

DEEPER GEOLOGIC DISPOSAL: A NEW LOOK AT SELF-BURIAL

Stanley E. Logan
S.E. Logan and Associates, Inc.
Santa Fe, NM 87501

ABSTRACT

Geologic disposal of spent fuel or vitrified high-level waste generally refers to emplacement in rooms established by conventional mining methods. The self-burial concept for deeper geologic disposal of high-level radioactive waste utilizes the radiodecay heat to melt rock and allow descent by gravity into crystalline rock for isolation. A recent advancement proposed by Byalko of Russia uses a sulfur-filled borehole as a conduit for conveying small capsules down several kilometers to an accumulation zone. Rock-melting descent proceeds from there. This paper investigates the feasibility of self-burial with the relatively low thermal output of R7/T7 French glass. The rock-melting self-burial and sulfur-filled borehole concepts are described. French glass produced by COGEMA is related to a reference high-level waste for modeling. Potential performance for various thermal densities is calculated and discussed. It is concluded that currently produced French glass can be disposed of at a self-burial facility, providing a "first capsule" filled with a higher thermal density is provided to melt a central channel in the sulfur at the start of a disposal campaign. A single facility with one borehole, and requiring no underground mining, could accept the waste from more than 200 reactor-years. The concept can be tailored to the needs of one or more small nations as well as providing an alternate method for nations which are large users of nuclear power.

INTRODUCTION

Geologic disposal of spent fuel or vitrified high-level waste generally refers to emplacement at modest depths in rooms established by conventional mining methods. This necessarily involves manned underground operations, usually limited to depths of one to two kilometers. The self-burial concept for deeper geologic disposal of high-level radioactive waste seeks to utilize the radiodecay heat emitted by the wastes to melt rock and allow descent by gravity into crystalline rock for isolation. Repository construction would consist of drilling a borehole from the surface and requires no underground operations. A paper by Logan published 25 years ago (1), representing an anniversary paralleling this 25th Waste Management Conference, developed the governing equations for the process. An advancement by Byalko of Russia proposes to overcome safety problems by using a sulfur-filled borehole as a conduit for conveying small capsules down to an accumulation zone at a safe depth of several kilometers (2,3). Small capsules (less than 0.5 m diameter) are relatively simple to fill and handle. Investigations indicate that once emplaced at an initial accumulation depth, rock-melting descent can proceed without an enveloping container (3). When high thermal density wastes are available, descents to depths approaching 10 km have been calculated (4). This paper investigates the feasibility of self-burial with the relatively low thermal density of currently produced R7/T7 French glass.

ROCK-MELTING SELF-BURIAL

The governing equations for self-burial were developed for capsules with a spherical container, though the concept is not limited to this shape. For a given medium environment, there is a threshold value for the volume heat generation rate (thermal density) of capsule contents. This is the value for which the surface temperature of an at-rest sphere is equal to the melting temperature of the surrounding rock or other medium. It is simply

$$(Eq. 1) \quad q_{th}''' = (3\lambda/a^2)(T_m - T_r), \quad W/m^3,$$

where λ is the thermal conductivity, W/m-K, a is the spherical radius, m, T_m is the rock melting temperature, °K, and T_r is the ambient rock temperature, °K. Considerably greater than the threshold rate is required to obtain useful descent rates. The energy criteria governing the rate of descent depends upon the heat output, the energy required per unit of volume to raise the temperature from local ambient through the melting range, and as before, velocity is inversely proportional to the square of the radius. In addition, a hydrodynamic criteria must be satisfied. The available negative buoyancy must cause the melt to be displaced and flow around the capsule. This is greatly dependant upon viscosity of the molten rock. Our ROKMELT computer code (1) simultaneously solves for velocity by both criteria, continuously adjusting for radioactive decay, increasing ambient rock temperature as depth increases, and automatically adjusts capsule temperature upward as required to lower rock viscosity as needed to satisfy the hydrodynamic criteria. The sulfur-filled borehole concept divides the burial process into two stages. In the borehole stage, a capsule with higher thermal density is first released to create an initial molten central core in the sulfur. This is followed by a procession of lower thermal density capsules. As the capsules accumulate in a zone at the bottom of the borehole, the required geometry develops, equivalent to a single larger sphere, which reaches and surpasses the local threshold condition and descent into crystalline rock proceeds.

