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**RADIATION DOSE DEPOSITION  
AND ENERGY ACCUMULATION  
IN A ROCK SALT WASTE REPOSITORY**

BY

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Abstract

Geological rock salt formations are widely considered as possible repositories for permanent disposal of nuclear fission waste. This highly radioactive material will intensely irradiate its direct surroundings and a minor fraction of the radiation energy will be deposited in the rock salt material by creation of defects. In the first part of the report information concerning the mechanisms of defect creation by irradiation of alkali-halides and their annealing afterwards and of the formation of colloidal alkali metal is briefly reviewed.

For a number of realistic configurations and strategies of waste storage calculations were performed to obtain the gamma flux in the rock salt surrounding the waste, the energy deposition rate and the absorbed dose as functions of distance to the container, irradiation time and some other parameters. Based on these results an estimate was made of the build-up of stored energy, depending on the temperature of the rock salt (data from Jenks and Bopp were used). The results indicate that the energy storage is negligible at distances from the container larger than about 24 cm, even if an increased storage rate at lower dose rates would be taken into account. Although the effects of radiation damage are significant, the range over which they extend is very limited and the amount of energy associated with it can have only very modest consequences for local temperature and pressure if it were released suddenly. The formation of colloidal sodium will not lead to fractions exceeding a few per cent.

Keywords:

SODIUM CHLORIDES	STORED ENERGY	RADIOACTIVE WASTE STORAGE
SALT DEPOSITS	COLOR CENTERS	RADIOACTIVE WASTE DISPOSAL
GAMMA RADIATION	DOSE RATES	COMPUTER CALCULATIONS
RADIATION EFFECTS	RADIATION DOSES	MEDIUM TEMPERATURE
CRYSTAL DEFECTS	RADIATION FLUX	T CODES



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## 1. INTRODUCTION

Geological rock salt formations are widely considered as possible repositories for permanent disposal of nuclear waste. For this purpose the nuclear waste will be incorporated in cylindrically shaped glass blocks which are then sealed in steel containers. Such waste containers will be deposited into vertical holes in bedded or domed rock salt. Generally these holes are at several tens of meters distance from each other.

Even if the nuclear waste is stored during several years before it is placed in a repository the highly radioactive material will intensely irradiate its direct surroundings. The major fraction of the gamma radiation energy will be deposited in the salt as heat. Partly by this effect the material will be raised in temperature, particularly during the first years after storage and in the region directly surrounding the waste. However, this heat will be gradually spread over the immense volume of the rock salt formation.

A minor fraction of radiation energy is deposited in the rock salt material by creation of defects.

Depending on temperature part of the defects will quickly anneal and the remainder may become stable or coagulate into regions of defective material. In such a way the energy associated with singular or conglomerated defects is fixed in the crystal lattice of the salt and may remain stored during longer periods of time.

Energy storage in alkali halides has been known for a long time as a result of ionization by gamma- or x-rays or by electrons. Besides the energy deposition in the distorted lattice the defect creation and subsequent processes may lead to a partial decomposition of the salt into its constituent elements.

Both effects, the energy storage and the chemical decomposition deserve careful consideration in order to evaluate possible consequences that they will have when this form of waste disposal is applied. In case of a rapid release of stored energy unwanted effects on the nuclear waste that has been stored might occur and a serious decomposition of the salt might create a local environment with chemical effects on the containment of the waste.

Among the effects of decay heat, energy storage and decomposition it is particularly the development of the temperature in the rock salt that has been studied in detail [1,2]. This development of temperature distributions in salt formations could be calculated with great accuracy. On the effect of stored energy due to irradiation damage extensive data have been collected [3-6] that can be applied to realistic conditions in a waste repository. The decomposition and more specifically the formation of free colloidal sodium have been studied in particular to establish the mechanism of formation and annealing [7-10] but less towards their effects under repository conditions [11].

It has become evident that for a reliable estimation of the influence of these irradiation effects it is of importance to have available reliable values for the radiation dose deposited in the salt and its variations with time and distance from the container.

In this study new calculations of dose depositions will be presented. They have been applied to a number of realistic configurations of waste storage. Together with calculations of temperature distributions due to decay heat, from such accurate dose calculations detailed estimates of the build-up and release of stored energy may be obtained by critical use of existing data on this effect.

Since from many investigations it has become evident that a narrow relation exists between energy build-up and colloidal metal concentration the latter may be calculated on the basis of dose calculations as well.

## 2. IRRADIATION EFFECTS IN ALKALI HALIDES

Mechanisms of defect creation by the irradiation of alkali halides and of their annealing afterwards have been subject of many theoretical and experimental studies [12,13] during the last decade. Such studies became of technological interest when geological rock salt formations were considered for use as nuclear waste repository medium. It is in view of such applications that the presently available knowledge and information will be briefly reviewed. Based on this information calculated values for irradiation dose deposition will be used to estimate such effects as build-up of stored energy and formation of colloidal alkali metal. It seems to be evident that a relation exists between these two effects although this may not be a simple one.

Most experimental investigations have been carried out by means of high energy electron beams from an accelerator facility or by means of gamma radiation or X-rays. It is important to understand that the effects in the alkali halide structure of gamma-ray produced Compton and photo-electric recoil electrons are very similar to those of high-energy electrons. Of course, the transmission properties through the material are very much different for the various types of radiation. In a study of stored energy effects Delgado and Alvarez Rivas [6] pointed out that there may occur appreciable quantitative differences in defect creation by gamma radiation and high energy electrons and for the latter there are very noticeable differences if the electron energy has different values.

Considering processes of irradiation damage, different stages of effects should be distinguished. The primary effect of electron or gamma radiation penetrating into the alkali halide lattice is ionization, i.e. the formation of a free electron and an electron hole. In many cases they will quickly afterwards recombine leaving an undamaged lattice in which the energy will be released as heat. In other cases the ionization products will be trapped in the lattice. Due to this ionization the chlorine anions in sodium chloride may become positively charged and are then easily expelled from their lattice positions. This may give rise to two effects of irradiations. The anion vacancy will catch an electron thus forming an F-centre and the chlorine ion will occupy an interstitial position.

