity levels, for the case of the storage facility is included in the cost of operations. Lacking published estimates, it is assumed that 3 crews of 15 men will be needed for surveillance in the storage facility; some equipment will be needed, too. With these assumptions, the annual surveillance cost in the storage facility is estimated, in the baseline case, at $ M 2 (1984). For the repository, where the waste cannot be easily stolen, the security crew can be much reduced. However, surveillance in the repository must include periodic monitoring of water flow and geologic stability, in addition to the control of the general level of radioactivity and temperatures. It is assumed that no off-shifts of crews will be required for the operations other than security forces, and most of the monitoring will be interpreted by computer. Expensive equipment is likely to be used. Under these assumptions, the annual surveillance cost in the repository is estimated in the baseline case at $ M 4 (1984 dollars).

4. Fixed schedules

The last group of input specifications is formed by the fixed schedules and they include:

1. Minimum storage period to start the optimization process, taken as 4 years (as a political

constraint), in the baseline.

2. Number of years before operation of the repository to drill the shafts, considered as 5 years in the baseline.
3. Period of time (in years) to excavate the avenues, set at 2 years in the baseline.
4. Number of years after the last shipment of HLW, to close (seal) the repository. This parameter is set at 4 years in the baseline.
5. Delay for backfilling of the rooms, i.e., time that the rooms are to remain open after the canisters have been already placed. This time is taken as 2 years in the baseline case.
6. Number of years ahead of disposal to excavate the rooms and corridors, taken as 2 years in the baseline.

Besides these schedules, which of course can be varied in the input, other schedules fixed in the program are:

1. Maximum storage time, within the optimization process, 100 years.
2. Period of time to excavate the shafts, 2 years.
3. Period of time to construct the storage facilities, taken as 5 years.
4. Period of time to construct the repository facilities, assumed also to be 5 years.

5. Period of time for decommissioning of the facilities, 1 year.

The summary of the baseline case is given in Table 14, where the values for the different parameters are specified, and the parameters that can be changed in the input are also pointed out. It must also be said that in the baseline case the material selected was salt. The selection was made in view of the first partial results. Because of the very high VNF (very-near-field thermal loading) permitted by salt, this host rock turned out to be the only one that allows the optimization process to be started for 4 years of storage. No other reason brought us to select salt as the baseline rock type.

Table 15. Summary of the baseline case for the economic optimization model[a,b]

Parameter	Selection in the baseline case	Observations
Rock type	SALT	(1)
Overall shape of repository	Square	(1)
Number of shafts	4	(1)
Diameter of the shafts (m)	9. 9. 4. 3.	(1)
Depth of the repository (m)	700.	(1)
Room dimensions (m)		
nominal length	30.	
width	2.5	
height	2.5	(1)
Pillar width (m)	7.5	(1)
Corridor dimensions (m)		
width	5.	
height	4.	(1)
Avenue dimensions (m)		
width	7.	
height	6.	(1)
Shipments of HLW in number of canisters		
years 1-2	1,382	
years 3-4	1,679	
years 5-30	1,891	(1)

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[a] All costs expressed in 1984 dollars.

[b] (1) - These parameters can be changed in the input; (2) - These parameters are fixed in the program.

Table 15. (Continued)

Parameter	Selection in the baseline case	Observations
Shaft excavation cost parameters		
Sinking A	16,570.	
B	382.	
Lining A	-4,612.	
B	2,676.	
	101.	
Water control A	-3,038.	
B	1,795.	(1)
Unit excavation costs ($/m3)		
Rooms	19.3	
Others	31.8	(1)
Hole drilling costs		
Parameter A	41.5	
Parameter B	1.16	(2)
Borehole dimensions (m)		
Diameter	0.75	
Depth	4.	(2)
Backfilling cost ($/m3)	9.7	(1)
Cost of storage facility ($ M)		
Fixed cost	146.	
Cap.-dependent param.	15.6	(1)
Operating cost of storage fac. (% over capital cost)	7.	(1)
Cost of repository facilities ($ M)	750.	(1)
Operating cost of repository facilities (% over capital cost)	10.	(1)

Table 15. (Continued)

Parameter	Selection in the baseline case	Observations
Land and site preparation cost (% over rep. facility cost)	3.	(1)
Architect-engineering cost (% over rep. facility cost)	10.	(1)
Decommissioning cost (% over capital cost)	20.	(1)
Surveillance cost ($ M annually)		
Storage facility	2.	
Repository	4.	(1)
Schedules (years)		
Minimum period of storage to start optimization	4	(1)
Time before oper. to drill shafts	5	(1)
Time to excavate avenues	2	(1)
Time after oper. to seal rep.	4	(1)
Backfill. delay	2	(1)
Time ahead disposal to excavate rooms	2	(1)
Maximum period of storage for optim.	100	(2)
Time to excavate shafts	2	(2)
Time to build storage facilities	5	(2)
Time to build rep. facilities	5	(2)
Time for decommis.	1	(2)

VI. RESULTS AND ANALYSIS

The program developed for the economic analysis has been run for different situations in order to study the sensitivity of the model to several of its varying parameters. The model was first applied to the baseline case to obtain the basis for comparison of the other cases. The baseline case is summarized in Table 15. The other cases were created by varying one or more input specifications with respect to the baseline. A summary of the different cases analyzed can be seen in Table 16.

The first parameter studied was the discount rate, which appeared to be a key parameter, showing a very strong influence on the optimal period of storage and, consequently, on the final cost of storage and disposal. Besides the baseline discount rate of 0 %, four other discount rates were analyzed for two different values of the cost of storage (cases 1-9). The optimum time of temporary storage shows a very peculiar behavior as a function of the discount rate. For 0 % DR, the temporary storage period should be as short as possible (the minimum period politically accepted), whereas for other DR the optimum period of storage ranges from 5 to 25 years, except for the case of 5 % DR and the low-cost assumption for storage. In this later situation, no optimization was possible within the 100 years assumed as a political maximum for the period of storage.

Table 16. Description of the cases analyzed, as variations with respect to the baseline case[a]

Variation	Discount rate %	Capacity-dependent parameter of storage facility ($ M)	Other variations
Baseline	0	15.6	–
1	0	31.2	–
2	2.5	15.6	–
3	2.5	31.2	–
4	5	15.6	-
5	5	31.2	–
6	7.5	15.6	–
7	7.5	31.2	–
8	10	15.6	–
9	10	31.2	–
10	0	15.6	Unit excavation costs, doubled
11	5	31.2	Unit excavation costs, doubled
12	10	15.6	Unit excavation costs, doubled

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[a] In the baseline the material is SALT; the repository facilities cost is $ M 750; the repository depth is 700 m.; the operating cost of storage is 7 % of the capital cost; the backfilling delay is 2 years; the closure delay is 4 years; the operating cost of the repository is 10 % of the capital investment; the VNF for TUFF is 1600 w/canister (borehole); the VNF for BASALT is 1900 w/canister (borehole).

Table 16. (Continued)

Variation	Discount rate %	Capacity-dependent parameter of storage facility ($ M)	Other variations
13	0	15.6	TUFF
14	5	31.2	TUFF
15	10	15.6	TUFF
16	0	15.6	GRANITE
17	5	31.2	GRANITE
18	10	15.6	GRANITE
19	0	15.6	BASALT
20	5	31.2	BASALT
21	10	15.6	BASALT
22	5	31.2	Rep. fac. cost $ 600 M
23	10	15.6	Rep. fac. cost $ 600 M
24	5	31.2	Rep. fac. cost $ 900 M
25	10	15.6	Rep. fac. cost $ 900 M
26	10	15.6	Depth = 500 m.
27	10	15.6	Depth = 900 m.
28	10	15.6	Storage operating cost = 10 %
29	10	15.6	Storage operating cost = 10 %
30	5	31.2	Backfill. delay: 3 y Closure delay: 5 y

Table 16. (Continued)

Variation	Discount rate %	Capacity-dependent parameter of storage facility ($ M)	Other variations
31	5	31.2	Backfill. delay: 5 y Closure delay: 10 y
32	10	15.6	Backfill. delay: 5 y Closure delay: 10 y
33	0	15.6	Repository oper. cost 5 %
34	5	15.6	Repository oper. cost 5 %
35	0	15.6	Repository oper. cost 15 %
36	5	31.2	Repository oper. cost 15 %
37	5	31.2	Repository oper. cost 5 %
38	10	31.2	Repository oper. cost 5 %
39	10	15.6	Repository oper. cost 15 %
40	10	31.2	Repository oper. cost 15 %
41	5	31.2	TUFF VNF= 1800 w/can.
42	10	15.6	TUFF VNF= 1800 w/can.
43	5	31.2	BASALT VNF= 2300 w/can.
44	10	15.6	BASALT VNF= 2300 w/can.

With these first ten situations, it can already be seen that the final costs are extremely dependent on the discount rate adopted. Because of this, the analysis of some other parameters was performed at more than one discount rate (0, 5 and 10 %). Such is the case of the unit excavation costs, rock type, repository facilities cost, and operating cost of the repository. 0 % DR, however, was not used very often because the optimum time of storage turned out to be always the shortest possible (4 years) and it did not offer much insight in the analysis.

From the results of the cases studying the discount rate effect, the influence of the storage facility cost can be observed. By increasing the cost of the storage facility (the capacity-dependent term), appreciable reductions in the length of the optimum period of storage were observed. The shortening of the optimum period is particularly drastic for 2.5 and 5 % DR. Since the cost of the storage facilities was seen as another key parameter, results for the two options were obtained when analyzing the other variables. The results of the different cases analyzing the sensitivity to the discount rate and to storage facility costs, are displayed in Table 17.

Variations of the unit excavation costs were also studied, for different discount rates and different costs of the storage facility. No sensible variations in either the optimum period of storage or in the final costs were observed. This result is not very surprising, since the repository in the model was designed in order to minimize the excavation volumes and, in all the cases, the excavation costs represent a small fraction of the total cost of disposal (between 2 and 5 %, excluding shaft excavation costs). The results for different unit excavation costs are shown in Table 18.

