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OPTIMIZATION METHOD FOR DIMENSIONING A GEOLOGICAL HLW WASTE REPOSITORY

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ABSTRACT

This method was developed by the CEA to optimize the dimensions of a geological repository by taking account of technical and economic parameters. It involves optimizing radioactive waste storage conditions on the basis of economic criteria with allowance for specified thermal constraints.

The results are intended to identify trends and guide the choice from among available options; simple and highly flexible models were therefore used in this study, and only nearfield thermal constraints were taken into consideration. Because of the present uncertainty on the physicochemical properties of the repository environment and on the unit cost figures, this study focused on developing a suitable method rather than on obtaining definitive results.

The optimum values found for the two media investigated (granite and salt) show that it is advisable to minimize the interim storage time, implying the containers must be separated by buffer material, whereas vertical spacing may not be required after a 30-year interim storage period. Moreover, the boreholes should be as deep as possible, on a close pitch in widely spaced handling drifts. These results depend to a considerable extent on the assumption of high interim storage costs.

NOMENCLATURE

D	Diffusivity ($m^2 \cdot s^{-1}$) (D_0: nominal value)
Px	Borehole pitch: horizontal distance between adjacent boreholes (Px_{min}: limit value)
Py	Gallery pitch: horizontal distance between adjacent galleries (Py_{min}: limit value)
Q_0	Power release on removal from the reactor
Sz	Vertical spacing between waste packages in borehole
t	Elapsed time since removal from the reactor
Tf	Interim storage time (Tf_{min}: limit value)
λ	Conductivity ($W \cdot m^{-1} {}^{\circ}C^{-1}$) ($\lambda_0$: nominal value)

DISPOSAL CONCEPTS

Spent fuel reprocessing allows waste materials to be separated from recyclable fuel. The high-level waste solutions containing fission products and small amounts of actinides are concentrated and stored for one year, then calcined and vitrified. The resulting glass is cast into stainless steel canisters 1.33 m high and 0.43 m in diameter, which are placed in interim surface storage until the thermal power level has dropped to a point at which they may be moved to a storage facility in a deep continental geological formation. This concept favors thermal diffusion into the host rock.

Conditioned wastes comprising spent fuel pin hulls and end-caps, bituminized sludges from liquid waste treatment units and intermediate-level technological wastes are also targeted for geological storage. The thermal power released is low enough to permit storage in compact systems such as vaults or silos.

These two types of wastes, "C" wastes including high-level glass packages and "B" waste comprising intermediate-level alpha-emitters, will therefore be transferred to a single geological repository site, but probably according to very different gallery concepts.

Four types of host rock formations are now under investigation in France: granite, schist, salt and clay. Current plans call for a future repository with a capacity of 350 000 m^3 of "B" waste and 14 000 m^3 of "C" waste. The borehole disposal concept is shown in Figure 1.[1]

Because of its high thermal power release, "C" waste requires greater spatial dilution in the host rock than other categories of waste materials. The optimization method was therefore developed and used for this type of waste, although it may of course be applied to other wastes as well.