SULFUR-FILLED BOREHOLE CONCEPT

The sulfur-filled borehole concept (2,3) is now further described. Sulfur is a low melting temperature (113°C) non-water-soluble material. A 0.4 to 0.8 m diameter borehole drilled to a 3 to 4 km depth into crystalline rock such as granite and filled with sulfur provides a conduit for self-burial transport of small capsules of waste down to an accumulation zone. At shallower depths, larger borehole diameters with casing are required through the various softer rock formations. It is expected that the hole will become enlarged at the bottom from natural processes as waste capsules accumulate and the temperature builds up. However, a cavity enlarged to about 1 m diameter near the bottom of the hole (such as with shaped charge perforation techniques) is proposed here as a guarantee that an adequate geometry exists for the commencement of rock-melting.

The waste loading sequence begins with release of a capsule about one-half the borehole diameter, having sufficient heat generation rate to melt a central path in the sulfur and sink to the bottom of the borehole in one to two years. Subsequent capsules released before the sulfur re-solidifies may have considerably lower heat outputs, and may be short cylinders as well as spherical in shape. As the capsules accumulate and slump to the bottom of the hole, the temperature builds up and the rock-melting descent phase begins. The lead portion descends until

the heat generation rate decays below the local threshold level. Discontinued loading leads to a vertical "log" of waste fixed in borosilicate glass and encased in solid granite or other crystalline rock medium.

FRENCH GLASS PRODUCED BY COGEMA

While reprocessing and waste vitrification have been defined in previous self-burial studies with high thermal density, the question arises: "Can the self-burial concept be applied with the lower thermal density of currently produced product such as R7/T7 French glass?" From two COGEMA papers at WM'98 (5,6), and personal correspondence, the operations and product at the La Hague plants are briefly as follows: Spent fuel up to 45,000 MWd/t are not reprocessed before 3 years, and for spent fuel above 45,000 MWd/t, it is 4 years. Vitrification with 18.5 weight percent waste oxides is performed one year after reprocessing. Interim storage is used prior to shipping until the thermal density drops to 13.3 kW/m^3 (2 kW in 150 L container). Going into interim storage, a range of $13.3 - 20. \text{ kW/m}^3$ is experienced. The liquid fission products (and residual actinides) are received and stored in large tanks before vitrification, with products from many different origins and cooling times mixed together. The R7/T7 glass specifications currently applied were approved by French regulatory and reprocessing customer's authorities. It should be recognized that these specifications are directed toward maintaining low temperatures in rock media for conventional geologic storage concepts, by limiting the thermal output to relatively low levels. Adjustments in specifications and the processing at a later date could obtain higher thermal density in the glass product. It should be stated that while COGEMA provided information requested for this study, there is no commitment at this time by COGEMA or by their regulatory authorities to accommodate a self-burial disposal program.