The results of comparing different host rock types are also very interesting. It must be pointed out that in materials other than salt, the optimization process starts for an initial storage period much longer than 4 years. This is because of the very-near-field thermal loading limit. For tuff (VNF=2,300 w/can.) the optimization begins for an initial period of storage of 26 years. This initial period is 10 years for granite (VNF=2,300 w/can.) and 18 years for basalt (VNF= 1,900 w/can.) For 0 % DR, the optimum period of storage is exactly the minimum dictated by the VNF thermal limit. As the discount rate increases, the optimum period of storage tends to do so, too. However, for tuff, 10 % discount rate is still not enough for increasing the optimum storage time. Nevertheless, while the final costs are very different (for the different rock types) at low discount rates, they become very similar at higher (10 %) DR, no matter what the optimum period of storage happens to be. If the total cost at low DR is higher for tuff, granite and basalt than for salt, it is because of the much higher cost of storage. The repository costs are, in fact, lower than in the case of salt, since the excavation volumes are considerably smaller. These results might be expected, because the only stricter thermal loading limit for tuff, granite and basalt with respect to salt, is the very-near-field, but not the areal loading. Table 19 contains the results for these situations with different rock

Table 17. Results for variations analyzing the sensitivity to the discount rate and storage facility cost

Case	DR %	Cap-dep. cost of storage ($ M)	Final costs ($ 1984) System ($ M)	Fuel ($/KHM)	Glass ($/Kg)	Optimum period storage (years)
Base.	0	15.6	4,478	62.2	323.8	4
1	0	31.2	4,783	66.4	345.8	4
2	2.5	15.6	2,809	39.0	203.1	25
3	2.5	31.2	3,500	48.6	253.	5
4	5	15.6	1,434	19.9	103.7	>100
5	5	31.2	2,478	34.4	179.2	15
6	7.5	15.6	1,354	18.8	97.9	23
7	7.5	31.2	1,955	27.1	141.4	15
8	10	15.6	1,161	16.1	84.	21
9	10	31.2	1,689	23.4	122.1	14

types.

The sensitivity of the model to variations in capital cost of the repository was also studied and the results are shown in Table 20. Slight differences in the final costs (less than 5 %) were obtained for variations of + or - 20 % in the repository facility costs, and significant changes in the optimum period of storage, especially at low discount rates, were also observed.

Table 18. Results of variations analyzing the sensitivity to the unit excavation costs[a]

Case	DR %	Cap-dep. cost of storage ($ M)	Unit exc. cost	Final costs ($ 1984 M) System ($ M)	Fuel ($/KHM)	Glass ($/Kg)	Optimum period storage years
Base.	0	15.6	Base.	4,478	62.2	323.8	4
10	0	15.6	Double	4,561	63.3	329.8	4
5	5	31.2	Base.	2,478	34.4	179.2	15
11	5	31.2	Double	2,497	34.6	180.6	15
8	10	15.6	Base.	1,161	16.1	84.	21
12	10	15.6	Double	1,165	16.1	84.2	21

[a] The baseline costs (salt) are 19.7 $/m3 in rooms, and 38 $/m3 in avenues and corridors. The doubled costs are 39.4 $/m3 in rooms and 76.0 $/m3. in avenues and corridors.

Table 19. Results of variations analyzing the sensitivity to the different types of host rock[a,b]

Case	DR %	Cap.-dep. cost of storage	Rock type	Final costs (1984 $)			Optimum period storage (years)	Observation
				System ($ M)	Fuel ($/KHM)	Kg. glass ($)		
Base.	0	15.6	SALT	4,478	62.2	323.8	4	
13	0	15.6	TUFF	6,186	85.9	447.3	26	(1)
16	0	15.6	GRANITE	4,948	68.7	357.8	10	(1)
19	0	15.6	BASALT	5,524	76.7	399.4	18	(1)
5	5	31.2	SALT	2,478	34.4	179.2	15	
14	5	31.2	TUFF	2,642	36.7	191.1	26	(1)
17	5	31.2	GRANITE	2,486	34.5	179.8	15	
20	5	31.2	BASALT	2,485	34.5	179.7	18	(1)
8	10	15.6	SALT	1,161	16.1	84.0	21	
15	10	15.6	TUFF	1,186	16.4	85.8	26	(1)
18	10	15.6	GRANITE	1,159	16.1	83.8	21	
21	10	15.6	BASALT	1,153	16.2	83.4	20	

[a] The rock type in the baseline case is salt.

[b] (1) - The optimization occurs at the minimum time required for the very-near-field thermal loading, which is more restrictive in materials different than salt.

For a constant discount rate and a constant cost of storage facility, no significant variations in the results were found for changes of + or - 20 % in the depth of the repository. As in the analysis of the unit excavation costs, this rather flat behavior of the final costs versus the depth of the repository, is due to the fact that the shaft excavation costs represent only a small fraction of the total cost of disposal. The results of sensitivity of the model to variations in the depth of the repository are in Table 21.

Table 20. Results of variations analyzing the sensitivity to the repository facilities cost[a]

Case	DR %	Cap-dep cost of storage ($ M)	Repos. facil. cost ($ M)	Final costs ($ 1984 M) System ($ M)	Fuel ($/KHM)	Glass ($/Kg)	Optimum period storage years
5	5	31.2	750	2,478	34.4	179.2	15
22	5	31.2	600	2,297	31.9	166.1	12
24	5	31.2	900	2,625	36.4	189.8	18
8	10	15.6	750	1,161	16.1	84.	21
23	10	15.6	600	1,121	15.5	81.1	19
25	10	15.6	900	1,194	16.5	86.4	22

[a] The baseline cost for the repository facilities is $ 750 M (1984 dollars).

Table 21. Results of variations analyzing the sensitivity to the depth of the repository[a]

Case	DR %	Cap-dep. cost of storage ($ M)	Depth (m)	Final costs ($ 1984 M) System ($ M)	Fuel ($/KHM)	Glass ($/Kg)	Optimum period storage years
8	10	15.6	700	1,161	16.1	84.	21
26	10	15.6	500	1,154	16.0	83.4	20
27	10	15.6	900	1,168	16.2	84.4	21

[a]The baseline depth was taken as 700 m.

The model has shown a higher sensitivity to the operating cost of the storage facility (Table 22). Although small changes in the optimum period of storage are observed for relatively large variations in the operating cost (about + or - 40 %), the changes in final cost are more significant.

Two parameters have shown almost no influence at all on the final costs or on the optimum period of storage. They are the delay of backfilling of the rooms after they have been filled with HLW canisters, and the delay of closure and sealing of the repository after disposal operations have been terminated. The results for the cases corresponding to variations of these parameters are shown in Table 23.

Table 24 shows the sensitivity analysis to the operating cost of the repository facilities. This is another parameter

Table 22. Results of variations analyzing the sensitivity to the operating cost of the storage facility[a]

Case	DR %	Cap-dep. cost of storage ($ M)	Oper. cost of storage (%)	Final costs ($ 1984 M) System ($ M)	Fuel ($/KHM)	Glass ($/Kg)	Optimum period storage years
8	10	15.6	7	1,161	16.1	84.	21
28	10	15.6	10	1,302	18.0	94.1	19
29	10	15.6	4	1,015	14.1	73.4	22

[a] The operating cost of the storage facility is expressed as a percentage of the facility cost. In the baseline case, this parameter is 7 %.

showing a great influence on costs and optimum periods of storage. The behavior of both the optimal situation and its corresponding total cost with respect to changes in the operating cost of the repository is rather irregular, depending also on the discount rate considered and on the option taken for the storage facility cost. For constant DR and storage facility cost, changes in the optimum time of storage are fairly small at very low (0 %) or very high (10 %) discount rates, whereas for 5 % DR, the changes are drastic. However, differences in cost follow a more continuous pace, becoming less important as the discount rate increases.

Because of the very interesting results found in the analysis of the costs for the different rock types, a final

Table 23. Results of variations analyzing the sensitivity to the schedules of backfilling and closure[a]

Case	DR %	Cap.-dep. cost of storage	Backfill. schedule (years)	Closure schedule (years)	Final costs (1984 $)			Optimum period storage (years)
					System ($ M)	Fuel ($/KHM)	Kg. glass ($)	
5	5	31.2	2	4	2,478	34.4	179.2	15
30	5	31.2	3	5	2,478	34.4	179.1	15
31	5	31.2	5	10	2,476	34.3	179.0	15
8	10	15.6	2	4	1,161	16.2	84.0	21
32	10	15.6	5	10	1,161	16.1	83.9	21

[a] The backfilling schedule (time that the rooms are to remain open after the HLW canisters have been emplaced) is set at 2 years in the baseline case. The closure schedule (time after operations to close and seal the repository) is set at 4 years in the baseline case.

Table 24. Results of variations analyzing the sensitivity to the operating cost of the repository facilities[a]

Case	DR %	Cap-dep. cost of storage ($ M)	Oper. cost of repos. (%)	Final costs ($ 1984 M) System ($ M)	Fuel ($/KHM)	Glass ($/Kg)	Optimum period storage years
Base.	0	15.6	10	4,478	62.2	323.8	4
33	0	15.6	5	3,354	46.5	242.5	4
35	0	15.6	15	5,603	77.8	405.2	4
4	5	15.6	10	1,434	19.9	103.7	>100
34	5	15.6	5	1,695	23.5	122.6	22
5	5	31.2	10	2,478	34.4	179.2	15
37	5	31.2	5	2,269	31.5	164.1	9
36	5	31.2	15	2,613	36.2	189.	19
9	10	31.2	10	1,689	23.4	122.1	14
38	10	31.2	5	1,647	22.8	119.1	12
40	10	31.2	15	1,722	23.9	124.5	15
8	10	15.6	10	1,161	16.1	84.	21
39	10	15.6	15	1,170	16.2	84.7	22

[a] The operating cost of the repository is given as a percentage of the facilities cost. In the baseline case this percentage is 10 %.

set of cases were run for studying the effect of the very-near-field thermal loading limit. The rock types chosen for this refinement were those with a more severe limit, tuff and basalt. The results are shown in Table 25. Important differences in cost were not observed by increasing the VNF thermal limit 12.5 % in tuff and 21 % in basalt. However, the optimum period of storage shows more considerable variations. It is important to observe that, for tuff, the optimum time of storage is the minimum the thermal limit permits, 21 years in the case of high VNF (1800 w/can.) and 26 for low VNF (1600 w/can.).

In summary, the most important parameters exerting influence on the optimization of storage and disposal costs, are, in decreasing order of importance:

1. Discount rate.
2. Cost of storage facility.
3. Operating cost of the repository.
4. Material excavated (rock type and its thermal loadings).
5. Repository facilities cost.
6. Operating cost of the storage facility.
7. Depth of the repository.
8. Unit excavation costs.
9. Schedules for backfilling and closure.

In general, the model becomes more sensitive to variations of the different parameters, for intermediate discount rates (5 %). Since the excavation costs turned out to be a small fraction of the repository cost, the savings in

Table 25. Results of variations analyzing the sensitivity to the VNF thermal loading[a,b]

Case	DR %	Cap.-dep. cost of storage	Rock type	VNF thermal loading	Final costs (1984 $)			Optimum period storage (years)	Observation
					System ($ M)	Fuel ($/KHM)	Kg. glass ($)		
14	5	31.2	TUFF	1,600	2,642	36.7	191.1	26	(1)
41	5	31.2	TUFF	1,800	2,533	35.1	183.1	21	(1)
15	10	15.6	TUFF	1,600	1,186	16.4	85.8	26	(1)
42	10	15.6	TUFF	1,800	1,161	16.1	84.0	21	(1)
20	5	31.2	BASALT	1,900	2,485	34.5	197.7	18	(1)
43	5	31.2	BASALT	2,300	2,471	34.3	178.7	15	
21	10	15.6	BASALT	1,900	1,153	16.0	83.4	20	(1)
44	10	15.6	BASALT	2,300	1,153	16.0	83.4	20	

[a] The VNF thermal loadings, in the baseline case, are 1,600 and 1,900 w/canister for tuff and basalt, respectively.

