

## HYDROTHERMAL EFFECTS ON CESIUM SORPTION AND FIXATION BY CLAY MINERALS AND SHALES

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**Abstract**—The effects of hydrothermal conditions on the sorption and fixation of cesium by various clay minerals and shales were investigated. Hydrothermal heating, which may be expected in a radioactive waste repository, altered the clay minerals and shales and led to a decrease in their cation-exchange capacity. Cesium sorption greatly decreased in micaceous vermiculite and in well-crystallized illites containing vermiculite upon hydrothermal treatment at 400°C and 300 bars pressure due to complete layer collapse. However, poorly crystallized illites heated as above showed either a small increase or only a slight decrease in Cs sorption because of partial layer collapse. These studies show that the decrease in Cs sorption is greater in well-crystallized illites than in poorly crystallized illites when treated similarly under hydrothermal conditions. Hydrothermal heating of Cs-sorbed and Cs-saturated samples increased the amount of Cs fixation in all minerals and shales as a result of collapse of the layers. For example, a sample of the Conasauga shale fixed only 18% of sorbed Cs before treatment but fixed 47% after hydrothermal treatment at 200°C and 300 bars pressure. Thus, hydrothermal conditions in a shale repository may be beneficial after leaked radioactive Cs ions are taken up by clay minerals in shales.

**Key Words**—Cesium, Hydrothermal, Illite, Ion fixation, Ion sorption, Shale, Vermiculite, Waste repository.

### INTRODUCTION

The rapid accumulation of high-level radioactive wastes from weapons programs and commercial power reactors warrants a quick solution to the radioactive waste-disposal problem. Deep geologic isolation is probably the most plausible alternative for the removal of radioactive waste from man's environment; however, if and when solidified, high-level radioactive wastes encapsulated in canisters are buried in rock formations, high temperatures of 200°–400°C (Cohen, 1977; Jenks, 1977) may be generated by the decaying wastes and thus lead to hydrothermal conditions in the repository (McCarthy *et al.*, 1978). In a shale repository, two types of hydrothermal effects can be envisioned: (1) an initial heating of the shale followed by a breaching of the canisters and the subsequent sorption of released ions by the minerals of the shale; and (2) an initial breaching of the canisters and subsequent sorption of released ions by the minerals of the shale followed by hydrothermal heating. In either case, the ability of the shale to sorb and fix Cs<sup>137</sup> and other hazardous ions released from the canisters is extremely important.

Because illite and other micaceous clay minerals in shale are well known to take up Cs preferentially from a mixture of ions by cation exchange (Tamura, 1964; Komarneni and Roy, 1978), and because Cs<sup>137</sup> is not only highly hazardous, but also highly soluble and more likely to migrate than the transuranic elements, the following investigation was carried out to determine the effects of hydrothermal treatment on the Cs-sorption and Cs-fixation properties of shales and micaceous clay minerals.

### EXPERIMENTAL

#### *Materials*

Twenty-eight samples of vermiculite, illite, glauconite, mica, shale and slate from four countries were examined in the present investigation, the localities and sources of which are listed in Table 1.

#### *Methods*

Vermiculite and mica samples were wet ground in a blender, and illite and shale samples were gently ground using an agate mortar and pestle and size-fractionated by sieving, sedimentation, and centrifugation (Jackson, 1974). X-ray diffraction (XRD) analysis of powdered samples mounted in cavities in glass slides was carried out with a Philips diffractometer using Ni-filtered CuK $\alpha$  radiation. The presence of vermiculite in illite and shale samples was determined by the K-saturation method of Jackson (1974). The crystallinity of illites was estimated by the sharpness of the 10-Å illite peak.

To simulate the changes in Cs sorption and Cs fixation that could be brought about by hydrothermal heating in a shale repository, samples were heated with 50% water by weight at 400°C and 300 bars pressure for 5 weeks in sealed gold capsules (Komarneni *et al.*, 1979). The mineralogical changes produced by this treatment were determined by XRD analysis. To determine how the fixation of Cs might be affected by hydrothermal treatment *after* Cs ions occupied exchange sites, a series of samples were first either Cs-sorbed or Cs-saturated and then treated hydrothermally at 200°C and 300 bars pressure for 2 months.

Table 1. Location and/or source of samples.

1. Vermiculite. Williams property, Enoree, South Carolina. Zonolite Division, W. R. Grace & Company.
2. Vermiculite. Poole property, Enoree, South Carolina. Zonolite Division, W. R. Grace & Company.
3. Micaceous vermiculite. Cooper property, Enoree, South Carolina. Zonolite Division, W. R. Grace & Company.
4. Micaceous vermiculite. Transvaal, South Africa. Ward's Natural Science Establishment, Rochester, New York.
5. Phlogopite (K-depleted). Ontario, Canada. Ward's Natural Science Establishment, Rochester, New York.
6. Lepidomelane (K-depleted). Ward's Natural Science Establishment, Rochester, New York.
7. Illite. Fithian, Illinois. Illinois Clay Products Company, Joliet, Illinois.
8. Illite. Goose Lake, Illinois. Illinois Clay Products Company, Joliet, Illinois.
9. Illite. Morris, Illinois. American Petroleum Institute (API #36).
10. Illite. Marblehead, near Lake Winnebago, Wisconsin (courtesy M. L. Jackson).
11. Glauconite. Madison, Wisconsin (courtesy M. L. Jackson).
12. Illite. Blaylock Formation, Beavers Bend, McCurtain County, Oklahoma.
13. Illite. Ouachita Mountains, southeast Oklahoma.
14. Illite (green). Ward's Natural Science Establishment, Rochester, New York.
15. Illitic clay. Fredericktown, Missouri.
16. Clay (Indian red). Tennessee (courtesy J. G. Moore).
17. Mica (green). Pacos de Caldas, Brazil.
18. Shale. Conasauga Formation, Tennessee.
19. Shale. Reedsville, Pennsylvania.
20. Shale. Source unknown (courtesy G. W. Brindley).
21. Shale. Eleana Formation, Nevada.
22. Shale. National Test Site, Nevada, sample ES-S-16.
23. Shale. National Test Site, Nevada, sample ES-S-8A'.
24. Shale. National Test Site, Nevada, sample ES-S-19A.
25. Shale. National Test Site, Nevada, sample UEIL-2931.
26. Shale-sandstone. Lewistown, Pennsylvania.
27. Slate (black). Chilibar, California.
28. Slate (weathered). Chilibar, California.