REFERENCE HIGH-LEVEL WASTE

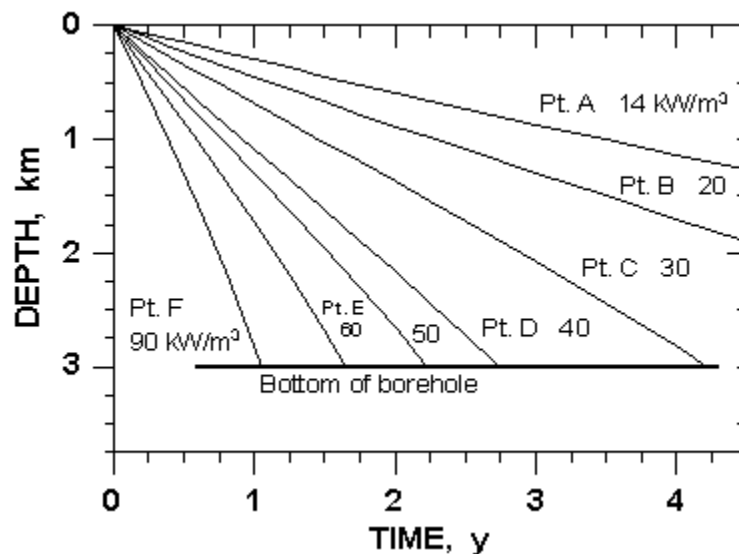
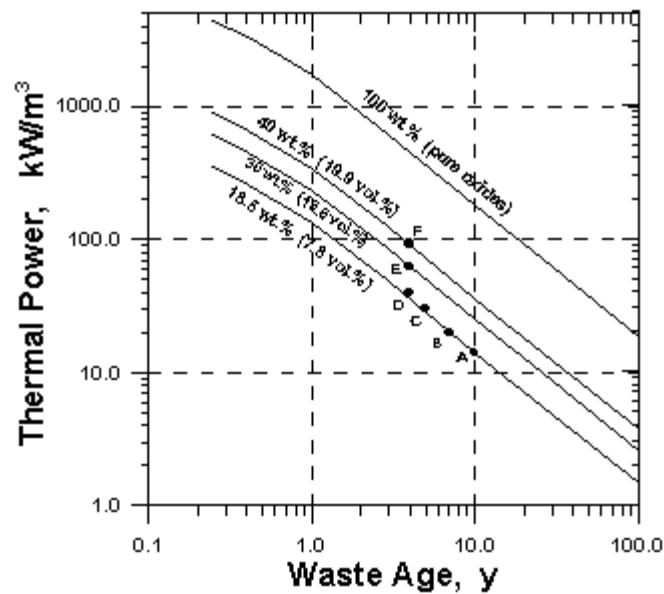
A reference waste from a reference reactor (7) is defined here to provide power densities, decay characteristics, and disposal capacities for demonstration calculations. A 1,000 MWe reactor with self-sustaining Pu recycle fuel (67% enriched U, 33% Pu) is assumed, with 33,000 MWd/MT average burnup ($2.57 \times 10^8 \text{ kWe-h/MT}$ at 32.5% thermal efficiency). The reprocessing waste contains 0.1% of the I and Br (balance released), all of the other fission products, 0.5% unrecovered U and Pu, and 100% of the other heavy metals. Calcined waste (oxides) is incorporated in borosilicate glass at various weight percentages. The resulting concentrations based upon metric tons of heavy metals in the spent fuel are about 12 MT/m^3 for 18.5 wt.%, and range up to about 30 MT/m^3 for 40 wt.% borosilicate glass. The annual discharge rate for this reactor is 26.4 MT. Figure 1 is a plot of the thermal power versus time for a range of waste concentrations. Results without use of Pu recycle would not be greatly different.

It is assumed in this study that the characteristics of the reference high-level waste can be applied to represent the French glass for modeling calculations. The lowest curve in Fig. 1 represents calcined waste (oxides) incorporated in borosilicate glass at 18.5 wt.%, as currently used for the French glass. The thermal density of this reference waste matches the previously described French glass range at ages between 7 and 10 years. Point A in Fig.1 represents 14 kW/m^3 at waste age 10 y, and point B represents 20 kW/m^3 at age 7 y. The other labeled points are discussed later.