[b] The VNF thermal loading limit loading limit is for a canister with a length of 3 meters, i.e., for a borehole with 3 1 m.-long canisters. (1) - The optimization occurs at the minimum time required for the very-near-field thermal loading.

disposal obtained by increasing the period of storage, are due principally to the deferral of the disposal expenses. For very low (0 %) discount rates, deferral of the repository expenses does not produce significant savings in disposal and, therefore, nothing is gained by aging the HLW before disposal. The optimum periods of storage are always the minimum politically acceptable. For high discount rates (10 %), considerable savings are found when aging the HLW, because of the deferral of the disposal cost. The optimum period of storage is always found around 20 years and the costs levelize to a more or less constant value in all the cases. Intermediate discount rates (5 %) represent the critical point, where the savings due to the deferral of the disposal cost are not as important as for 10 % DR. Therefore, the model becomes much more sensitive to the other specifications.

It must also be noticed that the optimum situations are always found within the first 30 years of storage. Case 4 was the only one that was not optimized during this period; for this case no optimization was possible within 100 years of storage. The reason for this behavior is that the maximum capacity of the storage facility keeps increasing for periods of storage up to 30 years. Consequently, the storage cost increase for one more year of storage (within this 30 years) is very large. For times of storage longer than 30 years, the maximum capacity remains constant and therefore, the storage cost increase for one more year of delay of disposal is not very substantial. Since, in general, the disposal costs are higher than the storage costs, the optimization would take place for very long (considerably longer than 100 years) periods of storage. Even though they are optimal, such long periods of storage, more than 30 years, might be politically unnacceptable.

The model also provides an estimate of the cost of deciding to terminate the storage after a period of storage different from the optimum. Some examples are provided in Table 26. As expected, the cost of disposing at a time different than the optimum is larger, the further the chosen time is fromthe optimum. The cost of a "non-optimum political decision" depends again on all the parameters and in the same order of importance that the final optimum costs depended on.

For the cost of political decisions, though, the most sensitive cases appear for high discount rates. For low DR, a decision five or ten years before the optimum period of storage would mean a relatively small increase in the total cost with respect to the optimum situation (less than 1 % and 3 % respectively). But, for 5 % DR, the increase in the total cost is already much higher: 1 to 3 % for 5 years before optimum, 6 to 10 % for 10 years and around 20 % for 15 years. In the cases of 10 % DR, the cost increases can be extraordinarily high: in the order of 3 to 7 % for disposing 5 years before the optimum time, 14 to 25 % for 10 years and from 45 up to 72 % in case of disposal 15 years before the optimum, depending on each particular situation.

Table 26. Cost of terminating storage after a period different than the optimum[a]

Case	DR %	Optimum period of storage (years)	Total cost for optim. period of storage ($ M)	Cost of terminating storage 5 years before optimum ($ M)	%	10 years before optimum ($ M)	%	15 years before optimum ($ M)	%
2	2.5	25	2,809	21	1	89	3	214	8
5	5	15	2,478	56	2	255	10		
36	5	19	2,613	27	1	180	7	500	19
37	5	9	2,269	30	1				
34	5	22	1,695	50	3	160	9	370	22
43	5	15	2,471	56	2				
8	10	21	1,161	48	4	220	19	650	56
9	10	14	1,689	50	3	342	20		
26	10	20	1,154	43	4	210	18	635	55
28	10	19	1,302	29	2	180	14	590	45
29	10	22	1,015	72	7	260	26	730	72

[a] The costs in absolute values and the percentages are approximate figures. All costs expressed in 1984 dollars.

VII. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

A. Introduction

The principal goals of this work have been achieved. Within the frame of a closed fuel cycle, the model for the back end was presented. The key parameters to be considered in a cost analysis were identified and discussed, for all the steps involved in the model for the back end of the fuel cycle. On the basis of the model adopted for the back end of the nuclear fuel cycle, the scenario for the first repository was developed, according to the present state of the nuclear industry and the political constraints currently expected.

The definition of the model and the proposal of the scenario have been two necessary steps for developing the economic model and performing the optimization analysis. In setting the basis for the economic optimization of the temporary storage and disposal of HLW, the different costs involved in these operations have been identified and discussed.

A computer program has been written to estimate and optimize the costs of storage and disposal. Most of the parameters involved in the optimization process are treated as parameters that can be changed in the input information that the user must supply. Based on other partial cost estimates, a baseline case and the results of the optimization have been found. However, many uncertainties are still involved in the cost issues, and the analysis of a particular situation could not provide a complete picture of the cost of storage and disposal of HLW. A single answer to the problem of the optimization of the temporary storage and disposal cannot be given with the present state of development. Therefore, the model has been applied to many other situations different from the baseline, in order to find how much the optimum results depended on the setting of some key parameters.

B. Conclusions and Discussion

Several conclusions can be drawn from analyzing the results of the economic optimization model applied to different situations. These conclusions refer to both general patterns observed and sensitivity analyses to particular parameters.

The first general finding is that a least-cost situation does exist for a very wide range of situations. There is only one case in which the optimum is not found until periods of storage longer than 100 years. Moreover, in the cases that can be optimized for reasonable periods of storage, the least-cost situation is always found for times of storage shorter than 30 years. This is a very encouraging result, because relatively short periods of storage (5 to 30 years) are more likely to meet public acceptance than longer (30 to 100 years) storage times. This situation suggests that the optimum period of storage is either found within the 30 first years of storage or at unacceptably long periods (over 100 years).

The behavior of the model to variations in the discount rate is one of the most interesting findings (Figure 8). There is not a direct proportionality between DR and the final optimum situation. The peculiar behavior appears for some situations (when cost of storage is relatively low) at intermediate discount rates. For low discount rates, the optimum period of storage is always the minimum acceptable, whereas for high discount rates the least-cost situation is found for times of storage in the upper half of the 30 year period. In general, the optimum costs tend to level off for high discount rates. At 10 % discount rate, the only parameter, among those studied, that is capable of making considerable differences in the outcome of the optimization, is the cost of the storage facility. Not even the rock type, with severe changes in the VNF thermal loading limit yields significantly different results. Therefore, a high discount rate situation turns out to be the most stable case with respect to the other varying parameters. Although this high discount rate situation is desirable, there exists a drawback; the penalty for terminating the storage at times different than the optimum is much higher than in the cases with a lower discount rate. In addition to the cost of the storage facility, the other parameters become more influencing on the results of the optimization for lower discount rates. The optimum cost is more sensitive to the varying parameters at 0 % discount rate, whereas the optimum period of storage is very sensitive to the parameters at intermediate discount rates.

A parameter that deserves further comments is the unit excavation cost of the repository. In all cases studied, the excavation costs contribute a small fraction to the total cost of the repository. Even when the unit excavation costs were multiplied by a factor of 2, no sensible changes ocurred in the optimal situation (neither in the cost nor in the optimum period of storage). It can be concluded that no major efforts should be directed to minimizing the excavated volume; reasonable changes in the excavation parameters will not sensibly alter the outcome of the economic analysis. Moreover, the length of the HLW canisters (that was set at 1 m. in order to reduce the height of the room) and the question of disposing the casks horizontally, are two issues that are not likely to affect the final cost of the repository in any substantial way.

Other important conclusions come from the comparison of the four different types of host rock. First of all, and because of the relatively small excavation costs, the differences found in the optimum situation for the four

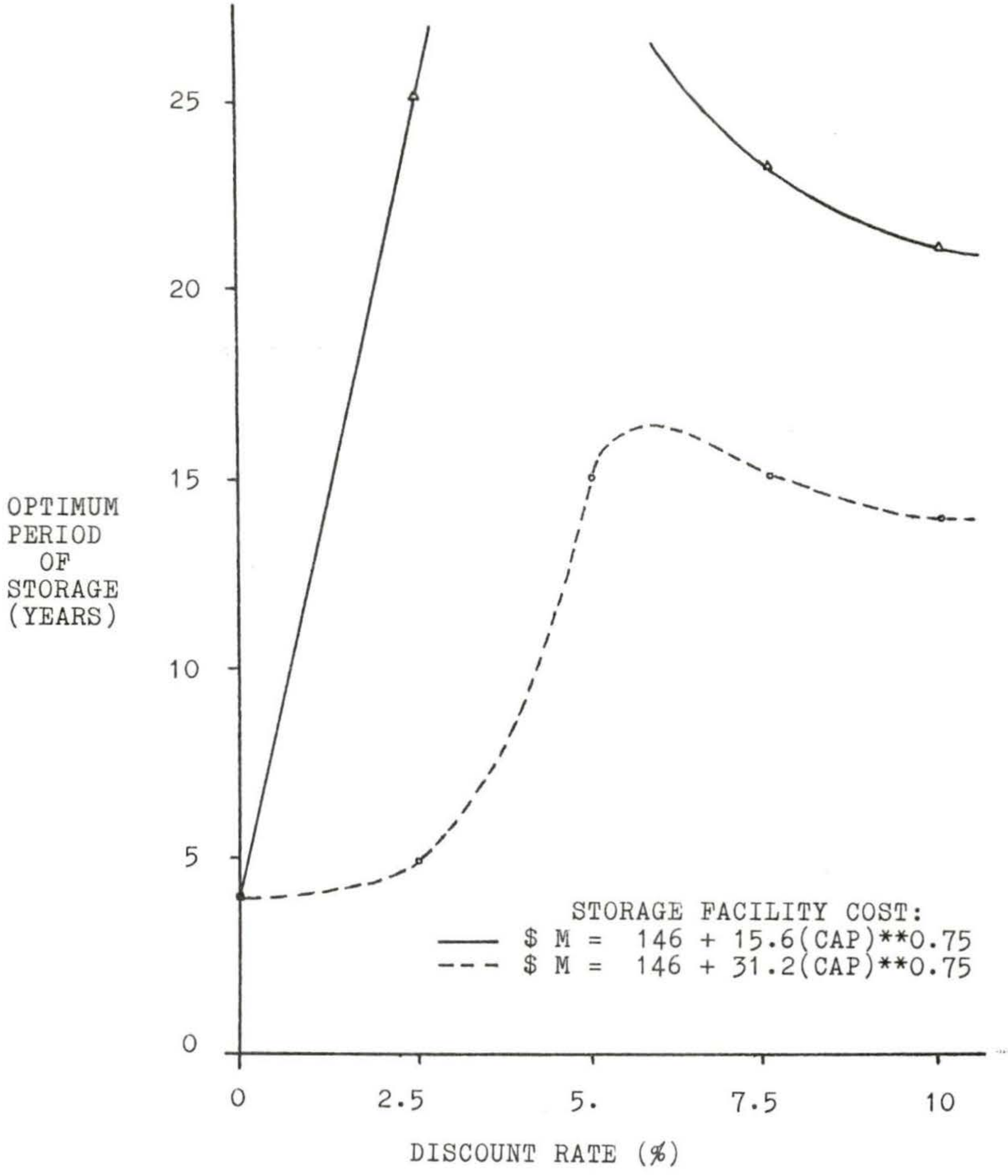

Figure 8. Sensitivity of the optimum period of storage to the discount rate

different materials are never due to the differences in unit excavation costs. The model is very sensitive to the very-near-field thermal loading limit. When this parameter becomes low (tuff, basalt), it imposes a restriction in the minimum age of the HLW to be disposed. Thus, for host rocks allowing a relatively low VNF thermal loading, the HLW must be aged to meet technical requirements, but not for economic reasons. If the VNF thermal loading had not imposed a severe restriction in tuff, basalt and granite (in decreasing order of severity), the results of the optimization in these host rocks would have been very similar to those for salt at any particular discount rate. Since poor VNF thermal loadings require older HLW at disposal, the differences in optimal costs for tuff, basalt and granite with respect to the costs for a repository in salt, become more evident at low discount rates. At high discount rates, the optimum period of storage is similar for all four materials, and the difference in final cost is not very substantial. It is important to notice that the increase in cost for tuff, basalt and granite at low discount rates is due to the increase in the period of storage. Furthermore, the cost of the repository is lower for host rocks other than salt, even though the unit excavation costs are higher. This is due to the fact that the pitches can be shorter for tuff, basalt and granite, since the severe restriction is in the VNF, but not in the areal thermal loading.