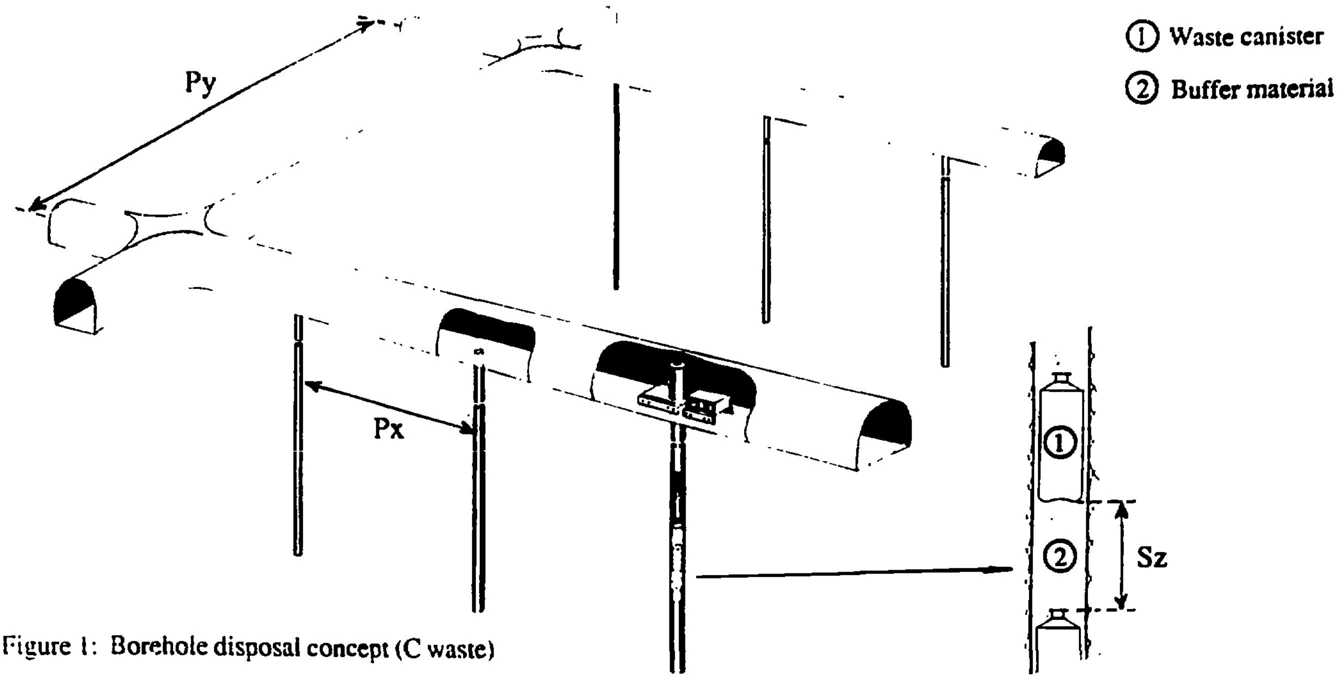

Figure 1: Borehole disposal concept (C waste)

OPTIMIZATION METHOD

For the purposes of this investigation, waste management involves two essential steps:

- Interim surface storage during which the waste packages are under constant surveillance and cooled by natural convection to allow radioactive and thermal power decay.
- Final storage in an underground repository (500 m below the surface in this study). The repository is assumed to comprise boreholes on a rectangular grid, with each hole containing a single stack of waste packages.

The investigation covered two aspects: identification of an economic criterion, and description of the limiting scenarios meeting the thermal constraint. Simultaneous analysis of both aspects provided a technical and economic optimum situation.

It was first necessary to model the waste management scenarios, i.e. to inventory their descriptive parameters and express the relations among them.

In this study the packages are described by their geometric specifications (height, diameter, number, etc.) and by their age which allows the rate of thermal power release to be determined at any given time. The interim storage phase is described by its duration, while the repository is represented primarily by its geometric characteristics (average depth, rectangular grid pitch, borehole depth and diameter, etc.).

A total of 16 parameters were identified. Analysis showed that the value of five parameters is related to the thermal constraint:

- the interim storage duration
- the number of packages per borehole
- the vertical spacing of the packages in each borehole (Sz)
- the borehole grid pitch (Px)
- the pitch on which storage galleries are laid out (Py)

The optimization therefore covered these five parameters.

Two types of host rock (granite and salt) were considered for the development of the method. This approach was adopted because consistent data was available for both media and because their properties are appreciably different:

- very different thermal properties
- a buffer material can be considered in granite, but not in salt
- the dimensioning constraints are significantly different in these two media.

THERMAL ANALYSIS

General

A nearfield thermal constraint corresponds to the existence of a temperature that cannot be exceeded without affecting the integrity of the medium, and thus the quality of the containment. Each of the media between the waste material and the biosphere (bedrock, engineered barrier, glass) serves as a containment barrier, and each can be characterized by a maximum permissible temperature. As a calculation exercise, the following limit values were selected as theoretical assumptions.

For glass, the frequently cited figure of 450°C is well below the recrystallization temperature marking the transition from an amorphous phase to an organized phase in which the radionuclide retention capacity would diminish.