SELF-BURIAL PERFORMANCE POSSIBLE WITH FRENCH GLASS

Loading Via Sulfur-Filled Borehole

A parametric study with a range of capsule diameters and thermal density was performed in this study, using the ROKMELT computer code (1). To accommodate lower thermal output in the current French glass, a capsule diameter larger than the 0.3 m used in a previous study (4) is found to be preferred. A diameter of 0.4 m is used here for illustration (waste contents volume 0.03 m^3). The threshold volume heat generation rate for a 0.4 m diameter sphere in sulfur is only 2.1 kW/m^3 . It is found that for the “first capsule”, the nominal French glass, with the range of relatively low thermal output would require an excessive 7 to 11 y to melt a central core in the sulfur in an 0.8 m diameter borehole and descend to a borehole depth of 3 km. Corresponding initial velocities are calculated to be only 0.8 - 1.3 m/d, which would permit releasing only one to two capsules per day. However, once a central core of molten sulfur is established (or while it is being established), it is found that R7/T7 French glass in subsequent capsules would have an acceptable descent time of less than one year, except as may be impeded by a slower lead capsule until that first capsule reaches the borehole bottom. The first capsule must therefore have a higher thermal density than the current nominal French glass to obtain adequate performance. Figure 2 is a plot of descent curves for thermal densities ranging from 14 to 90 kW/m^3 (points A through F in Fig. 1). For a defined need, selected reprocessing batches of spent fuel at the young end of an age range and corresponding batches of higher waste oxide loading during vitrification, can produce a glass product with thermal density adequate for the first capsule needs. Only one such capsule is needed for an entire disposal campaign at a self-burial facility. In Fig. 2, selecting 5 y age waste would obtain 30 kW/m^3 (point C). Selecting 4 y age waste and increasing the loading in glass slightly from 18.5 to 22 wt.% would obtain 40 kW/m^3 (point D). This thermal output has a calculated descent time of 2.7 y (Fig. 2), which is still longer than desired. Waste with 30 wt.% waste oxide loading and 4 y age, and 40 wt.% loading and 4 y age represent thermal densities of 60 and 90 kW/m^3 , respectively (points E and F). A first capsule with this waste would descend to the 3 km depth in corresponding times of 1.7 and 1.1 y, and have initial velocities of 4.6 and 6.8 m/d, respectively. This would provide for release of up to eight capsules per day initially, with some spacing.



Following the establishment of the central molten core with the higher thermal output first capsule, subsequent loading can use much lower thermal output waste. Modeled calculations assume that spacing between releases is not more than a few hours and that re-solidification of only the outer 1.5 cm of the molten core has occurred. On this basis, French glass at 14 kW/m³ (point A) descends, with initial velocity of 5.7 m/d, to the 3 km depth in 1.2 y (compared to 11 y if released prior to creating the molten core). French glass at 20 kW/m³ (point B) descends, with an initial rate of almost 9 m/d, to the 3 km depth in 0.8 y. These thermal outputs would permit corresponding release rates of eight to twelve capsules per day. Younger age French glass (points C and D) would permit up to 16 capsules per day. Table I summarizes results for the first capsule and subsequent capsules. The unusual viscosity property of molten

sulfur in which viscosity increases by a factor of 100 in a narrow temperature band above 160°C provides an automatic spacing regulator. If any one capsule overtakes and closely approaches the one ahead, the temperature increase in the intervening sulfur will increase. The corresponding increase in viscosity will cause the capsule to slow down and an equilibrium will obtain. The accumulation of capsules near the bottom of the borehole leads into the rock-melting phase, described next.

Rock-Melting Descent

Representative values of properties of granite, as used in the original study (1), assume 0.6 wt% water. Water acts as a fluidizing aid, leading to a melting temperature of 950°C. However, viscosity at that temperature is extremely high. Viscosity is 10^7 Pa-s at 1,000 °C, decreasing exponentially to 10^3 Pa-s at 1,700 °C. Specific heat is 837 J/kg-K at 0°C, increasing to 1,140 J/kg-K at 1,000 °C. Thermal conductivity is 2.64 W/m-K at 0°C, decreasing to 1.26 W/m-K at 1,000 °C, approximately ten times that of sulfur. The heat of fusion is 4.18×10^5 J/kg. Other crystalline rock formations, such as basalt, can also be utilized for disposal.