Associating with another chlorine ion located at a lattice site it can form a pair of chlorine ions now located around the lattice position and aligning its molecular axis either along the direction [110] or [111]. Defects in the form of such molecular centres are generally characterized as H-centres [14]. Depending on temperature, impurities and dislocation density both the F-centres and the H-centres may become mobile and then give rise either to the formation of conglomerates or to annealing and restoring of the original lattice. Conglomeration of F-centres will lead to local regions with excess of sodium ions and if such regions become sufficiently large it is probable that due to gradually changed atom potentials the electron energy bands will be rearranged according to a scheme for sodium metal. In that case one may speak of particles of colloidal sodium. Similarly a mechanism of coagulation of chlorine molecular centres may be expected, giving rise to minor chlorine bubbles.

Although the processes for the primary defect creation are now reasonably well understood, the complexity of secondary processes is still such that no unified description has been accomplished.

With the purpose of making estimates of the build-up of stored energy due to radiation damage and the possible hazards of this phenomenon when using salt mines as waste repositories, an experimental programme was carried out at Oak Ridge National Laboratory by Jenks and Bopp [3,4,5]. They measured the stored energy build-up in rock salt specimens from a variety of sources and irradiated by  $\gamma$ -radiation to several dose values and they studied the kinetics of the defect creation, of the simultaneously occurring back-reaction and a following annealing process. It is important to note that they carried out their investigations in the range of dose levels that will be encountered in rock salt directly surrounding waste containers in a repository. Their observations and conclusions can be summarized as follows.

The rate of formation of stored radiation energy can be expressed by

$$dE/dt = k_1 I \quad (2.1)$$

Here  $E$  is the amount of stored energy,  $I$  is the dose rate and  $k_1$  is the formation constant.

Taking into account a term for radiation induced annealing the expression becomes

$$\frac{dE}{dt} = k_1 I - k_2 I E \quad (2.2)$$

where  $k_2$  is an annealing constant.

The formation term  $k_1 I$  can be understood on the basis of defect-formation as has been described above. The form of the back-reaction term can be explained if it is assumed that a fraction of the freshly formed primary radiation defects react with existing defects to form undamaged NaCl.

That fraction is proportional to the number of defects already present in the crystal. The reaction constant  $k_2$  varies with temperature since the back reaction term in expression (2.2) depends on the state of aggregation of these defects. At lower temperatures the defects will be more in the form of F-centres whereas at higher temperatures they will have coagulated into colloidal sodium. It is evident that mobilities associated with the two states of defects will be different. Expression (2.2) leads to the integral

$$E = \frac{k_1}{k_2} (1 - \exp(-k_2 D)) + E_0 \exp(-k_2 D) . \quad (2.3)$$

Here  $D$  is the collected radiation dose  $D = \int I dt$  and  $E_0$  is the stored energy at zero time, which usually can be taken equal to zero.

Expression (2.3) shows that this phenomenology leads to a saturation for the amount of stored energy.

At temperatures above  $150^\circ\text{C}$  the annealing apparently occurs according to an additional term in equation (2.2), which turned out to be of zero-kinetic order:  $dE/dt = -K$ . This means that the rate of annealing is independent of the amount of stored energy. This is a rather rarely occurring process, which can be explained by assuming a rapidly adjusting equilibrium between coagulated and single defects, e.g. colloidal sodium and F-centres. The rate determining step is some kind of an "evaporation" process due to which the concentration of evaporated single defects does not depend on the amount of conglomerated defects.

This concentration will be maintained at a constant value until e.g. the colloidal sodium has disappeared. The evaporation process is thermally activated and consequently the single defect concentration is temperature dependent. For temperatures significantly higher than 150°C the effect of this annealing process is such that build-up of stored energy can be neglected. With this additional process taken into account expression (2.2) becomes

$$\frac{dE}{dt} = k_1 I - k_2 I E - K \quad (2.4)$$

and by integration

$$E = \frac{k_1 - KI^{-1}}{k_2} (1 - \exp(-k_2 D)) \quad (2.5)$$

Here the zero-time stored energy has been neglected.

The saturation level associated with expression (2.5) depends strongly on the temperature regime. Between 100 and 150°C it amounts to about 75 J/g and below 100°C it rises to 245 J/g. Assuming a stored energy of 4.25 eV per defect pair [12] these saturation values correspond to a defect concentration of 1.1% and 3.5% mole fraction. Lidiard [12] pointed out that such large concentrations can only be retained by colloids since F-centre concentrations saturate at much lower values. However, he argues that according to the Jain-Lidiard theory [7] the rate of energy release is not compatible with the evaporation of F-centres from colloids being the rate-determining step, but that it is rather the recombination of F-centres with molecular centres. This can only be a valid interpretation if the molecular centres are clustered together, because of the zero-order character of the reaction. The F-centres apparently maintain an equilibrium by relatively rapid evaporation from colloids.

In agreement with the above-mentioned theory it was found by Jenks and Bopp [4: i) that the formation of stored energy in the dose regime when saturation may be reached is insensitive for dose rate and ii) that beyond a maximum temperature and a minimum dose rate the build-up of stored energy is negligible.

The measurements of the energy release were confirmed by chemical analysis determining the amounts of hydrogen and  $OCl^-$ , that were formed by solution of specimens in water.

Delgado and Alvarez Rivas [6,8] who studied the temperature variation of the stored energy release found that the capability to store energy increases markedly with decreasing cation size.

They find the stored energy for F-centres too large to explain the release of energy by F-centre recombinations and they suggest that some other type of radiation damage should be involved.

Recently radiation induced formation of color centres and colloids have been studied intensively by Levy et al. [9] at Brookhaven making optical measurements during irradiation by 1.5 MeV electrons. They observed that F-centre absorption increases monotonically with dose until a well-defined plateau.

The growth of absorption bands associated with colloidal sodium showed an induction period of almost equal duration as was needed for reaching F-centre saturation. After that period a rapid growth of colloidal sodium was observed according to the character of nucleation and growth and approximated by  $C.t^n$  where C and n are constants and t is irradiation time with constant dose rate. Both F-centre and colloid growth were strongly temperature dependent, the first being a maximum between 100 and 115°C whereas the second was strongest from 150 to 170°C.

In addition the effects of varying dose rates, impurity concentration and amounts of plastic strain and deformation were investigated. They could explain the appreciable spread of colloid formation in specimens from different origins.