Clay buffer material was assumed in granite, and the temperature constraint was set at 150°C. In a granite massif the maximum rock face temperature was assumed to be between 100°C and 120°C. Reliable figures were not available for salt, and therefore no specific constraint was applied.

The severest maximum temperature value is the design basis constraint. The following nominal values were initially adopted: 120°C rock face temperature in granite, and 300°C glass core temperature in a salt environment. The interim storage period was subsequently set at 20–30 years, and the following nominal values were adopted: 450°C glass core temperature in a granite repository with the waste package surrounded by a small air gap and a buffer material with low thermal conductivity, and 100°C rock face temperature with the package surrounded by a clayey nearfield engineered barrier material; the glass core temperature in salt was set at 400°C and 450°C.

The study was conducted for PWR waste glass (fuel burnup: 33 000 MWd·t^{-1} reprocessed after 3 years of cooling). Temperature profiles were obtained by solving the heat equation for an isolated borehole with conductive heat transfer, and then superposing the profiles obtained for each hole using the linearity property of the heat equation.

Several methods are available for obtaining a numerical solution to this equation (e.g. finite differences or finite element methods). In view of the assigned objectives, each borehole was assimilated with a continuous line source of finite length. This hypothesis allows a numerical integral solution to the heat equation.[2]

The borehole wall temperature versus time was determined by this method, while the profile in the engineered barrier was calculated by applying a logarithmic correction factor and the profile in the waste package was calculated using a parabolic correction. This assumes that the actual profiles in the engineered barrier and in the waste package at any given time can be represented with acceptable accuracy by a profile with the same shape as the steady-state profiles.

Calculations were performed for a simplified model using the *TS* code, written in FORTRAN 77 and running under UNIX. The results obtained for a single borehole were qualified by comparison with those provided by a finite-element code: the simplified model was found to give correct results within the parameter limits investigated here, as shown in Figure 2.

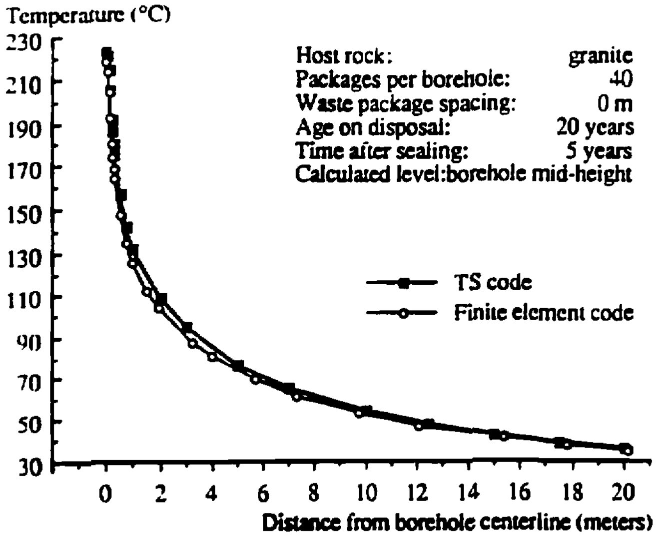

Figure 2

Results of the Calculation Exercise

Granite

Various (Px,Py) curves were plotted by imposing values on two of the other three parameters. The resulting curves are symmetrical along Px and Py, tending towards two asymptotes: Px_{min} and Py_{min}.

When waste packages are stacked with little or no separation, a minimum interim storage time after waste conditioning is necessary before geological disposal is possible. This is illustrated by the following graphs, representing the permissible geometric limits:

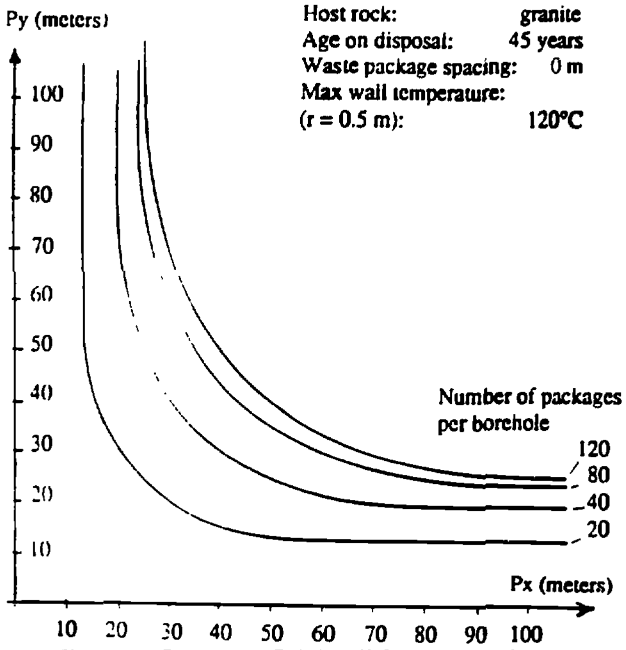

Figure 3: Py versus (Px) for different Np values

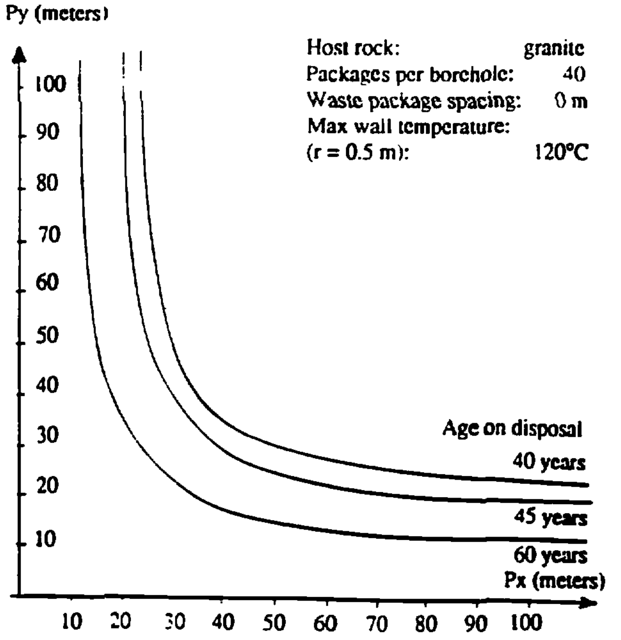

Figure 4: Py versus (Px) for different Tf values

After identifying the asymptotes Px_{min} and Py_{min}, the study concentrated on (Px_{min} and Py_{∞}) pairs: when the gallery pitch (Py) exceeds 80 m, two adjacent galleries may be considered thermally independent for practical purposes (this corresponds to Py_{∞}). The y-axis in Figures 5, 6 and 8 refers to the minimum horizontal distance between boreholes.

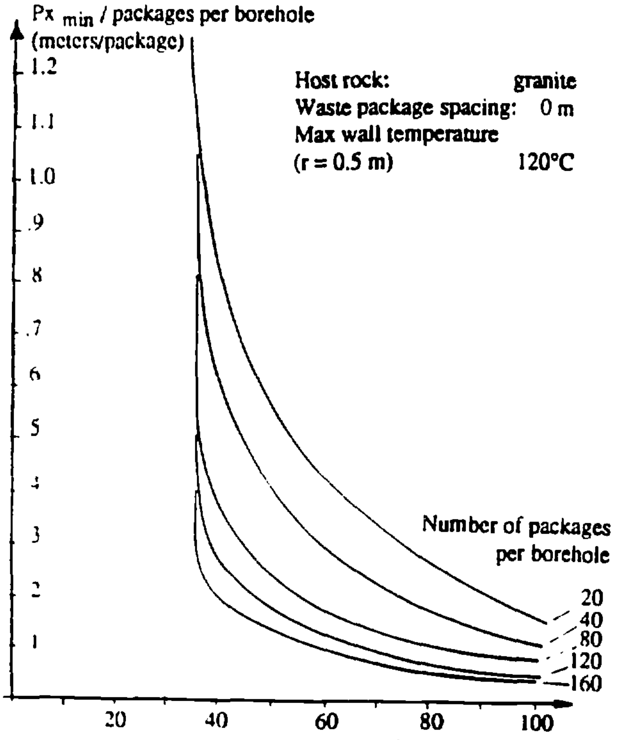

Figure 5

The effect of waste package spacing was also examined. From a nearfield standpoint, package spacing results in vertical dilution of the power introduced into the host rock, causing Px_{min} to diminish as the spacing increases. The effect on the minimum pitch becomes more significant for small vertical spacing and large numbers of packages in the hole.