Table I. Loading via sulfur-filled borehole.

Point in Fig. 1	Thermal Power kw/m ³	Initial Velocity m/d	Descent Time y
Initial Capsule:			
E	60	4.6	1.7
F	90	6.8	1.1
Subsequent Capsules:			
A	14	5.7	1.2
B	20	8.9	0.8
C	30	11.0	0.6
D	40	11.0	0.6

The loading process via the sulfur-filled borehole may continue for years. The capsules accumulate in the lower portion of the borehole, filling the full borehole diameter and the enlarged section at the bottom. The weight of the column bears down on the lower units and, as temperature builds up from the increased concentration of heat sources, slumping into a tightly packed heating mass is expected. Sulfur in the bottom zone is consumed by penetration into thermal stress cracks in the surrounding rock, accompanied by chemical and mineralization reactions that form water-insoluble pyrite and pyrrhotite. These reactions are examined in detail by Byalko (2). The proposed 1 m diameter enlarged cavity at the bottom of the borehole insures that an adequate geometry will exist for the start of rock-melting. Table II lists the threshold

volume heat generation rates for a range of diameters of the heating mass. The actual diameter that will become established depends upon the feed rate down the borehole (number of capsules per day) and the heat generation rate in the waste. The diameter of the descending column in granite and its descent velocity will automatically adjust to match the feed conditions. Results from a parametric series of cases for the borehole descent and rock-melting descent phases obtained the set of performance curves in Fig. 3 for the range of thermal densities represented by points A through F in Fig. 1. Values for the associated parameters are listed in Table III for points A through D, which represent current French glass waste oxide loading. As expected, the duration of sinking and the depths attained increase with the thermal density. The curves and tabulation for points A and B indicate that 300 to 500 m descent can be obtained with the relatively low thermal output of the current R7/T7 French glass. Selecting younger age waste (points C and D) attains up to 800 m descent. As discussed in the previous section, this depends upon using a "first capsule" having thermal output enhanced by selective processing to establish the initial molten sulfur conduit.

Table II. Threshold Thermal Density in Granite at 3 km Depth.

Diameter, m	q_{th}''' , kW/m ³
1.0	16.2
1.25	10.6
1.5	7.3
2.0	4.0

BOREHOLE DRILLING CAPABILITIES

Drilling technology for deep boreholes in crystalline rock is not well developed in the United States, but it is elsewhere. Geological, geophysical and hydrogeological investigations of crystalline formations in several regions in the former USSR over the past nearly 30 years have produced several boreholes with depths from 4 to 12.3 km (8). The Kola Superdeep Borehole, located on the Kola Peninsula of Russia, has reached a depth of 12,261 m. Diameters are 0.72 m to a depth of 39 m, 0.32 m to 2,000 m, and 0.25 m to 8,770 m. The Krivoy Rog Superdeep Borehole in the Ukrainian Shield has reached a depth of 5,000 m with diameters of 0.72 m to 62 m depth, 0.51 to 850 m, and 0.43 m to 2,800 m. The Tyrnauz Deep Borehole in the Caucasus has reached 4,001 m in granite. In Germany, the KTB-borehole (German Continental Deep Drilling Program) has reached a depth of 7,170 m in crystalline basement rocks (9). In Sweden, the proposed VDH (Very Deep Holes) (10) concept considered drilling about 38 boreholes in crystalline rock with a diameter of 1.4 m to 2.0 km depth and 0.8 m diameter to 4.0 km depth. Deposition of waste was planned in the section between 2.0 and 4.0 km depth. The basic principle of the VDH concept "is to place the waste at such great depth that the time for migration of radionuclides to the biosphere becomes so long that adequate decay has occurred to eliminate any safety hazard." One of the proposed VDH boreholes, with a diameter of 0.8 m to a depth of 2-4 km, would suffice for a self-burial repository.