Since the observations do not extend beyond an integrated dose of 300 Mrad it can be understood that they do not reach the level of irradiation where according to Jenks and Bopp [5] very evidently saturation effects occur. Although the description according to nucleation and growth is very useful for better understanding of the mechanism of the active processes it is by no means justified to apply this model and in particular the observed parameters to doses of a few tens of Grads as can be encountered in material directly surrounding waste containers in a repository. In this respect Lidiard's estimate of a few percent of colloidal sodium obtained at doses at which stored energy has reached saturation value seems to be more realistic than the extrapolation of observations at appreciably lower doses. In view of such unjustified extrapolations Levy's estimates [15] of colloid concentrations of 10 to 50 percent mole fraction must be considered as unlikely.

Summarizing, it may be concluded that it is evident that there is a correlation between colloid formation and energy storage. However, discrepancies with theory make it uncertain that the rate of energy release is related with the evaporation of F-centres from colloids. Possibly the evaporation of molecular anion defects from cluster plays a rate-determining role.

Jain and Lidiard's theory did not predict saturation effects but could very well allow for them. In view of the very obvious experimental results it is not justified to apply a far reaching extrapolation in the estimates of colloid formation neglecting possible and even probable saturation phenomena.



### 3. CALCULATION OF GAMMA DOSIS AND ENERGY STORAGE

#### 3.1. General description

The waste containers, buried in the salt, are long cylinders, filled homogeneously with vitrified radioactive high level waste.

To obtain the material composition of this high level waste, a burn-up calculation was performed for the fuel of a Pressurized Water Reactor, using the code ORIGEN [16]. The code continues with the calculation of the decay of the fission products after discharge of the fuel from the reactor. After a cooling time of some years the fuel is reprocessed, whereby a small fraction of the remaining nuclear fuel is lost to the (high level) waste. After vitrification of the waste several strategies are possible for the encapsulation and subsequent burial in the rock salt, in which some of the variables are: waiting time before burial, diameter of the containers, the volume of glass that is used to accommodate the high level waste obtained from one tonne of the original reactor fuel. In this design care has to be taken of the fact that the temperature-rise of the rock salt after emplacement of the container is not allowed to exceed a certain limit. Therefore, some calculations were performed with the code TASTE [17] to obtain the temperature distributions in the salt as a function of the time of storage.

From the ORIGEN calculations we thus obtain the time dependent radioactive source of gamma radiation present in the containers.

Next, for the different cases studied, calculations were made of the resulting gamma flux in the rock salt surrounding the container, This gives the energy deposition rate, and after integrating over time one obtains the absorbed dose as a function of irradiation time, distance to the container, container diameter, and some other parameters.

Finally, the build-up of stored energy as a function of time and at various distances from the waste containers is calculated, taking into account the influence of the local temperature of the salt.

### 3.2. Calculation of the radioactive source

For the burn-up calculation with ORIGEN the reactor characteristics were chosen as follows:

Enrichment : 3.3% <sup>235</sup>U  
 Specific power : 40 MW/tonne U  
 Load factor : 0.75  
 Specific burn-up: 33 GWd/tonne U

For the chemical reprocessing after burn-up the following assumptions were made:

- No gaseous fission products (Kr, Xe) are present in the high level waste;
- The high level waste contains 0.5% of the uranium and of the plutonium that were present in the fuel after discharge from the reactor.

For the time of reprocessing two cases were considered: in the first the reprocessing takes place five years after discharge from the reactor, in the second case after ten years.

Finally, as a function of time, one obtains the heat source and the gamma-radiation source present in the waste. The energy spectrum of the gamma radiation is represented in ten energy groups.

### 3.3. Calculations of the energy deposition in the salt

The energy deposition rate or absorbed dose rate due to the gamma radiation from the waste, as a function of the irradiation time (decay time)  $t$ , the inner radius  $R$  and thickness  $c$  of the container wall and the distance  $d$  from the container wall in the salt, is given by the expression:

$$A(\mu_s, \mu_i, \mu_m, R, c, d, t) = \sum_i \phi_i(\mu_s, \mu_i, \mu_m, R, c, d, t) E_i \frac{\mu_{ai}}{\rho C} = \sum_i I_i(\mu_s, \mu_i, \mu_m, R, c, d, t) \frac{\mu_{ai}}{\rho C}, \quad (3.1)$$

in which  $\phi_i$  is the photon flux density at distance  $d$ ;  $E_i$  is the average energy of the photons considered;  $\mu_s$ ,  $\mu$  and  $\mu_m$  are the attenuation coefficients in the source, the iron wall and the surrounding medium, respectively;  $\frac{\mu_{ai}}{\rho}$  is the mass absorption coefficient of the salt, and  $C$  is

a factor to convert  $J\text{ kg}^{-1}$  to rad. The summation is over the energy groups  $i$ .  
The energy flux density is given by

$$I_i(\mu_{s,i}, \mu_i, \mu_{m,i}, R, c, d, t) = \sum_j \frac{S_{ij}(t)}{V_s} K_i(\mu_{s,i}, \mu_i, \mu_{m,i}, R, c, d), \quad (3.2)$$

in which the energy release rate of the source is given by

$$S_{ij}(t) = N_j(t) \lambda_j \alpha_{ij} E_i. \quad (3.3)$$

In our case the source was assumed to consist of the waste obtained from one tonne of irradiated fuel;  $V_s$  is the volume of glass needed to accommodate this quantity of waste;  $N_j$  is the number of atoms of radioactive nuclide  $j$ ;  $\lambda_j$  its decay constant,  $\alpha_{ij}$  gives the number of photons released in energy group  $i$  per desintegration. (Note that the total radioactivity of the source is given by  $\sum_j N_j(t) \lambda_j$ ).  
The summation over  $j$  in (3.2) is a summation over the gamma emitting nuclides in the source.

For the calculation of the photon flux use was made of the point kernel integration method, in which the container is considered as a cylindrical self-absorbing volume source.

The attenuation kernel is of the form:

$$K(\mu r) = B(\mu r) \frac{e^{-\mu r}}{4\pi r^2}. \quad (3.4)$$

After integration one obtains an expression of the form:

$$K_i(\mu_{s,i}, \mu_i, \mu_{m,i}, R, c, d) = \frac{R}{\pi} B_i(\mu_{s,i}, \mu_i, \mu_{m,i}, R, c, d) \cdot G_i(\mu_{s,i}, \mu_i, \mu_{m,i}, R, c, d) \quad (3.5)$$

The factor  $G_i$  accounts for the direct ray transmission, while  $B_i$  is the so-called build-up factor ( $\geq 1,0$ ) which corrects for the extra-contribution to the dose rate in the receptor point from scattered photons (travelling along alternative transmission paths and having lost part of their energy) [18-20].