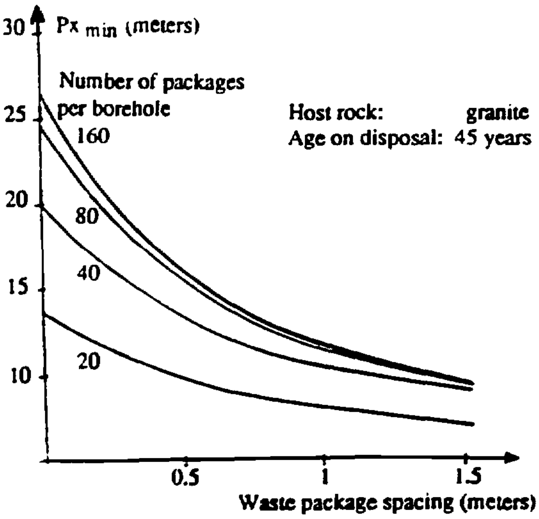

Figure 6

Doubling the waste package axial pitch would reduce the linear power by 50%, but would not affect the total power. The power released from the package can be estimated by an exponential function of the form $Q_0 exp(-t/40)$, implying that the power is reduced by 50% every 28 years. Consequently, the maximum temperature is the same whether the waste package is sealed after a 28-year delay or the axial pitch of the waste packages is doubled: in each case, the linear power in the borehole is reduced by half.

The nominal results were supplemented by investigation of sensitivity to variations in the basic parameter values, including environmental conductivity and diffusivity, and different numerical values for the design basis thermal constraint.

- **Sensitivity to numerical constraint value**

Reducing the maximum permissible temperature from 120°C to 100°C significantly increases the minimum pitch values (i.e. Px_{min} and Py_{min}) and the minimum interim storage time prior to disposal (Tf_{min}) as shown in the following tables:

Table 1 - Minimum Pitch Values in meters (Tf = 60 years)

Packages per Borehole	Maximum Temperature 120°C	100°C	Variation %
20	8.75	12.5	+43
40	12	18	+50
80	14.5	22	+52
120	16	23	+44

Table 2 - Minimum Age before Sealing

Packages per Borehole	Maximum Temperature 120°C	100°C	Variation %
20	33	43	+20
40	36	45	+25
80	36	45	+25
120	36	47	+30

- **Sensitivity to Host Rock Conductivity Variations**

The borehole wall temperature is inversely proportional to the conductivity of the host rock. A 5% drop in conductivity thus causes the temperature to rise by about 10°C and increases the risk of exceeding the maximum permissible temperature value.

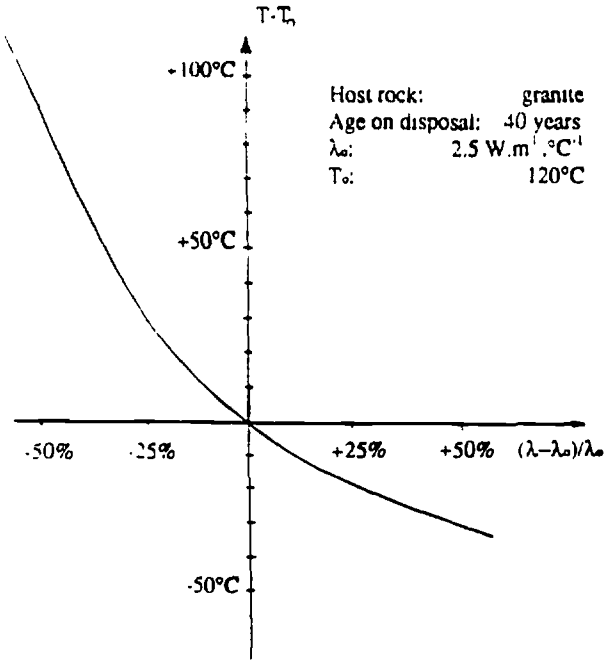

Figure 7

The value of Px_{min} rises as the conductivity diminishes. A 25% to 50% drop in conductivity makes it impossible to meet the thermal constraint by modifying only the distance between boreholes (i.e. the wall temperature of an isolated borehole[*] exceeds 120°C).