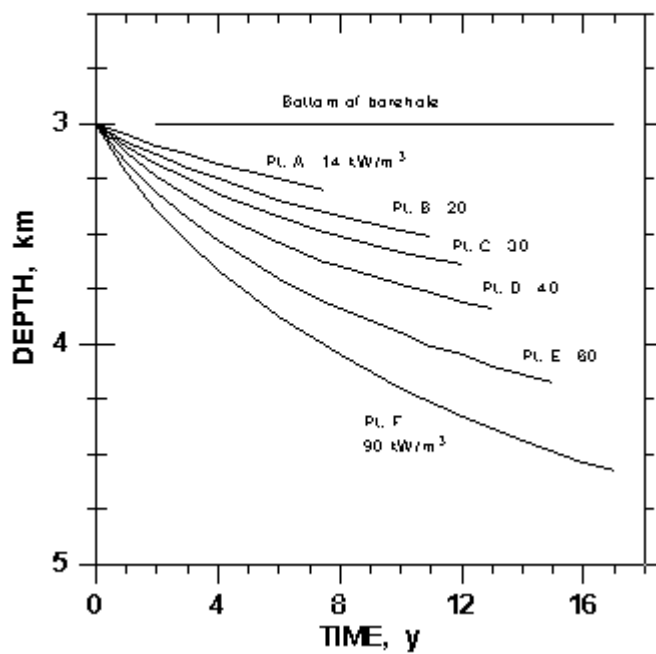


Table III. Waste characteristics and performance parameters for descent in granite from bottom of 3 km-deep sulfur-filled borehole.

Waste Characteristics				Feed Rate, capsules per day	Descent in granite				
Point in Fig.1	wt. pct.	Age y	kW/m ³		dia. m	Initial m/d	Descent m	Depth km	Time y
A	0.185	10	14	8	1.50	0.15	300	3.3	7.5
B	0.185	7	20	12	1.50	0.22	500	3.5	11.0
C	0.185	5	30	14	1.44	0.30	600	3.6	12.0
D	0.22	4	40	16	1.30	0.41	800	3.8	13.0

DISCUSSION

The cases listed in Table III for descent in granite do not address accommodating the volume of molten rock displaced by the descending hot mass of waste material. The displaced

rock volume will be accompanied by some compression of surrounding rock, some flow into cracks (hydrofracture) and voids, flow into interstices in the rubble initially at the bottom of the borehole, and any remainder will back-extrude around the descending hot mass. The back-extrusion may require terminating feed prior to the lead portion of the descending column reaching the maximum depth. If this is the case, the descending “log” will continue “coasting” down to the maximum depth, with additional isolating resolidified rock accumulating above.

The first case in Table III is for waste corresponding to the present R7/T7 French glass production at the time of shipment after interim cooling, with 18.5 wt.% oxide loading in borosilicate glass and a thermal density of about 14 kW/m^3 . As discussed earlier, one capsule with higher thermal output (60 to 90 kW/m^3) would be required at the beginning of the disposal campaign to melt a central core in the sulfur-filled borehole. This higher thermal density can be achieved by selecting a waste source that is not diluted with older or lower-burnup wastes, plus loading somewhat higher than the 18.5 wt.% level. The calculated performance for the first case is a descent of up to 300 m with a 1.5 m diameter column over a 7.5 y period, representing a volume of 530 m^3 . At 12 MT/m^3 , the waste volume represents 6,360 MT of heavy metals in spent fuel, or the waste from $6,360/26.4 = 240$ reactor-years. The second case in Table III is for waste corresponding to the present R7/T7 French glass production at it enters interim cooling, with a thermal density of about 20 kW/m^3 . For this case, the calculated descent is up to 500 m in 11 y, with a 1.5 m diameter column. This is a waste volume of 880 m^3 , representing 10,600 MT or 400 reactor-years. If the available thermal density in the waste is further increased, the potential disposal capacity increases, subject to limitation by accommodation of displaced rock-melt.