3.4. The cases considered

The calculations were performed for ten cases, the characteristics of which can be found in table 3.1. For the inner diameter of the cylinder two values were chosen (30 and 42 cm), both with a wall thickness (iron) of 0.5 cm.

An important parameter is the specific glass volume  $V_g$ , that is the glass volume used to accomodate the waste obtained from one tonne of original fuel (U).

In the waste repository in the salt dome the cylindrical containers are placed in a regular square pattern. For the cases considered here this distance varies from 85 to 120 meters. As a result the contribution of neighbouring containers to the local maximum temperature (second column in table 3.2) is negligible.

Table 3.1. Specification of ten cases of nuclear waste storage in rock salt for which gamma dose deposition and energy storage has been calculated.

case no	time of reprocessing (year)	decay time after reprocessing before burial (year)	inner diameter of container (cm)	specific glass volume of waste (liter)	at time of burial	
					total heat source/original tonne U (W)	strength of linear heat source (W/m)
101	10	0	30	150	1080	430
102	10	0	42	150	1080	850
103	10	17	30	90	650	430
104	10	17	42	90	650	850
51	5	0	30	150	1920	769
52	5	0	42	270	1920	837
53	5	5	30	150	1060	425
54	5	5	42	150	1060	830
55	5	20	30	90	650	430
56	5	20	42	90	650	850

An other variable is the decay time between reprocessing and burial. The various parameters have to be chosen such that the maximum local temperature rise will not exceed a certain value, for which here two possible values have been used, 110°C and 160°C (see table 3.2).

In the final presentation of the results in this report only two cases (56 and 52) have been given in detail, because the results of the other cases are similar and in between these two extreme cases.

For the configurations 56 and 52 the time development of the gamma dose deposition has been calculated from 0.25 cm to 24 cm distance from the container wall. The results are given in figures 1a and 1b. From these data the radial distribution after several periods of time have been derived and they are given in figures 2a and 2b.

### 3.5. Calculation of energy storage

Based on the calculations of radiation dose deposition in rock salt around radioactive waste containers it has been attempted to make estimates of the build-up of energy storage. It has been pointed out in chapter 2 that this energy build-up is strongly dependent on the temperature of the rock salt. For the configurations that were considered and that have been specified in table 3.1. the development of temperature with time has been calculated at several distances from the waste containers.

These calculations are carried out by means of the code TASTE (Three-dimensional Analysis of Saltdome Temperature) [17] and the maximum temperature values that are reached have been given in table 3.2.

These calculations show that in only a few configurations the material directly surrounding a container will reach temperatures above 150°C and then only during a limited period of time. Therefore, it has been assumed that the zero-order annealing process according to the third term in expression (2.4) may be neglected. In the few cases in which this process may be active it will have the effect to decrease both the build-up of stored energy and the formation of colloidal sodium. The calculations have been carried out according to expressions (2.2) and (2.3) with the assumption that the zero-time stored energy is equal to zero.

From the investigations by Jenks and Bopp [4,5] it follows that the energy build-up is strongly temperature dependent. From their results the following data have been used in the calculations.

$$\begin{aligned} \text{For } T > 100^{\circ}\text{C} : k_1 &= 6.95 \cdot 10^{-9} \text{ J.g}^{-1} \cdot \text{rad}^{-1} \\ k_2 &= 9.3 \cdot 10^{-1} \text{ rad}^{-1} \end{aligned}$$

$$\begin{aligned} \text{For } T < 100^{\circ}\text{C} : k_1 &= 20.9 \cdot 10^{-9} \text{ J.g}^{-1} \cdot \text{rad}^{-1} \\ k_2 &= 8.5 \cdot 10^{-11} \text{ rad}^{-1} \end{aligned}$$

For each configuration the dose calculations have been carried out at distances equal to 0.25, 4, 8, etc. ...24 cm from the wall of a waste container. For each position the TASTE-computations provided the time after which the temperature became lower than 100°C.

The energy build-up due to dose deposition after that time was calculated using the second set of parameters.

For configurations 56 and 52 the results of the stored energy calculations have been plotted in figures 3a and 3b as function of time of storage and at distances from 0.25 cm to 24 cm. In figures 4a and 4b the radial distributions of stored energy after a number of periods of time have been given.

It can be seen from table 3.1 that in configuration 52 the decay time before burial is much shorter than in configuration 56 and it is obvious that due to the relatively higher concentrations of short-living nuclei the irradiation in configuration 52 will fall off much more quickly. This gives rise to not only a lower radiation dose but also to a more quickly decreasing temperature. In figure 3b applying to configuration 52 it can be seen that after 10 years already the high level of energy build-up becomes active, whereas in fig. 3a for configuration 56 it is only after 50 years that this state is reached.

Corresponding differences can be noticed in figures 4a and 4b. It is hard to believe that the drastic change of particularly the  $k_1$  value is very sharp with changing temperature. However, no experimental data on the details of this variation are available. The rather sudden increases in the stored energy developments particularly visible in fig. 3a will in practice be a more gradual growth. More evident is the very different level of saturation which the temperature change gives rise to.

Due to the strong saturation effect in the stored energy build-up the fall-off of this quantity with radial distance is much slower than for the radiation dose. Nevertheless, it is obvious that the range within which this effect amounts to an appreciable value is still very limited.

For all configurations that were considered the total amounts of stored energy after 100000 years within a cylinder of 1 m height and 24 cm around a container were calculated. These values have been tabulated in table 3.2. together with the maximum values of the local temperature that were calculated.

Table 3.2. Maximum local temperature  $T_{\max}$  reached in the salt around a waste container and the total amount of stored energy  $E_{24}$  collected after 100000 years within a cylindrical ring of 1 m height and 24 cm thickness around the container.

case number	$T_{\max}$ (in °C)	$E_{24}$ (in MJ)
101	106	60.9
102	157	60.9
103	109	62.8
104	163	68.6
51	138	63.9
52	139	59.6
53	103	61.5
54	151	61.2
55	109	64.3
56	164	70.3

For configuration 56 the amount of 70.3 MJ would be sufficient to raise the temperature of the salt out to a distance of 24 cm from the container by 71°C.

In these calculations it has not been taken into account that the damage of the crystal and the storage of energy may be higher at low dose rates, particularly when the saturation level is not reached.