This phenomenon becomes increasingly important for shorter interim storage times.

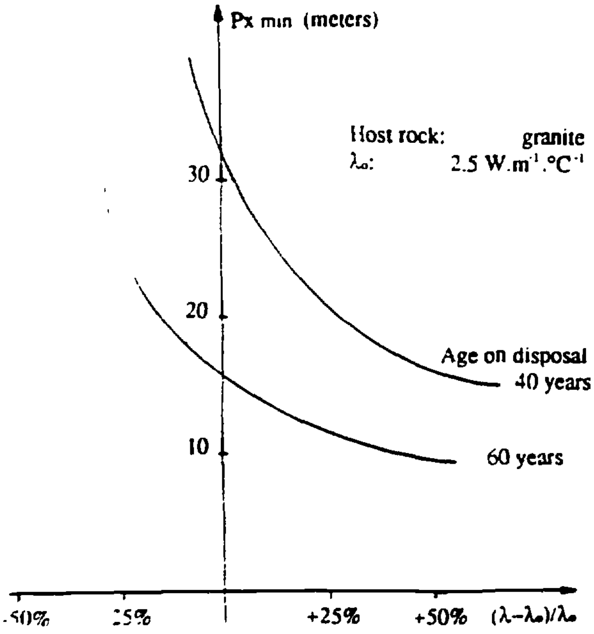

Figure 8

- **Sensitivity to Host Rock Diffusivity Variations**

For equal percentage variations the diffusivity parameter has less effect than conductivity. The wall temperature increases with diffusivity when the conductivity is held constant.

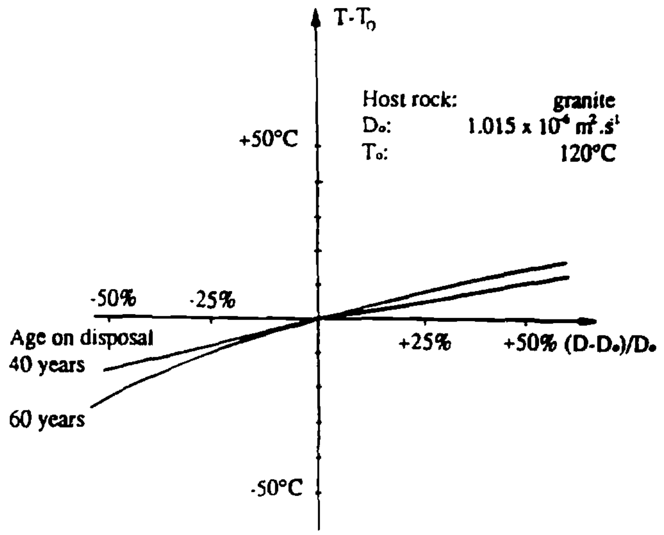

Figure 9

- **Sensitivity to Borehole Radius Variations**

At any given point in time the temperature profile decreases to a minimum at the midline between adjacent boreholes. Increasing the borehole radius is equivalent to a lower thermal constraint, and results in lower Px_{min} values.

Table 3 - Borehole Radius versus Borehole Pitch

Borehole Radius (m)	0.22	0.35	0.5	0.65	0.8
Px_{min}	∞	42	32	29	27

Salt

The same approach was applied to salt formations to determine permissible geometric limits. The physico-chemical properties of salt are more favorable than for granite, as the conductivity and diffusivity are significantly higher.