The concept described here flies in the face of the “retrievability criterion.” This author sums up the retrieval requirement as: “We require that the disposal zone be placed with minimal isolation so that we can change our minds and retrieve wastes if we decide the degree of isolation is too minimal.” It is suggested that deeper geologic disposal calls for reconsideration of the retrieval criterion. The concept does not appear to be attractive for application to spent fuel. While the United States is not currently reprocessing spent fuel, shipment to foreign processors is a recommended option, with return of vitrified high-level waste for disposal in a self-burial repository.

CONCLUSIONS

In conclusion, it is found that the present R7/T7 French glass vitrified waste can be disposed of at a self-burial facility, providing a “first capsule” filled with a higher thermal density is provided to start a disposal campaign. The higher thermal output for the “first capsule” can be obtained by a selective reprocessing batch with young spent fuel (instead of from many ages and origins accumulated in a large storage tank), and by increasing the waste oxide content in the vitrification batch by a factor of 1.5 to 2.0 from the current production loading of 18.5 wt.%. A single facility with only one borehole, and requiring no underground mining, could accept the waste from 200 to 400 reactor-years, as R7/T7 French glass, and provide much deeper isolation than by conventional geologic disposal means. Only one borehole, with specifications as proposed for the Swedish VDH concept, would suffice for a self-burial repository. Any increase from 18.5 wt.% in the production glass waste oxide content can greatly increase the final disposal

depth and capacity. This self-burial concept can be tailored to the needs of one or more small nations as well as providing an alternate method for nations which are large users of nuclear power, and should be actively pursued further.

REFERENCES

1. S.E. LOGAN, "Deep Self-Burial of Radioactive Wastes by Rock-Melting Capsules," Trans. American Nuclear Soc., **16**, (1973); Nuclear Tech., **2**, pp111-124, (1974).
2. A.V. BYALKO, Nuclear Waste Disposal: Geophysical Safety, CRC Press, Boca Raton, New York, London, Tokyo, (1994).
3. A.V. BYALKO, "HLW Disposal in Deep Sulfur-Filled Boreholes: Start of R&D," Proceedings of Waste Management 96, WM Symposia, Tucson, AZ, (1996).
4. S.E. LOGAN, "Advances in the Self-Burial Concept for Deep Geological Disposal of Radioactive Waste," Proceedings of International Conference on Deep Geological Disposal of Radioactive Waste, Winnipeg, MB, Canada, Sep. 16-19, 1996, pp 6-51/6-60, Canadian Nuclear Soc., (Sept. 1996).
5. R. LIBERGE, J-L. DESVAUX, D. PAGERON, C. SALICETI, "Industrial Experience of HLW Vittrification at La Hague and Marcoule," Proceedings of Waste Management 98, WM Symposia, Tucson, AZ, (1998).
6. E. PLUCHE, J. JEANNETTE, "Quality Assurance and Quality Control of Vittrified HLW," Proceedings of Waste Management 98, WM Symposia, Tucson, AZ, (1998).
7. Siting of Fuel Reprocessing Plants and Waste Management Facilities, ORNL-4451, Oak Ridge National Lab., Oak Ridge, TN, (1970).
8. "Characterization of Crystalline Rocks in Deep Boreholes. The Kola, Krivoy Rog and Tyrnauz Boreholes," SKB Technical Report 92-39, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden, (Dec. 1992).
9. M. LIENERT, H. BERKHEMER, "Comparison of p-wave velocities in the KTB-borehole and in drill cores," Scientific Drilling, 6: 113-119, (1997).
10. L. OLSSON, H. SANDSTEDT, "Project on Alternative Systems Study - PASS . Comparison of Technology of KBS-3, MLH, VLH, and VDH Concepts by Using an Expert Group," SKB Technical Report 92-42, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden, (Sept. 1992).