The problem presented by the materials with a low VNF thermal loading could be partially reduced by decreasing the heat load in a single borehole. This could be attained by reducing the content of waste in the HLW glass. Although an increase in the repository surface area (and excavated volume) would be produced with this measure, its effect in the optimum cost would presumably be lower than the effect of the VNF restriction, for the model is not very sensitive to the excavation costs.

In summary, the results at different discount rates, (0, 5, and 10 %) lead us to conclude that the parameters that need to be more carefully analyzed are, as shown in Table 27, the cost of the storage facility in all cases, and the operating costs (of both the storage and repository facilities) and the rock type at intermediate and low discount rates. In taking the decision about the period of disposal, the situation turns over, and the case that must be more carefully studied is the high discount rate situation, in order to avoid high economic penalties with respect to the least-cost situation.

Finally, and according to the results observed in our economic model, some recommendations can be made concerning the research areas involved in the storage and disposal of the HLW. The major research efforts should be directed towards the parameters that are more influencing on the final cost, such as the thermal loadings for the different host rocks considered, and the costs incurred in the storage of the HLW. Improvements in the other parameters (such as the excavation parameters) will not produce a substantial change in the least-cost situation for the storage and disposal.

Table 27. Sensitivity of the model to the different changing parameters, at given discount rates[a]

Parameter	Effect on the final outcome					
	0 % D.R.		5 % D.R.		10 % D.R.	
	Optim.	Cost	Optim.	Cost	Optim.	Cost
Storage facility cost	5	2	1	1	2	2
Repository facilities cost			3	3	4	4
Operating cost of storage f.					4	3
Repository depth					5	5
Backfilling and closure schedules			5	5	5	5
Operating cost of repository f.	5	2	5	3	4	4
Excav. costs	5	4	5	5	5	5
Rock type	2	3	3	4	4	5
Cost of terminating storage at times different from opt.	Low		Intermediate		High	

[a]1 - Extremely large effect; 2 - Very large effect; 3 - Considerable effect; 4 - Little effect; 5 - Insignificant effect.

C. Suggestions for Future Work

The results obtained with the economic optimization model depend on the quality of the information available. Therefore, a first step in further work on this field, should be directed towards the improvement of this information. In particular, as the results suggest, some cost issues should be better analyzed, such as the operating cost of the facilities and, especially, the cost of the storage facility. In the development of the designs of the storage and repository facilities, major efforts should be put on reducing the costs of storage and the operating cost of the repository, for their great impact on the final system cost.

More research is also needed on the host rock properties. A suggestion here is that on-site tests should be carefully performed to establish a VNF thermal loading as accurate as possible. The confirmation of the accepted values of the VNF used or any change will increase the confidence in the results predicted by the model. Improvements in setting the excavation parameters or some geometric characteristics of the repository (although they are important for geologic stability) will not contribute substantially to reduce the final cost. It would be very interesting to run the program with lower concentrations of waste oxides in the glass (and consequently, a larger number of canisters of HLW), for the cases of disposal in tuff, basalt and granite. The excavation costs would be larger, but the optimum period of storage would presumably be shorter, thus reducing the costs of storage. The results obtained for these situations could change the conclusion that the disposal in materials with low VNF is expensive because of the long storage period. It could be checked if the savings obtained in storage by using lower concentrations of waste in the HLW glass are higher than the additional excavation costs incurred.

Another interesting further development of the economic model would be its application to the case of SF disposal. As was explained, the length of the canisters of SF (about 4 m.) are not likely to affect the final cost. However, the SF has a more restrictive VNF thermal loading and this could certainly yield a much higher cost for disposal of SF. To avoid the restriction imposed by the VNF thermal loading limit, the amount of SF per borehole could be reduced, thus enlarging the size of the repository. Since the volume of SF is roughly four times that of HLW, a repository 3 to 4 times larger could be needed for SF. In that case, the excavation cost may become an important fraction of the total repository cost. The differences in HLW and SF disposal costs should be evaluated. The results could provide more information to be used in deciding whether to reprocess or not.

Finally, the model optimization of the storage and disposal of the HLW could be extended to the entire back end of the nuclear fuel cycle. An economic optimization of the whole back end, would test some of the assumptions that were made in defining the model for the storage and disposal. Furthermore, the economic model of the back end of the fuel cycle could be incorporated to the economic analysis of the front end (in-core fuel management) for economically testing the practices being currently performed.

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X. APPENDIX. LISTING OF THE COMPUTER PROGRAM DEVELOPED FOR THE ECONOMIC OPTIMIZATION

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C OPTIMIZATION PROGRAM FOR THE STORAGE AND DISPOSAL OF HLW. THE
C ANALYSIS IS RESTRICTED TO A MAXIMUM AGE OF 100 YEARS FOR THE
C HLW. THE HOST ROCK OF THE REPOSITORY, SOME GEOMETRIC CHARAC-
C TERISTICS, THE ANNUAL SHIPMENTS OF HLW PACKAGES, THE UNIT COSTS
C AND THE SCHEDULES ARE GIVEN IN THE INPUT.

      INTEGER IYAR,IYST,IS,ID,NSHAFT,IBK,IC,WARN,IYSHE,IAS
      INTEGER ISH,IAV,IYAVE,IYRE,IYBCK,IYBCS,IYLS,IYMC
      INTEGER IYSD,NCPH,IFA,IDC,N,IPREP,MUSSOL,OPT,SOPES
      INTEGER NROOM(30),TNROOM,NCAN(30),NHPR(30),HODR(30)
      INTEGER CUCAP(120),SHPD(120),MAXCAP
      REAL VNF,NF,FF,RW,RLI,RH,CW,CH,PW,CDBR,T1,T2,T3,Q1,Q2,Q3,T
      REAL MTPP1,MTPP2,MTPP3,PITCH1,DEPTH,VOLSH,PI,TLOC,OS,A,B
      REAL NCOL,NROW,AVW,AVH,VOLAV,TOTHD,FAC,FACC,PWAUX,CPRE,AEC
      REAL AEPER,DEPER,DUSURVC,SUSURVC,MAPER,PWDS,DSPER,PWBCS,AJU
      REAL PWOEX,MAXCAT,FSTF,FSTFY,PSFTF,RST,RSPER,TSTC
      REAL TSHC,UCEX1,UCEX2,CEXAV,PAR,UBCK,CUSI,CUDS
      REAL CEXAVY,DR,PWCHS,PWCAT,PWCE,YUBCKC,PWBCKS
      REAL PWBCK,PWBCT,TRC,RAT,PWOET,PWLOS,PWLOA,PWOSD
      REAL FCS,PWRST,PWRSTA,TCEX,TCBCK,TCAUX,TREPC,REPDC
      REAL PREPC,TMANC,COST1,COST2,DISPS(100),STINC(100),CPC
      REAL PWCE1,PWCE2,PWCE3
      REAL PITCH(30),HELP(0:7),D(5),RL(30),RNCPR(30),VOLR(30)
      REAL LOC(30),VOLC(30),HDCPY(30),CEXC(30),CEXR(30)
      REAL VOLBCK(30),VOLBLO(30),HDVOL(30)
      REAL PWCAV(5),PFAC(5),MANC(30),SUR(50),SSUR(120),PWS(120)
      REAL BCKCY(30),PWBCKY(30),PWLOAV(5),PWOEZ(30),PSFTFY(5)
      REAL PWCEY(30),PWCEZ(30),PWCEW(30)
      CHARACTER*4,ROCK
      CHARACTER*2,LAB4
      CHARACTER*1,LAB1,LAB2,LAB3,LAB5

      PI=3.1415926
      NCPH=3
      AVH=6.
      AVW=7.
      COST1=1.E30
      COST2=0.