In the initial stage of storage the dose rate close to the waste container is  $1 \cdot 10^5$  rad/hr gradually decreasing to 0.1 rad/hr after 100.000 years. At a distance of 12 cm these values are lower by about a factor of ten. Levy [15] found that at a dose rate level of  $10^7$ - $10^9$  rad/hr a decrease by a factor of ten would have about 8 times more damaging effect. It is by no means certain that this number is applicable in situations with  $10^4$  times lower dose rates and this extrapolation seems not very justifiable. However, if it would be assumed that such a higher damaging would occur its effect would be a slightly larger region (10-15 cm) with saturation level energy build-up.

In case of heat release initiated by a temperature rise this heat will quickly spread over the surrounding salt due to the high thermal conductivity. According to Jenks and Bopp [4] the dose rate effect is small in the dose region of saturation.

In chapter 2 it has been argued that the concentration of free colloidal sodium metal may be estimated from the amount of stored energy rather than by extrapolation from data applying to much less intensive irradiations.

The stored energy saturation value of 245 J/g corresponds to 3.5% mole fraction colloidal sodium.

To a first approximation the radial distributions for the stored energy give a proper estimate for the mole fraction values at varying distance from a waste container.



#### 4. CONCLUDING REMARKS

Extensive experimental results on irradiation effects in rock salt are presently available, but the complexity of the processes involved is such that still more information is required in order to decide upon the exact process associated with the energy release and that which determines the kinetics of the phenomena.

In addition it is desirable to have better information on effects of dose rate, impurities, local strain and deformation and to study the formation of colloidal sodium in realistic conditions of dose and type of radiation. Although much information is still needed to unravel these problems concerning the description of the fundamental processes, not all such information is required for considering the inferences for the application of waste repositories.

The phenomenology of the creation of stored energy and its release is rather well known in the actual dose regime of interest.

The present new calculations of dose deposition in rock salt around a radioactive waste container form a more accurate basis than previously available for a proper estimation of the irradiation effects and their possible consequences.

The results of these calculations show clearly that there are significant effects of radiation damage but they also make clear that the range over which they extend is very limited and that the amount of energy associated with it can have very modest consequences for local temperature and pressure. In addition the formation of colloidal sodium will not reach fraction values higher than a few percent.

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FIGURE LEGEND

Figure 1a and 1b

Development of gamma dose deposition in rock salt surrounding a waste container at 0.25(a), 4(b), 8(c), 12(d) and 16 cm (e) distance for configurations 56 (fig. 1a) and 52 (fig. 1b).

Figure 2a and 2b

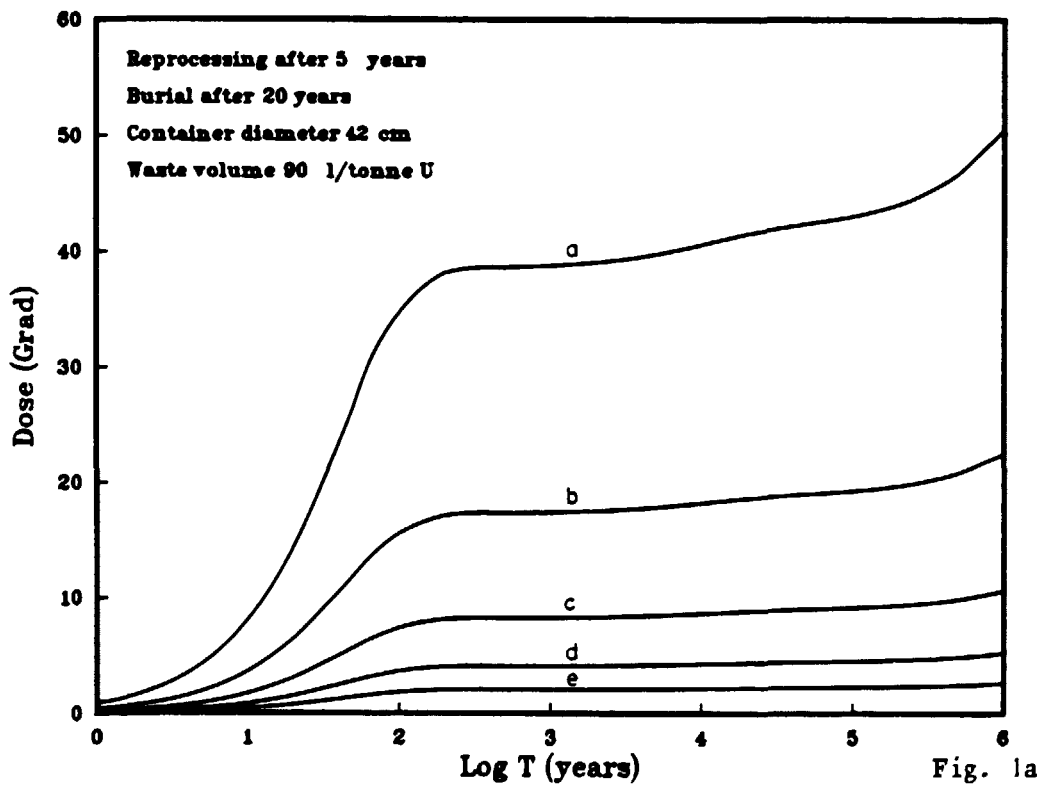
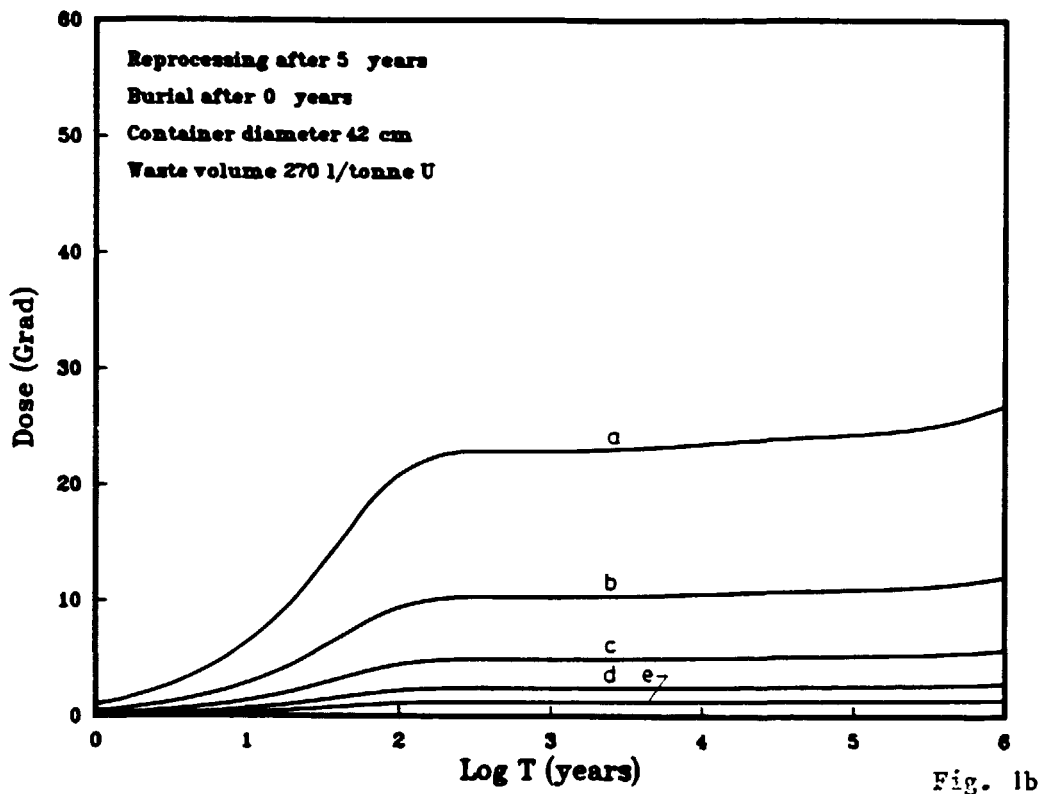
Radial distributions of gamma dose deposition in rock salt surrounding a waste container after 10(a), 50(b), 100(c), 1000(d), 10.000(e) and 100.000 years (f) for configurations 56 (fig. 2a) and 52 (fig. 2b).