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[*] $Px = Py = \infty$

The resulting graphs are similar in shape to those obtained for granite, as shown in the following figure:

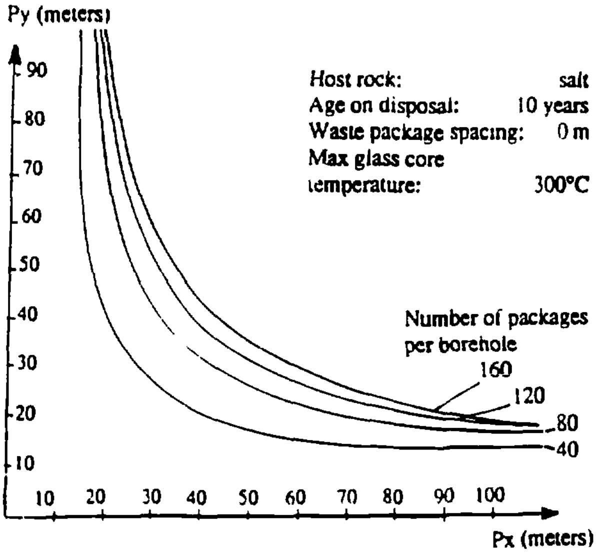

Figure 10

From a thermal standpoint, salt allows packages to be placed in the repository after a shorter period of interim storage (e.g. 10 years in Figure 10) and on a closer pitch.

Parameter sensitivity studies were conducted in the same way as for granite. The crucial point is to examine the effect of variations in the thermal constraint on the minimum interim storage period:

Table 4 - Waste Package Age Sensitivity
to Maximum Permissible Temperature Value

Maximum Temperature (°C)	240	270	300	330	360	390
Variation	-20%	-10%	0	+10%	+20%	+30%
Tf_{min} (years)	8.5	5.5	3.5	2.5	1.75	1.5
Variation	142%	57%	0	-29%	-50%	-57%

ECONOMIC ANALYSIS

General

The cost estimates used for this study did not cover all factors related to HLW management, but were limited to interim storage (creation and operating costs) and to the portion of the repository assigned to HLW glass packages. Costs related to reception and handling of waste packages at the surface facilities were excluded, as were the cost of the repository access shafts and intermediate level waste (ILW) materials assumed to be stored at the same site.

The total cost function constitutes the economic criterion to be optimized. An itemized cost breakdown was prepared in parameter form (e.g. gallery building cost = cost per meter × length in meters). A parameter expression for each basic cost item was defined from our economic analysis. These costs are generally expressed by a linear relation of optimization parameters, based on approximations that can be considered acceptable in this type of study.

The creation and operation of interim surface storage and underground repository sites will cover several decades, so the total cost function should include provision for calculating the present value.

Expenditures were not discounted in this analysis, however. This would have entailed considerable difficulties since above a certain discount rate the total cost (interim and final storage) may be a diminishing function of the interim storage time. Repository storage is the major capital cost item, and present value discounting can diminish this cost more quickly than it increases the interim storage cost. The optimum value would thus be reached with a virtually infinite interim storage time, which is unrealistic in view of other vital considerations including long-term safety and sociological or political considerations.

Finally, the economic cost criterion was expressed in terms of the five optimization variables. The constraints are not expressed in literal form, so an analytical method cannot be used for optimization purposes. An optimum value was determined graphically by considering the optimization variables in pairs. Isoconstraint and isocost values were plotted on the same graph; the point of tangency corresponding to the lowest cost represents the economic optimum under the constraints imposed.

Results of the Calculation Exercise

The following table is an example of optimum design values determined during the first stage of the process for granite and salt repositories, assuming a 120°C granite face temperature and 300°C glass core temperature in salt, with no allowance for present value conversion.

Table 5

Storage Parameter	Granite	Salt
Borehole spacing in galleries	25 m	4.2 m
Storage gallery pitch	80 m	80 m
Vertical spacing of packages	2.4 m	2.7 m
Cooling time	short	short
Borehole depth	maximum	maximum

The table shows that optimization on the basis of technical and economic criteria would involve a short interim storage time and wide vertical spacing of the waste packages. In fact, because of additional constraints (e.g. repository construction deadlines and compliance with transport regulations for highly irradiated waste packages) the minimum cooling time must be 20–30 years.