      OPEN(UNIT=14, NAME='INPUT.DAT',STATUS='OLD')
      OPEN(UNIT=23, NAME='OUTPUT.DAT',STATUS='NEW')
```

```
300     FORMAT(' ',1X,A,18X,A)
301     FORMAT(' ',1X,A,6X,A,3X,A,3X,A)
302     FORMAT(' ',1X,A,5X,F6.1,2X,A,4X,F4.1,2X,A,3X,F4.1,2X,A)
303     FORMAT(' ',1X.5(F4.1.5X))
304     FORMAT(' ',1X,A,4X,A,4X,A)
305     FORMAT(' ',1X,F4.1,6X,F4.1,10X,F5.1)
306     FORMAT(' ',1X,A,4X,A)
307     FORMAT(' ',1X,F4.1,6X,F4.1)
308     FORMAT(' ',8X,A,8X,A)
309     FORMAT(' ',3X,A,2X,A,4X,A,4X,A,6X,A,4X,A,4X,A)
310     FORMAT(' ',7X,F6.4,2X,F6.4,2X,F6.4,4X,F6.4,2X,F6.4,2X,F6.4)
311     FORMAT(' ',A,6X,A,5X,A)
312     FORMAT(' ',35X,F5.2,5X,F5.2)
313     FORMAT(' ',A,10X,F5.2)
315     FORMAT(' ',6X,F5.2,21X,F4.1)
316     FORMAT(' ',5X,F12.2,3X,A)
318     FORMAT(' ',25X,F5.2)
319     FORMAT(' ',4X,F6.1,12X,F6.1)
320     FORMAT(' ',1X,7(A,2X))
321     FORMAT(' ',42X,A)
322     FORMAT(' ',3X,I4,11X,I2,2(15X,I1),15X,I2,2(15X,I1))
323     FORMAT(' ',1X,A,3X,A,3X,A,3X,A)
324     FORMAT(' ',10X,A,11X,A,8X,A)
325     FORMAT(' ',1X,I4,7X,I4,14X,I4,9X,I5)
326     FORMAT(' ',1X,I4,10X,'0',14X,I4,9X,I5)
327     FORMAT(' ',1X,A,3X,8(A,4X))
328     FORMAT(' ',1X,I4,2X,F8.1)
329     FORMAT(' ',1X,I4,11X,F8.1)
330     FORMAT(' ',1X,I4,23X,F7.1,4X,F7.1,3X,I4)
331     FORMAT(' ',1X,I4,23X,F7.1,4X,F7.1,3X,I4,9X,I4)
332     FORMAT(' ',1X,I4,23X,F7.1,4X,F7.1,3X,I4,9X,I4,10X,F7.1)
333     FORMAT(' ',1X,I4,57X,I4,10X,F7.1)
334     FORMAT(' ',1X,I4,71X,F7.1)
335     FORMAT(' ',1X,I4,85X,F8.1)
336     FORMAT(' ',35X,A)
337     FORMAT(' ',1X,A,4(5X,A),10X,A)
338     FORMAT(' ',12X,A,10X,A,10X,A,16X,A,14X,A)
339     FORMAT(' ',1X,I4,5X,F7.2,60X,F8.2)
340     FORMAT(' ',1X,I4,19X,F6.2,11X,F6.2,30X,F8.2)
341     FORMAT(' ',1X,I4,53X,F7.2,12X,F8.2)
342     FORMAT(' ',1X,A,4X,F7.2,6X,F7.2,10X,F7.2,11X,F7.2,12X,F8.2)
343     FORMAT(' ',1X,15(A,3X))
344     FORMAT(' ',1X,I4,63X,F6.3,1X,F6.3,32X,F8.3)
345     FORMAT(' ',1X,I4,2X,F7.3,44X,F7.3,39X,F6.3,3X,F8.3)
346     FORMAT(' ',1X,I4,11X,F6.3,36X,F7.3,39X,F6.3,3X,F8.3)
347     FORMAT(' ',1X,I4,20X,F6.3,3X,F6.3,1X,F6.3,11X,F7.3,39X,F6.3,
     +  3X,F8.3)
348     FORMAT(' ',1X,I4,20X,F6.3,3X,2(F6.3,1X),F6.3,35X,F6.3,9X,
     +  F6.3,3X,F8.3)
```

```
 349    FORMAT(' ',1X,I4,20X,F6.3,3X,2(F6.3,1X),F6.3,35X,F6.3,1X,
     +  F6.3,2X,F6.3,3X,F8.3)
 350    FORMAT(' ',1X,I4,43X,F6.3,35X,F6.3,1X,F6.3,11X,F8.3)
 351    FORMAT(' ',1X,I4,84X,F6.3,1X,F6.3,11X,F8.3)
 352    FORMAT(' ',1X,I4,84X,F6.3,18X,F8.3)
 354    FORMAT(' ',1X,I4,77X,F6.3,25X,F8.3)
 355    FORMAT(' ',A,2X,F6.2,3X,F5.2,3X,F6.2,3X,F6.2,2X,F5.2,1X,F6.2,
     +  5X,F7.2,3X,2(F5.2,2X),F5.2,1X,F6.2,2X,2(F5.2,3X),F8.2)
 444    FORMAT(' ',50X,A)

C SET THERMAL LOADINGS. THE PROGRAM PROVIDES THE THERMAL LOADINGS,
C BUT THE USER CAN CHANGE THEM FROM THE INPUT.

        READ(14,*)ROCK
        READ(14,*)LAB1

        IF(LAB1 .EQ. 'Y')THEN
          READ(14,*)VNF,NF,FF
        ELSE
          CALL THLOAD(ROCK,VNF,NF,FF)
        ENDIF

        WRITE(23,*)'     DATA FOR THE ANALYSIS'
        WRITE(23,*)'     ----------------------'
        WRITE(23,*)' '
        WRITE(23,*)' '
        WRITE(23,300)'ROCK','THERMAL LOADINGS'
        WRITE(23,301)'TYPE','VERY NEAR FIELD','NEAR FIELD','FAR FIELD'
        WRITE(23,302)ROCK,VNF,'W/CAN',NF,'W/m2',FF,'W/m2'
        WRITE(23,*)' '

C SET EXCAVATION PARAMETERS. DEPTH, NUMBER OF SHAFTS AND DIAMETER,
C AND OVERALL SHAPE ARE DEFINED BY THE USER. CORRIDOR, ROOM AND
C PILLAR DIMENSIONS ARE SUPPLIED BY THE PROGRAM, BUT CAN BE
C CHANGED BY THE USER.

        READ(14,*) OS
        READ(14,*) NSHAFT
        READ(14,*) DEPTH
        READ(14,*) (D(I),I=1,NSHAFT)
        READ(14,*) LAB2
        IF(LAB2 .EQ. 'Y')THEN
          READ(14,*)RW,RH,RLI,CW,CH,PW
        ELSE
          CALL EXPAR(ROCK,RW,RH,RLI,CW,CH,PW)
        ENDIF

        CDBR = PW + RW
```

```
      WRITE(23,*)'     REPOSITORY GEOMETRY PARAMETERS'
      WRITE(23,*)'     ------------------------------'
      WRITE(23,*)' '
      WRITE(23,*)'NUMBER OF SHAFTS: ',NSHAFT
      WRITE(23,*)'DIAMETER (m)'
      WRITE(23,303) (D(I),I=1,NSHAFT)
      WRITE(23,*)' '
      WRITE(23,*)'DEPTH ',DEPTH,' m'
      WRITE(23,*)' '
      WRITE(23,*)'ROOM DIMENSIONS: (IN m)'
      WRITE(23,304) 'WIDTH','HEIGHT','NOMINAL LENGTH'
      WRITE(23,305) RW,RH,RLI
      WRITE(23,*)' '
      WRITE(23,*)'CORRIDOR DIMENSIONS: (IN m)'
      WRITE(23,306)'WIDTH','HEIGHT'
      WRITE(23,307)CW,CH
      WRITE(23,*)' '
      WRITE(23,*)'PILLAR WIDTH: ',PW,' m'
      WRITE(23,*)' '
      WRITE(23,*)'AVENUE DIMENSIONS: (IN m)'
      WRITE(23,306)'WIDTH','HEIGHT'
      WRITE(23,307)AVW,AVH
      WRITE(23,*)' '

C CALCULATE EXCAVATION OF SHAFTS

      VOLSH = 0.
      DO 20 I=1,NSHAFT
        VOLSH=VOLSH+(PI*DEPTH*(D(I)/2.)**2)
 20   CONTINUE

C CALCULATE SHAFT EXCAVATION COST (NOT PRESENT WORTH). THE COSTS
C PARAMETERS ARE GIVEN IN THE SUBROUTINE.

      CALL SHCOST(ROCK,NSHAFT,D,DEPTH,TSHC)

C READ IN NUMBER OF CANISTERS PER YEAR

      DO 25 I=1,30
        READ(14,*)NCAN(I)
 25   CONTINUE

C READ IN UNIT COSTS AND DISCOUNT RATE

      READ(14,*)LAB5
      IF(LAB5 .EQ. 'Y')THEN
        READ(14,*)UCEX1,UCEX2
      ELSE
        CALL UEXCOST(ROCK,UCEX1,UCEX2)
      ENDIF
```

```
      READ(14,*)DR
      READ(14,*)UBCK
      READ(14,*)LAB4
      IF(LAB4 .EQ. 'OF')THEN
        READ(14,*)TRC,RAT
      ENDIF
      READ(14,*)FCS,PAR
      READ(14,*)FAC
      READ(14,*)CPRE
      READ(14,*)AEPER
      READ(14,*)DEPER
      READ(14,*)DUSURC
      READ(14,*)SUSURC
      READ(14,*)MAPER
      READ(14,*)RSPER
      READ(14,*)DSPER

C READ SCHEDULES

      READ(14,*)IYAR
      READ(14,*)ISH
      READ(14,*)IAV
      READ(14,*)IAS
      READ(14,*)IBK
      READ(14,*)IC
      IYST=2000

C SET PARAMETERS FOR DECAY POWER CALCULATION

      Q1=0.6471
      Q2=0.8235
      Q3=0.9529
      MTPP1=1.7365
      MTPP2=1.4294
      MTPP3=1.2691

      WRITE(23,*)'PARAMETERS FOR DECAY POWER ESTIMATES'
      WRITE(23,308)'NORMALIZATION FACTOR','MTIHM PER CANISTER'
      WRITE(23,309)'BU:','2.2%','2.8%','3.2%','2.2%','2.8%','3.2%'
      WRITE(23,310)Q1,Q2,Q3,MTPP1,MTPP2,MTPP3
      WRITE(23,*)' '
      WRITE(23,*)'ECONOMIC DATA'
      WRITE(23,*)'DISCOUNT RATE:',DR
      WRITE(23,311)'UNIT EXCAVATION COSTS ($/m3):','ROOMS','OTHERS'
      WRITE(23,312)UCEX1,UCEX2
      WRITE(23,313)'BACKFILLING COST ($/m3): ',UBCK
      WRITE(23,*)'ROCK DISPOSAL'
      IF(LAB4 .EQ. 'OF')THEN
        WRITE(23,*)'OFF-SITE'
        WRITE(23,306)'TRANSP.COST ($/m3)','RATIO OF BACKFILLING (%)'
```