Figure 3a and 3b

Build-up of stored energy in rock salt surrounding a waste container at 0.25(a), 4(b), 8(c), 12(d) and 16 cm (e) distance for configuration 56 (fig. 3a) and 52 (fig. 3b).

Figure 4a and 4b

Radial distributions of energy build-up in rock salt surrounding a waste container after 10(a), 50(b), 100(c), 1000(d), 10.000(e) and 100.000 years (f) for configurations 56 (fig. 4a) and 52 (fig. 4b).



Development of gamma dose deposition in rock salt surrounding a waste container at 0.25(a), 4(b), 8(c), 12(d) and 16 cm (e) distance for configurations 56 (fig. 1a) and 52 (fig. 1b).

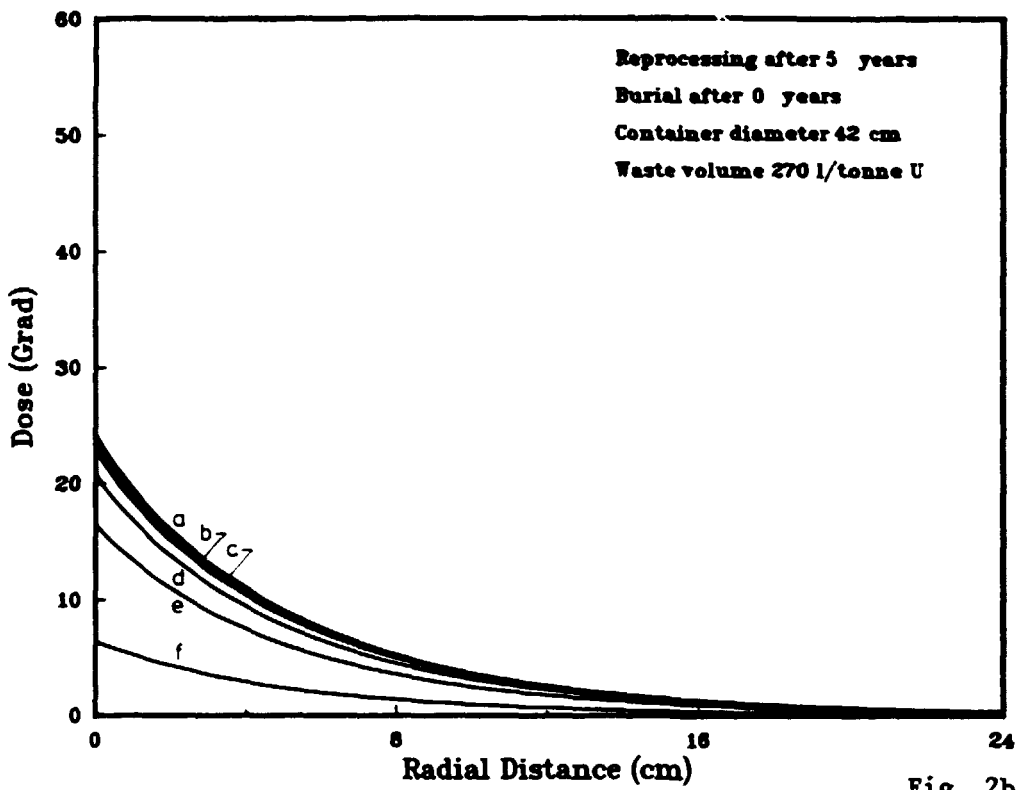


Fig. 2b

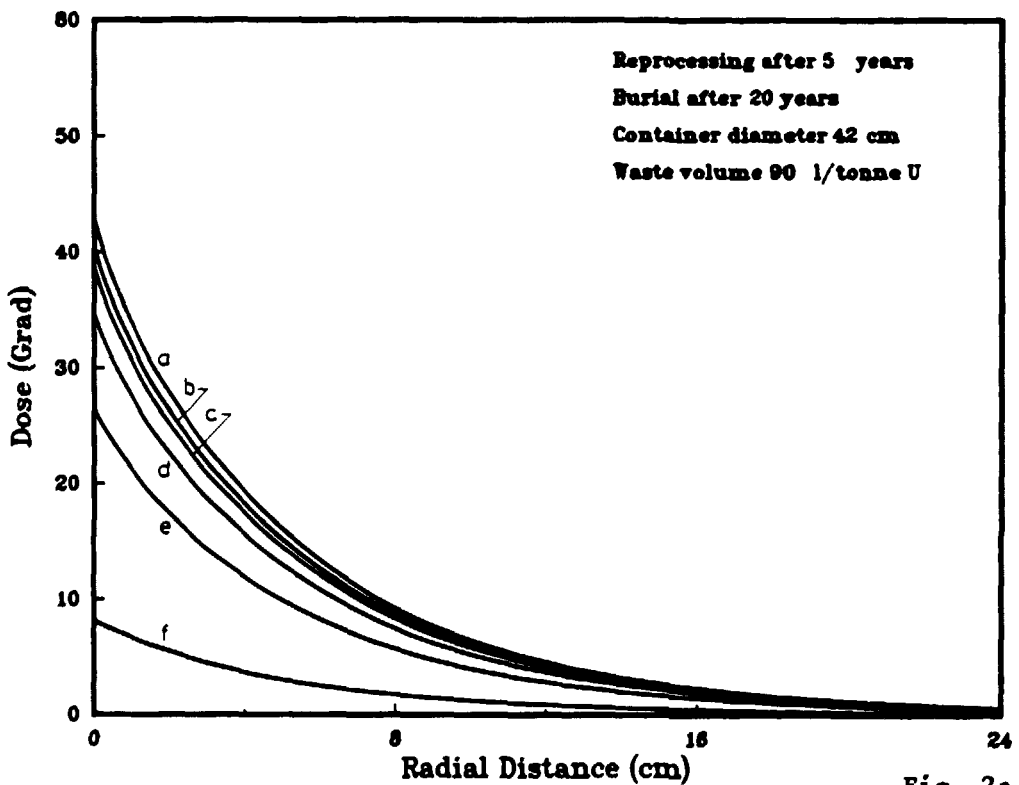
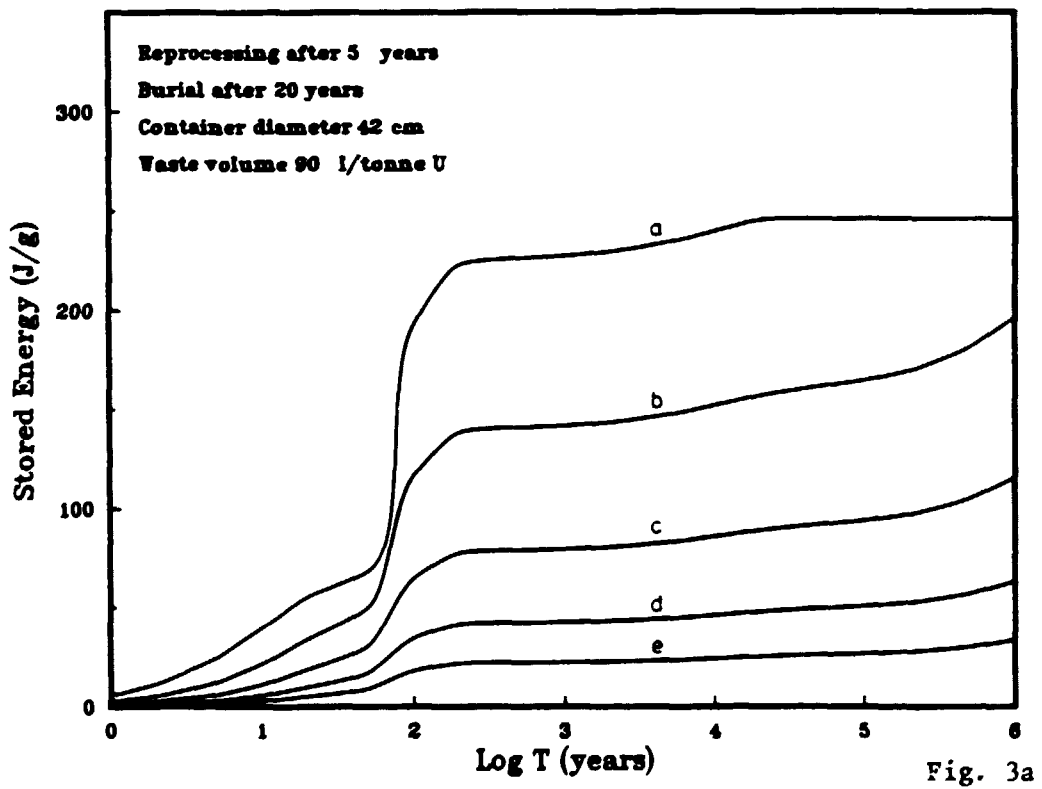
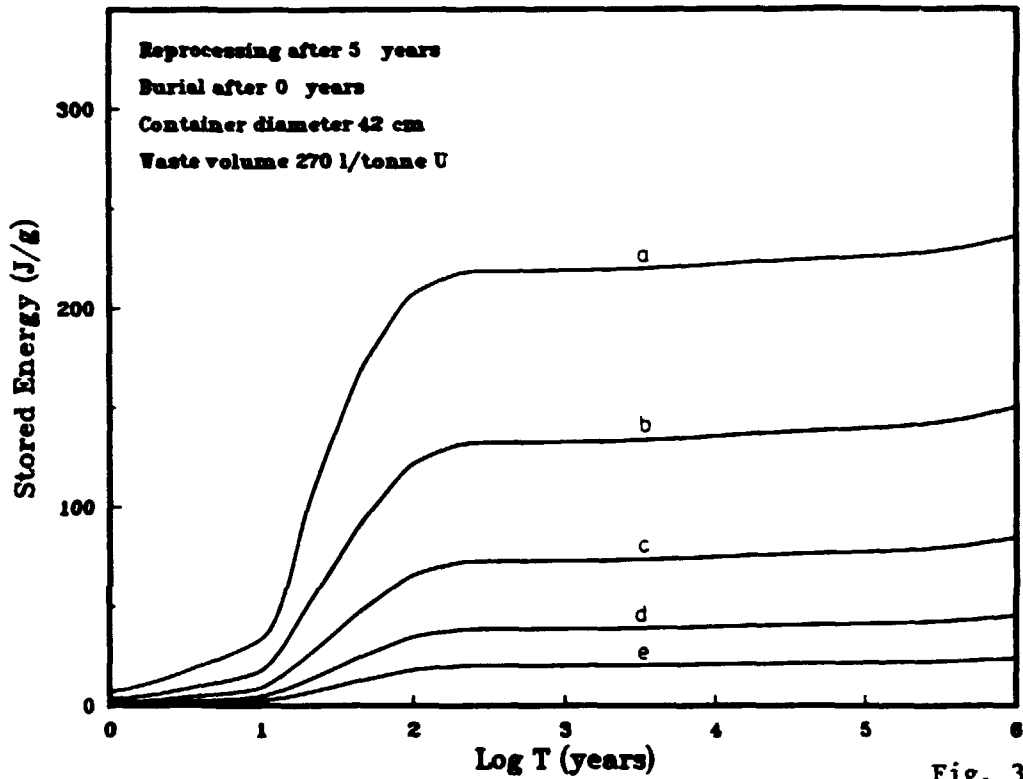
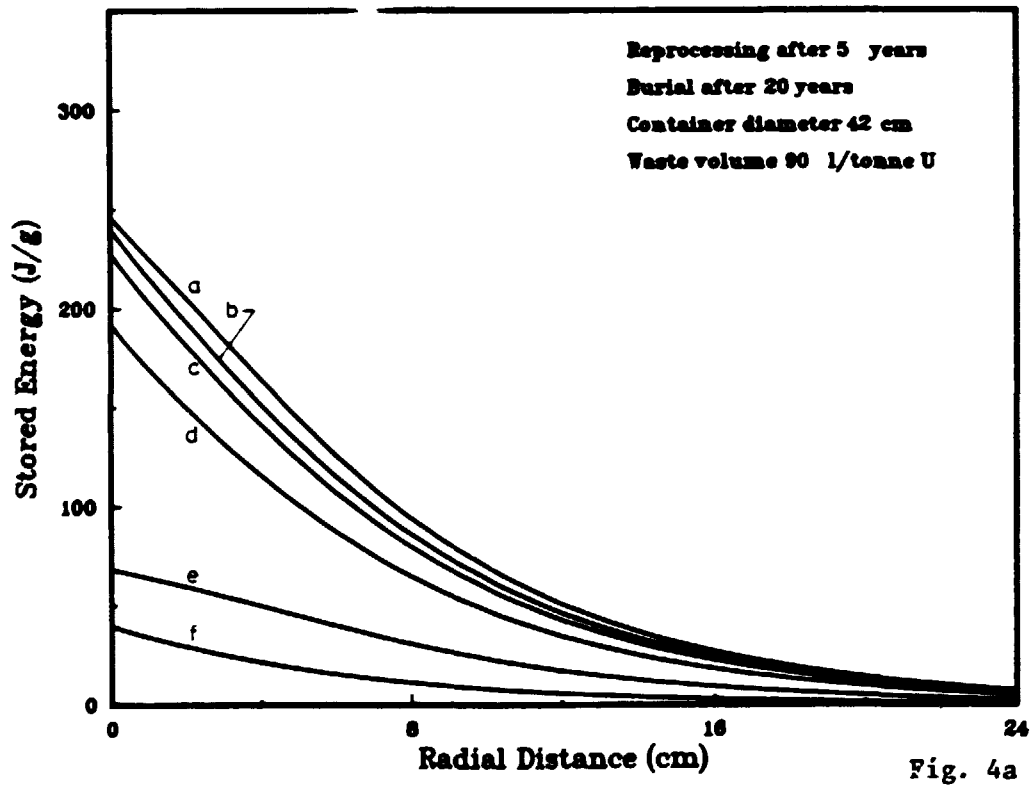
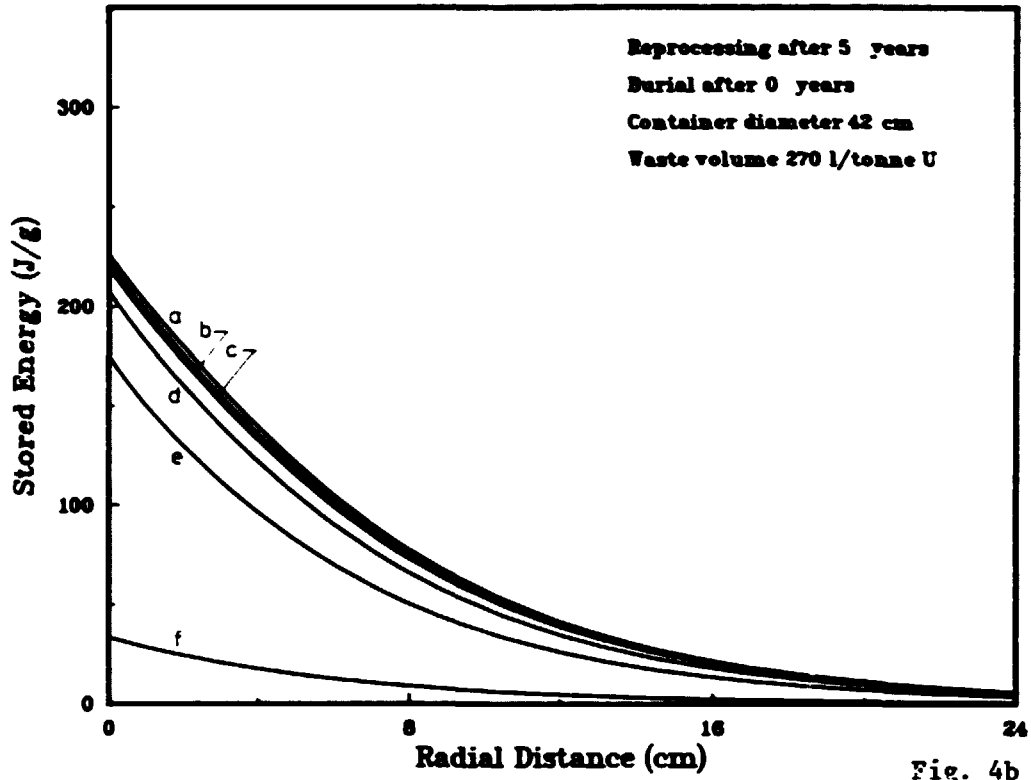


Fig. 2a

Radial distributions of gamma dose deposition in rock salt surrounding a waste container after 10(a), 50(b), 100(c), 1000(d), 10.000(e) and 100.000 years (f) for configurations 56 (fig. 2a) and 52 (fig. 2b).



Build-up of stored energy in rock salt surrounding a waste container at 0.25(a), 4(b), 8(c), 12(d) and 16 cm (e) distance for configurations 56 (fig. 3a) and 52 (fig. 3b).



Radial distributions of energy build-up in rock salt surrounding a waste container after 10(a), 50(b), 100(c), 1000(d), 10,000 (e) and 100,000 years (f) for configurations 56 (fig. 4a) and 52 (fig. 4b).