The model was then used to determine the extent to which the optimum value is affected by variations in unit costs.

The following figure illustrates a typical analysis during the second stage of the calculation process, assuming a 100°C granite face temperature and a clayey nearfield engineered barrier material.

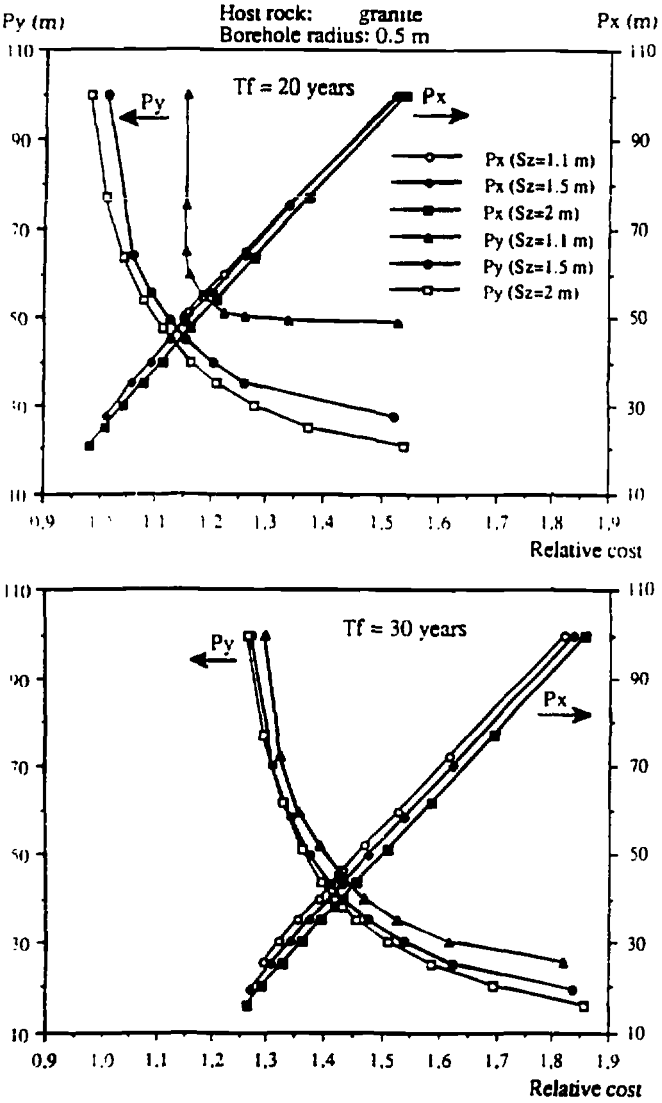

Figure 11

The following optimum values were determined for this example:

Table 6

Borehole spacing in galleries:	21 m
Storage gallery pitch:	100 m
Vertical spacing of waste packages:	2 m
Cooling time:	20 years
Packages per borehole:	80

CONCLUSION

The model developed and the method implemented are highly flexible, allowing geometries to be rapidly defined; this, together with modular processing of the cost item data base, allows basic policy orientations to be determined in a relatively short time.

The principal conclusions that can be drawn from this calculation exercise at the present time include the following:

- The boreholes should be as deep as practicable in view of site geology, boring and package disposal considerations.
- Individual holes should be spaced on a close pitch in the access gallery, while the galleries should be widely spaced.
- Interim storage time should be held to a minimum and buffer material should be packed between each waste package.
- Conversely, if the interim storage time exceeds 30 years, vertical spacing of the waste packages may not be necessary.

These conclusions are valid for a basic scenario in which interim storage costs are of primary importance. As a general rule, the optimum values are closely related to the relative weight of each term constituting the economic criterion.

The investigation must therefore be pursued by taking account of additional constraints (e.g. power in the host rock, dimensions of the host massif, safety requirements, mechanical limits, repository scheduling requirements, etc.) and by identifying unit costs and their formal expressions in greater detail.

The methodology developed in this study was initially used with a set of data and hypotheses to identify preliminary orientations which may be confirmed or modified on the basis of more detailed information concerning the fundamental geological, technical and economic factors involved.

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