```
          WRITE(23,315)TRC,RAT
        ELSE
          WRITE(23,*)'ON-SITE'
        ENDIF

        WRITE(23,*)'ESTIMATED COST OF REPOSITORY FACILITIES'
        WRITE(23,316)FAC,'$1984'
        WRITE(23,*)'LAND PREPARATION COST'
        WRITE(23,*)' (PERCENTAGE OF COST OF FACILITY)'
        WRITE(23,318)CPRE
        WRITE(23,*)'ARQUITECT-ENGINEERING COSTS'
        WRITE(23,*)' (PERCENTAGE OF FACILITIES AND PREPARATION COSTS)'
        WRITE(23,318)AEPER
        WRITE(23,*)'DECOMMISSIONING COST OF FACILITIES'
        WRITE(23,*)' (PERCENTAGE OF FACILITIES COST)'
        WRITE(23,318)DEPER
        WRITE(23,*)'ANNUAL COST OF SURVEILLANCE (REPOSITORY)'
        WRITE(23,316)DUSURC,'$1984'
        WRITE(23,*)'MAINTENANCE COST OF REPOSITORY FACILITIES (ANNUAL)'
        WRITE(23,*)' (PERCENTAGE OF COST OF FACILITIES)'
        WRITE(23,318)MAPER
        WRITE(23,*)'PARAMETERS FOR COST OF STORAGE FACILITY ($1984 M)'
        WRITE(23,306)'INDEP. OF CAP.','DEP. OF CAP.'
        WRITE(23,319)FCS,PAR
        WRITE(23,*)'OPERATING COST OF STORAGE FACILITY (ANNUAL)'
        WRITE(23,*)' (PERCENTAGE OF FACILITY COST)'
        WRITE(23,318)RSPER
        WRITE(23,*)'DECOMMISSIONING COST OF STORAGE FACILITY'
        WRITE(23,*)' (PERCENTAGE OF FACILITY COST)'
        WRITE(23,318)DSPER
        WRITE(23,*)'ANNUAL COST OF SURVEILLANCE OF STORAGE FAC.'
        WRITE(23,316)SUSURC,'$1984'
        WRITE(23,*)' '
        WRITE(23,*)' '
        WRITE(23,*)' '
        WRITE(23,321)'FIXED SCHEDULES'
        WRITE(23,321)'---------------'
        WRITE(23,320)'STORAGE  *','YEARS AFTER  *','YEARS BEFORE  *',
     +  'N. OF YEARS  *','YEARS AFTER  *','YEARS AFTER  *','YEARS AHEAD'
        WRITE(23,320)' STARTS  *','REP. START   *','OPER. TO EX-  *',
     +  'TO EXCAVATE  *','OPERAT. TO   *','DISPOSAL FOR *','DISPOSAL TO'
        WRITE(23,320)'AT YEAR  *','DISP. (INIT) *','CAVATE SHAFTS *',
     +  '  AVENUES    *','CLOSE REPOS. *','BACKFILLING  *','EXC. ROOMS'
        WRITE(23,322)IYST,IYAR,ISH,IAV,IC,IBK,IAS

C HOLE DRILLING REQUIREMENTS PER YEAR
```

```
      TOTHD=0
      DO 50 I=1,30
        HODR(I)=NCAN(I)/3
        TOTHD=TOTHD+HODR(I)
 50   CONTINUE


C HOLE DRILLING COSTS

      CALL HDCOST(ROCK,NCAN,HODR,HDCPY,HDVOL)

C INITIALIZE YEARS AND INDEXES

      MUSSOL=0
      READ(14,*)N
      IS=0
900   IYSD=2000+IYAR
      ID=IYSD-2000

C CALCULATE DENSITY OF DISPOSAL FOR EVERY YEAR AND EVERY IYAR

C CALCULATE PITCHES

      T1=REAL(IYAR)+12.-0.74
      T2=REAL(IYAR)+12.-0.37
      T3=REAL(IYAR)+12.-0.1

      T=T1+13.
      CALL DENDIS(Q1,T,VNF,NF,FF,CDBR,RLI,CW,MTPP1,PITCH1,WARN)
      IF(WARN .EQ. 1)THEN
        IYAR=IYAR+1
        GO TO 900
      ENDIF
      PITCH(1)=PITCH1

      T=T1+11.
      CALL DENDIS(Q1,T,VNF,NF,FF,CDBR,RLI,CW,MTPP1,PITCH1,WARN)
      IF(WARN .EQ. 1)THEN
        IYAR=IYAR+1
        GO TO 900
      ENDIF
      PITCH(2)=PITCH1

      T=T2+9.
      CALL DENDIS(Q2,T,VNF,NF,FF,CDBR,RLI,CW,MTPP2,PITCH1,WARN)
      IF(WARN .EQ. 1)THEN
        IYAR=IYAR+1
        GO TO 900
      ENDIF
      PITCH(3)=PITCH1
```

```
      T=T2+8.
      CALL DENDIS(Q2,T,VNF,NF,FF,CDBR,RLI,CW,MTPP2,PITCH1,WARN)
      IF(WARN .EQ. 1)THEN
        IYAR=IYAR+1
        GO TO 900
      ENDIF
      PITCH(4)=PITCH1

      DO 10 I=0,7
        T=T3+REAL(I)
        CALL DENDIS(Q3,T,VNF,NF,FF,CDBR,RLI,CW,MTPP3,PITCH1,WARN)
        IF(WARN .EQ. 1)THEN
        IYAR=IYAR+1
        GO TO 900
      ENDIF
        HELP(I)=PITCH1
 10   CONTINUE
      PITCH(5) = HELP(7)
      PITCH(6) = HELP(7)
      PITCH(7) = HELP(7)
      PITCH(8) = HELP(6)
      PITCH(9) = HELP(6)
      PITCH(10)= HELP(6)
      PITCH(11)= HELP(5)
      PITCH(12)= HELP(5)
      PITCH(13)= HELP(5)
      PITCH(14)= HELP(5)
      PITCH(15)= HELP(4)
      PITCH(16)= HELP(4)
      PITCH(17)= HELP(4)
      PITCH(18)= HELP(3)
      PITCH(19)= HELP(3)
      PITCH(20)= HELP(3)
      PITCH(21)= HELP(3)
      PITCH(22)= HELP(2)
      PITCH(23)= HELP(2)
      PITCH(24)= HELP(2)
      PITCH(25)= HELP(2)
      PITCH(26)= HELP(1)
      PITCH(27)= HELP(1)
      PITCH(28)= HELP(1)
      PITCH(29)= HELP(1)
      PITCH(30)= HELP(0)

C CALCULATE EXCAVATION REQUIREMENTS

C ROOM EXCAVATION PER YEAR
```

```
        TNROOM = 0
        DO 30 I=1,30
          NHPR(I)=INT((RLI-2.)/PITCH(I))
          RL(I)=NHPR(I)*PITCH(I) + 2.
          NROOM(I)=NINT(NCAN(I)/(NHPR(I)*3.))
          TNROOM=TNROOM+NROOM(I)
          VOLR(I)=NROOM(I)*RL(I)*RW*RH
  30    CONTINUE

C CORRIDOR EXCAVATION PER YEAR

        TLOC =0.
        DO 40 I=1,30
          LOC(I)=NROOM(I)*CDBR/2.
          TLOC=TLOC+LOC(I)
          VOLC(I)=LOC(I)*CW*CH
  40    CONTINUE

C AVENUES EXCAVATION AND OVERALL DIMENSIONS OF THE REPOSITORY

        NCOL = NINT(SQRT(OS*TNROOM*CDBR/(RLI+CW)))
        NROW = NINT(TNROOM/NCOL)
        A = NROW*CDBR
        B = NCOL*(RLI+CW)
        OS1=A/B

        VOLAV=(3*A + 3*B)*AVW*AVH

C OTHER EXCAVATION

        CALL OEXCOST(ROCK,UCEX1,UCEX2,VOLAV,VOLC,VOLR,CEXAV,CEXC,CEXR)

C FACILITIES, UTILITIES AND AUXILIARY COSTS

        IFA=IYSD-ISH-2000
        FACC=FAC/ISH
        PWAUX=0.
        DO 106 I=1,ISH
          PFAC(I) = FACC/(1.+DR)**(IFA+I-1)
          PWAUX=PWAUX+PFAC(I)
 106    CONTINUE

C PREOPERATIONS COSTS

        IPREP=IYSD-2000-(ISH+1)
        PREPC=CPRE*FAC/(1.+DR)**IPREP

C ARQUITECT-ENGINEERING COSTS

        AEC=AEPER*(PREPC+PWAUX)
```

```
C DECOMMISSIONING COSTS

        REPDC = DEPER*FAC/(1.+DR)**(IYSD+30+IC-2000)

C SURVEILLANCE COSTS

        DSURVC=0.
        DO 108 I=1,30+IC
          SUR(I)=DUSURC/(1.+DR)**(ID+I-1)
          DSURVC=DSURVC+SUR(I)
 108    CONTINUE

C MAINTENANCE COSTS

        TMANC = 0.
        DO 107 I=1,30
          MANC(I)=(MAPER*PWAUX)/(1.+DR)**(ID+I-1)
          TMANC=TMANC+MANC(I)
 107    CONTINUE

C BACKFILLING AND BACKFILLING COSTS

        IYBCK=IYSD+IBK-2000
        DO 74 I=1,30
          VOLBCK(I)=VOLC(I)+VOLR(I)
  74    CONTINUE
        PWBCK = 0.
        DO 75 I=1,30
          BCKCY(I)=VOLBCK(I)*UBCK
          PWBCKY(I)=BCKCY(I)/(1.+DR)**(IYBCK+I-1)
          PWBCK=PWBCK+PWBCKY(I)
  75    CONTINUE

        IBCKS=ID+30+IC-1
        PWBCS=(VOLAV+VOLSH)*UBCK/(1.+DR)**IBCKS
        PWBCT=PWBCK+PWBCS

C PRESENT WORTH OF OTHER COSTS

        IYSHE=IYSD-ISH-2000
        PWCSH=TSHC/(1.+DR)**IYSHE

        CEXAVY=CEXAV/IAV
        PWCAT=0.
        DO 60 I=1,IAV
          IYAVE=IYSD-2000-(ISH-I)
          PWCAV(I)=CEXAVY/(1.+DR)**IYAVE
          PWCAT=PWCAT+PWCAV(I)
  60    CONTINUE
```

```
        IYRE=IYSD-IAS-2000
        PWCE1=0.
        PWCE2=0.
        PWCE3=0.
        DO 64 I=1,30
          H=(1.+DR)**(IYRE+I-1)
          PWCEY(I)=HDCPY(I)/H
          PWCEZ(I)=CEXC(I)/H
          PWCEW(I)=CEXR(I)/H
          PWCE1=PWCE1+PWCEY(I)
          PWCE2=PWCE2+PWCEZ(I)
          PWCE3=PWCE3+PWCEW(I)
  64    CONTINUE
        PWCE=PWCE1+PWCE2+PWCE3

C DISPOSAL OF LEFTOVER ROCK

        IF(LAB4 .EQ. 'DF')THEN
          PWLOS=VOLSH*RAT*TRC/(1.+DR)**IYSHE
          PWLOA=0.
          AJU=VOLAV/IAV
          DO 80 I=1,IAV
            IYAVE=IYSD-2000-(ISH-I)
            PWLOAV(I)=AJU*RAT*TRC/(1.+DR)**IYAVE
            PWLOA=PWLOA+PWLOAV(I)
  80      CONTINUE
          PWOET=0.
          DO 81 I=1,30
            PWOEX=(VOLC(I)+VOLR(I)+HDVOL(I))*RAT*TRC
            PWOEZ(I)=PWOEX/(1.+DR)**(IYRE+I-1)
            PWOET=PWOET+PWOEZ(I)
  81      CONTINUE
          PWOSD=PWLOS+PWLOA+PWOET
        ELSE
          PWLOS=0.
          DO 82 I=1,IAV
            PWLOAV(I)=0.
  82      CONTINUE
          DO 83 I=1,30
            PWOEZ(I)=0.
  83      CONTINUE
          PWOSD=0.
        ENDIF

C REPOSITORY TOTAL COST (PRESENT WORTH $1984,  START DISCOUNT AT 2000)

        TCEX = PWCSH + PWCAT +PWCE
        TCBCK = PWBCT + PWOSD
        TCAUX = PWAUX + TMANC
        TREPC =TCEX+TCBCK+TCAUX+REPDC+PREPC+DSURVC+AEC
```

```
C TEMPORARY STORAGE

C STORAGE SCHEDULE

        IYLS=IYAR+30
        CUCAP(1)=NCAN(1)
        DO 96 I=1,IYAR
          SHPD(I)=0
  96    CONTINUE
        DO 97 I=IYAR+1,IYAR+30
          SHPD(I)=NCAN(I-IYAR)
  97    CONTINUE
        DO 98 I=IYAR+31,IYLS
          SHPD(I)=0
  98    CONTINUE
        DO 99 I=2,30
          CUCAP(I)=CUCAP(I-1)+NCAN(I)-SHPD(I)
  99    CONTINUE
        DO 100 I=31,IYLS
          CUCAP(I)=CUCAP(I-1)-SHPD(I)
 100    CONTINUE

C MAXIMUM CAPACITY OF STORAGE FACILITY

        MAXCAP=CUCAP(1)
        DO 101 I=2,30
          IF(CUCAP(I) .GT. MAXCAP)THEN
            IYMC=I
            MAXCAP=CUCAP(I)
          ENDIF
 101    CONTINUE
        MAXCAT=MAXCAP*MTPP3

C FIXED COST OF STORAGE FACILITY

        FSTF=(FCS+PAR*(MAXCAT/1000.)**0.75)*1.E06
        FSTFY=FSTF/5.
        PSFTF=0.
        DO 110 I=1,5
          PSFTFY(I)=FSTFY/(1.+DR)**(IS-6+I)
          PSFTF=PSFTF+PSFTFY(I)
 110    CONTINUE
C OPERATING COSTS OF STORAGE FACILITY

        PWRST=0.
        RST=RSPER*FSTF
        DO 109 I=1,IYLS
          PWS(I)=RST/(1.+DR)**(IS+I-1)
          PWRST=PWRST+PWS(I)
 109    CONTINUE
```

```
C SURVEILLANCE COSTS

        SSURVC=0.
        DO 666 I=1,IYLS
          SSUR(I)=SUSURC/(1.+DR)**(IS+I-1)
          SSURVC=SSURVC+SSUR(I)
 666    CONTINUE

C DECOMMISSIONING COSTS

        IDC=IS+IYLS
        PWDS=DSPER*FSTF/(1.+DR)**IDC

C TOTAL COST OF STORAGE

        TSTC = PWRST + PSFTF + PWDS + SSURVC

C COMPARISON SAVINGS VS. COST INCREASE

        IF(MUSSOL .EQ. 1)GO TO 501
        WRITE(23,*)'    YEAR      ST. COST        REP. COST      TOTAL'
        WRITE(23,*)IYAR,'  ',TSTC,'  ',TREPC,'  ',TSTC+TREPC
        DISPS(IYAR)=COST1-TREPC
        STINC(IYAR)=TSTC-COST2
        WRITE(23,*)'       YEAR   DISPOSAL SAVINGS   ST.COST INCREASE'
        WRITE(23,*)IYAR,'   ',DISPS(IYAR),'   ',STINC(IYAR)
        IF(DISPS(IYAR) .GT. STINC(IYAR))THEN
          COST1=TREPC
          COST2=TSTC
          IF(N .LT. 2)GO TO 501
 555      N=N+1
          IF(IYAR .GE. 100)GO TO 999
          IYAR=IYAR+1
          GO TO 900
        ENDIF

        GO TO 909
 999    WRITE(23,*)'NO OPTIMIZATION WAS POSSIBLE WITHIN THE'
        WRITE(23,*)'100 YEARS'
        WRITE(23,*)'RESULTS OF THE LAST YEAR'
        OPT=IYAR
        GO TO 501
 909    WRITE(23,*)' '
        WRITE(23,*)'RESULTS OF THE OPTIMIZATION'
 500    WRITE(23,*)' '
        MUSSOL=1

        IYAR=IYAR-1
        OPT=IYAR
        GO TO 900
```

```
501    WRITE(23,*)'N IS',N,'  AND IYAR IS: ',IYAR
       WRITE(23,*)' '
       WRITE(23,*)'             STORAGE CAPACITY'
       WRITE(23,*)'             ----------------'
       WRITE(23,*)' '
       WRITE(23,323)'YEAR','N. OF CANISTERS','N. OF CANISTERS',
    +  'CAPACITY'
       WRITE(23,324)'RECIEVED','SHIPED','(CAN)'
       DO 201 I=0,IYLS-1
         IF(I .LT. 30)THEN
           WRITE(23,325)IYST+I,NCAN(I+1),SHPD(I+1),CUCAP(I+1)
         ELSE
           WRITE(23,326)IYST+I,SHPD(I+1),CUCAP(I+1)
         ENDIF
201    CONTINUE
       WRITE(23,*)' '
       WRITE(23,*)'MAXIMUM CAPACITY:',MAXCAP,' AT YEAR ',IYMC
       WRITE(23,*)' '
       WRITE(23,*)' '
       WRITE(23,*)'       REPOSITORY PARAMETERS (m AND m3)'
       WRITE(23,*)'       --------------------------------'
       WRITE(23,*)' '
       WRITE(23,*)'TOTAL LENGTH OF REPOSITORY: ',A
       WRITE(23,*)'TOTAL WIDTH OF REPOSITORY:  ',B
       WRITE(23,*)'NUMBER OF COLUMNS ',NCOL
       WRITE(23,*)'NUMBER OF ROWS ',NROW
       WRITE(23,*)' ROOM LENGTHS AND PITCHES, SORTED BY YEARS:'
       DO 777 I=1,30
         WRITE(23,*)RL(I),'  ',PITCH(I)
777    CONTINUE
       WRITE(23,*)' '
       WRITE(23,327)'YEAR','SHAFT','AVENUE','CORRIDOR','ROOM',
    +  'HOLE','N.OF CANISTERS','BACKFILLING','BACKFILLING'
       WRITE(23,327)'        EXC ',' EXC  ','  EXC   ','  EXC',
    +  'DRILL','              ','ROOM & COR.','AV. & SHAFT'
       WRITE(23,*)' '
       K=IYSD-ISH
       WRITE(23,328)K,VOLSH
       DO 202 I=1,IAV
         WRITE(23,329)K+I,VOLAV/IAV
202    CONTINUE
       K1=K+IAV
       DO 203 I=1,IAS
         WRITE(23,330)K1+I,VOLC(I),VOLR(I),HODR(I)
203    CONTINUE
       K2=K1+IAS
       DO 204 I=1,IBK
         K3=I+IAS
         WRITE(23,331)K2+I,VOLC(K3),VOLR(K3),HODR(K3),NCAN(I)
```

```
204   CONTINUE
      K4=K2+IBK
      DO 205 I=1,30-IBK-IAS
        K5=I+IAS+IBK
        K6=I+IBK
      WRITE(23,332)K4+I,VOLC(K5),VOLR(K5),HODR(K5),NCAN(K6),VOLBCK(I)
205   CONTINUE
      K7=K2+30-IAS
      DO 206 I=1,IAS
        K8=30-IAS
        WRITE(23,333)K7+I,NCAN(K8+I),VOLBCK(I+30-IBK-IAS)
206   CONTINUE
      K9=K7+IAS
      DO 208 I=1,IBK
        WRITE(23,334)K9+I,VOLBCK(I+30-IBK)
208   CONTINUE
      WRITE(23,335)K9+IBK+1,VOLAV+VOLSH
      WRITE(23,*)' '
      WRITE(23,*)' '
      WRITE(23,*)' ROCK DISPOSAL'
      WRITE(23,*)' -------------'
      WRITE(23,*)' '
      IF(LAB4 .EQ. 'ON')THEN
        WRITE(23,*) ' ON-SITE ROCK DISPOSAL'
      ELSE
        WRITE(23,*) ' OFF-SITE ROCK DISPOSAL'
      ENDIF
      DO 209 I=1,30
        TV1=(VOLC(I)+VOLR(I)+HDVOL(I))*RAT
209   CONTINUE
      TV=RAT*(VOLAV+VOLSH)+TV1
      WRITE(23,*)'TOTAL ROCK DISPOSED ',TV,' m3'
      WRITE(23,*)' '
      WRITE(23,*)' '
      WRITE(23,336)'STORAGE COSTS ($1984 M)'
      WRITE(23,336)'-----------------------'
      WRITE(23,*)' '
      WRITE(23,337)'YEAR','FACILITY','OPERATING','SURVEILLANCE',
     + 'DECOMMISSIONING','TOTAL'
      WRITE(23,338)'COST','COST','COST','COST','COST'
      WRITE(23,*)' '
      DO 210 I=0,4
        X1=PSFTFY(I+1)/1.E06
        WRITE(23,339)IYST-5+I,X1,X1
210   CONTINUE
      DO 211 I=0,IYLS-1
        X2=PWS(I+1)/1.E06
        X3=SSUR(I+1)/1.E06
        WRITE(23,340)IYST+I,X2,X3,X2+X3
211   CONTINUE
```

```
      X7=PWDS/1.E06
      WRITE(23,341)IYST+IYLS,X7,X7
      WRITE(23,*)' '
      X4=PSFTF/1.E06
      X5=PWRST/1.E06
      X6=SSURVC/1.E06
      X8=TSTC/1.E06
      WRITE(23,342)'TOTAL',X4,X5,X6,X7,X8
      WRITE(23,*)' '
      WRITE(23,*)' '
      WRITE(23,*)' '
      WRITE(23,444)'REPOSITORY COSTS ($1984 M)'
      WRITE(23,444)'--------------------------'
      WRITE(23,*)' '
      WRITE(23,343)'YEAR','SHAFT','AVEN.','CORRIDOR','ROOM','HOLE',
     + 'MANT','FACILITIES','PREP','A-E','DECOM','SURV','BACK',
     + 'ROCK D.','TOTAL'
      WRITE(23,*)' '
      WRITE(23,344)K-1,PREPC/1.E06,AEC/1.E06,(PREPC+AEC)/1.E06
      G1=PWCSH/1.E06
      G2=PFAC(1)/1.E06
      G3=PWLOS/1.E06
      WRITE(23,345)K,G1,G2,G3,G1+G2+G3
      DO 212 I=1,IAV
        G4=PWCAV(I)/1.E06
        G5=PFAC(I+1)/1.E06
        G6=PWLOAV(I)/1.E06
        WRITE(23,346)K+I,G4,G5,G6,G4+G5+G6
212   CONTINUE
      DO 213 I=1,IAS
        G7=PWCEZ(I)/1.E06
        G8=PWCEW(I)/1.E06
        G9=PWCEY(I)/1.E06
        G10=PFAC(I+IAV+1)/1.E06
        G11=PWOEZ(I)/1.E06
        WRITE(23,347)K1+I,G7,G8,G9,G10,G11,G7+G8+G9+G10+G11
213   CONTINUE
      DO 214 I=1,IBK
        K3=I+IAS
        R1=PWCEZ(K3)/1.E06
        R2=PWCEW(K3)/1.E06
        R3=PWCEY(K3)/1.E06
        R4=MANC(I)/1.E06
        R5=SUR(I)/1.E06
        R6=PWOEZ(K3)/1.E06
        WRITE(23,348)K2+I,R1,R2,R3,R4,R5,R6,R1+R2+R3+R4+R5+R6
214   CONTINUE
      DO 215 I=1,30-IBK-IAS
        K5=I+IAS+IBK
```

```
          U1=PWCEZ(K5)/1.E06
          U2=PWCEW(K5)/1.E06
          U3=PWCEY(K5)/1.E06
          U4=MANC(I+IBK)/1.E06
          U5=SUR(I+IBK)/1.E06
          U6=PWBCKY(I)/1.E06
          U7=PWOEZ(K5)/1.E06
          U8=U1+U2+U3+U4+U5+U6+U7
          WRITE(23,349)K4+I,U1,U2,U3,U4,U5,U6,U7,U8
215     CONTINUE
        DO 216 I=1,IAS
          O1=MANC(30-IAS+I)/1.E06
          O2=SUR(30-IAS+I)/1.E06
          O3=PWBCKY(30-IBK-IAS+I)/1.E06
          O4=O1+O2+O3
          WRITE(23,350)K7+I,O1,O2,O3,O4
216     CONTINUE
        DO 217 I=1,IBK
          B1=SUR(30+I)/1.E06
          B2=PWBCKY(30-IBK+I)/1.E06
          WRITE(23,351)K9+I,B1,B2,B1+B2
217     CONTINUE
        DO 218 I=1,IC-IBK-1
          WRITE(23,352)K9+IBK+I,SUR(30+IBK+I)/1.E06,SUR(30+IBK+I)/1.E06
218     CONTINUE
        V1=SUR(30+IC)/1.E06
        V2=PWBCS/1.E06
        WRITE(23,351)K9+IC,V1,V2,V1+V2
        WRITE(23,354)K9+IC+1,REPDC/1.E06,REPDC/1.E06
        WRITE(23,*)' '
        A1=PWCAT/1.E06
        A2=PWCE2/1.E06
        A3=PWCE3/1.E06
        A4=PWCE1/1.E06
        A5=TMANC/1.E06
        V=PWAUX/1.E06
        A6=PREPC/1.E06
        A7=AEC/1.E06
        A8=REPDC/1.E06
        A9=DSURVC/1.E06
        AA=PWBCT/1.E06
        AB=PWOSD/1.E06
        AC=TREPC/1.E06
        WRITE(23,355)'TOTAL',G1,A1,A2,A3,A4,A5,V,A6,A7,A8,A9,AA,AB,AC
        WRITE(23,*)' '
        WRITE(23,*)' '
        WRITE(23,*)' '
        WRITE(23,*)'TOTAL COST: ',TREPC+TSTC
        CPC=(TREPC+TSTC)/55288.
```

```
      WRITE(23,*)'COST PER MTIHM: ',(TREPC+TSTC)/72000.
      WRITE(23,*)'COST PER Kg. OF HLW GLASS: ',(TREPC+TSTC)/13830255.
      IF(MUSSOL .EQ. 0 .AND. IYAR .LT. 100)GO TO 555

C     CALCULATE COST OF POLITICAL DECISSION

      WRITE(23,*)' '
      WRITE(23,*)'      COST OF POLITICAL DECISSIONS'
      WRITE(23,*)'      -----------------------------'
      WRITE(23,*)' '
      CUSI=0.
      CUDS=0.
      IF(OPT .EQ. 100)THEN
        DO 801 I=10,90,10
          DO 802 J=I+1,OPT
            CUSI=CUSI+STINC(J)

            CUDS=CUDS+DISPS(J)
 802      CONTINUE
          WRITE(23,*)' '
          WRITE(23,*)'COST OF TERMINATING STOR. AFTER ',I,' YEARS'
          WRITE(23,*)CUDS-CUSI
          CUSI=0.
          CUDS=0.
 801    CONTINUE
      ELSE
        SOPES = 5
        DO WHILE (SOPES .LT. OPT)
          DO 803 I=SOPES+1,OPT
            CUSI=CUSI+STINC(I)
            CUDS=CUDS+DISPS(I)
 803      CONTINUE
          WRITE(23,*)' '
          WRITE(23,*)'COST OF TERMINATING STO. AFTER ',SOPES,' YEARS'
          WRITE(23,*)CUDS-CUSI
          SOPES=SOPES+5
          CUSI=0.
          CUDS=0.
        ENDDO
      ENDIF
      STOP
      END
      SUBROUTINE DEHEAT(Q,T,HEAT)

      REAL Q,T,HEAT

      HEAT=Q*(2831.*EXP(-.321*T)+1038.*EXP(-.02345*T)+7.)

      RETURN
      END
```

```
SUBROUTINE UEXCOST(ROCK,UEXC1,UEXC2)

REAL UEXC1,UEXC2
CHARACTER*4,ROCK

IF(ROCK .EQ. 'SALT')THEN
  UEXC1=19.3
  UEXC2=31.8
ELSE IF(ROCK .EQ. 'TUFF')THEN
  UEXC1=25.0
  UEXC2=37.2
ELSE IF(ROCK .EQ. 'BAST')THEN
  UEXC1=41.8
  UEXC2=55.8
ELSE
  UEXC1=40.5
  UEXC2=53.0
ENDIF

RETURN
END
SUBROUTINE EXPAR(ROCK,RW,RH,RLI,CW,CH,PW)

REAL RW,RLI,RH,CW,CH,PW
CHARACTER*4,ROCK

IF(ROCK .EQ. 'SALT')THEN
  RW=2.5
  RLI=30.
  RH=2.5
  CW=6.
  CH=5.
  PW=7.5
ELSE IF(ROCK .EQ. 'TUFF')THEN
  RW=2.5
  RLI=30.
  RH=2.5
  CW=5.
  CH=4.
  PW=8.
ELSE
  RW=2.5
  RLI=30.
  RH=2.5
  CW=5.
  CH=4.
  PW=7.
ENDIF

RETURN
END
```

```
      SUBROUTINE DENDIS(Q,T,VNF,NF,FF,C,R,CW,WT,PIT,WARN)

      INTEGER WARN
      REAL Q,T,VNF,NF,FF,C,R,CW,WT,PIT,AUX1,AUX2,AHET

      WARN=0
      CALL DEHEAT(Q,T,HEAT)
      AUX1=WT*3.*HEAT
      IF(AUX1 .GT. VNF)THEN
        WARN=1
        GO TO 23
      ENDIF

      PIT=AUX1/(NF*C)
      AHET=3.*WT*HEAT*R/PIT
      AUX2=2.*AHET/(C*(CW+2.*R+C))
      IF(AUX2 .GT. FF)THEN
        PIT=3.*HEAT*R*2./(C*FF*(CW+2.*R+C))
      ENDIF

23    RETURN
      END


      SUBROUTINE THLOAD(ROCK,VNF,NF,FF)

      CHARACTER*4,ROCK
      REAL VNF,NF,FF

      IF(ROCK .EQ. 'SALT')THEN
        VNF=3600.
        NF=30.
        FF=30.
      ELSE IF(ROCK .EQ. 'TUFF')THEN
        VNF=1600.
        NF=30.
        FF=30.
      ELSE IF(ROCK .EQ. 'GRAN')THEN
        VNF=2300.
        NF=25.
        FF=25.
      ELSE
        VNF=1900.
        NF=25.
        FF=25.
      ENDIF

      RETURN
      END
```

```
      SUBROUTINE SHCOST(ROCK,NSHAFT,D,DEPTH,TSHC)

      INTEGER NSHAFT
      REAL TSHC,D(5)
      CHARACTER*1,LAB3
      CHARACTER*4,ROCK

      READ(14,*)LAB3
      IF(LAB3 .EQ. ´Y´)THEN
        READ(14,*)PAMAS,PAMBS
        READ(14,*)PAMAL,PAMBL
        READ(14,*)PAMAW,PAMBW
        GO TO 66
      ENDIF
      IF(ROCK .EQ. ´GRAN´)THEN
        PAMAS=23578.
        PAMAL=1276.
        PAMAW=1136.
        PAMBS=97.
        PAMBL=0.
        PAMBW=29.
      ELSE IF(ROCK .EQ. ´BAST´)THEN
        PAMAS=15142.
        PAMAL=666.
        PAMAW=162.
        PAMBS=101.
        PAMBL=0.
        PAMBW=21.
      ELSE
        PAMAS=16570.
        PAMAL=-4612.
        PAMAW=-3028.
        PAMBS=382.
        PAMBL=2676.
        PAMBW=1795.
      ENDIF
66    SHSC=0.
      SHLC=0.
      SHWC=0.
      DO 10 I=1,NSHAFT
        PSHSC=PAMAS + PAMBS*D(I)
        PSHLC=PAMAL + PAMBL*D(I)
        PSHWC=PAMAW + PAMBW*D(I)
        SHSC=SHSC+PSHSC
        SHLC=SHLC+PSHLC
        SHWC=SHWC+PSHWC
10    CONTINUE
      TSHC=(SHSC+SHLC+SHWC)*DEPTH

      RETURN
      END
```

```
      SUBROUTINE HDCOST(ROCK,NCAN,HODR,HDCPY,HDVOL)

      INTEGER NCAN(30),HODR(30)
      REAL HDCPY(30),HDVOL(30),PAMAH,PAMBH,HCOST,HDT,HDI

      HDI=0.5
      HDT=4.

      IF(ROCK .EQ. 'BAST')THEN
        PAMAH=1695.
        PAMBH=1.31
        HCOST=HDT*PAMAH*(HDI**PAMBH)
      ELSE IF(ROCK .EQ. 'GRAN')THEN
        PAMAH=1614.
        PAMBH=1.31
        HCOST=HDT*PAMAH*(HDI**PAMBH)
      ELSE
        PAMAH=41.5
        PAMBH=1.16
        HCOST=HDT*PAMAH*EXP(PAMBH*HDI)
      ENDIF
      DO 10 I=1,30
        HDVOL(I)=(HDI/2.)**2.*PI*HDT*HODR(I)
        HDCPY(I)=HCOST*HODR(I)
10    CONTINUE

      RETURN
      END


      SUBROUTINE OEXCOST(ROCK,U1,U2,VV,VC,VR,CV,CC,CR)

      REAL U1,U2,VV,VC(30),VR(30),CV,CC(30),CR(30)

      CV=VV*U2

      DO 10 I=1,30
        CC(I)=VC(I)*U2
10    CONTINUE
      DO 20 I=1,30
        CR(I)=VR(I)*U1
20    CONTINUE

      RETURN
      END
```