Cesium *sorption* is defined here as the partial uptake of Cs ions from a dilute CaCl<sub>2</sub> solution. A CaCl<sub>2</sub> solution was used to simulate the groundwater in a shale repository. Twenty-five milliliters of 0.02 N CaCl<sub>2</sub> solution containing 0.0002 N CsCl (~pH = 5.4, CO<sub>2</sub>-buffered) was added to the untreated or hydrothermally treated samples, and the mixtures were shaken for 24 hr at 25° or 45°C (Komarneni, 1979a). The solution to solid ratios were 62.5 for illites and shales and 1250 for vermiculites. The solid and solution phases were separated by centrifugation. The amount of Cs sorbed was estimated by determining the amounts of Cs remaining in solution by atomic absorption spectroscopy (AA). The high concentrations of Cs used in this study might occur in the immediate vicinity of a canister containing high-level waste after breaching (McCarthy *et al.*, 1979).

Samples were *saturated* with Cs at 25°C in glass tubes by repeated washings with CsCl solutions. The samples

were exposed to 0.001 N CsCl washes initially, followed by a 0.05 N CsCl wash (Komarneni and Roy, 1978). The difference between Cs-sorbed and Cs-saturated samples is that only a small fraction of the exchange sites are presumably occupied by Cs in the former, while most of the exchange sites are presumably occupied by Cs in the latter samples. The Cs-sorbed and Cs-saturated samples were washed free of excess salts with water and acetone prior to their use in the Cs-fixation studies.

*Fixation* of Cs is defined as the amount of Cs retained by a Cs-exchanged solid phase after one extraction with 0.1 N KCl. Fixation of Cs was determined by shaking a Cs-sorbed or a Cs-saturated sample with 20 ml of a 0.1 N KCl solution for 24 hr. The amount of Cs displaced by the potassium was measured and subtracted from the total amount of Cs originally exchanged by the sample to yield the amount of Cs fixed by the sample.

Cation-exchange capacities (CEC) were measured by the Dolcater *et al.* (1968) method. All ions in solution were analyzed by AA using a Perkin Elmer PE403 instrument. Results of duplicate analyses were within a mean deviation of ±2%.

## RESULTS AND DISCUSSION

### *Changes in mineralogy by hydrothermal treatment*

Mineralogical changes upon hydrothermal treatment are reported in Table 2. Micaceous vermiculite transformed into a regularly interstratified mica/vermiculite with a spacing of 24 Å (Table 2), and a trace amount of talc was produced. In general, well-crystallized illites seemed to remain unchanged, poorly crystallized illites became well-crystallized, i.e., displayed a sharpened X-ray diffraction peak (Figure 1), and discrete vermiculite in shales and illites collapsed by hydrothermal heating (Table 2). However, the reactions do not seem to have gone to completion in these runs of 5-weeks duration as indicated by the presence of Kaolinite (Table 2) after hydrothermal treatment at 400°C. These experiments lasted only 5 weeks, which is an instant compared with the estimated thermal period (about 200 years) of a repository. Therefore, the results presented here give only trends of changes that can occur in shales under such conditions.

### *Changes in cation-exchange capacity by hydrothermal treatment*

Cation-exchange capacity diminished greatly for all the hydrothermally heated samples except for 3 poorly crystallized illites (Table 3) as a result of changes in mineralogy and collapse of expandable layers (see Table 2). A decrease in cation-exchange capacity should be accompanied by a decrease in the sorption of all the ions that are not sorbed selectively by minerals. Strontium is not selectively sorbed by clay minerals (Jacobs and Tamura, 1960), and therefore its sorption should

Table 2. Mineralogical composition of clays and shales (<105- $\mu$ m fraction) before and after hydrothermal treatment.<sup>1</sup>

Sample <sup>2</sup>	Mineralogy (in order of abundance)	
	Untreated	Treated
<i>Micaceous vermiculite</i>		
Cooper micaceous vermiculite (1–50- $\mu$ m fraction)	Vermiculite (14.34 Å) + randomly interstratified mica/vermiculite (12.49 Å), + regularly interstratified mica/vermiculite (24.07 Å).	Regularly interstratified mica/vermiculite (24 Å) + trace talc
<i>Poorly crystallized illites</i>		
Wisconsin illite	Illite (broad peak)	Illite (somewhat better crystallized)
Goose Lake illite	Illite (broad peak) + quartz	Illite (somewhat better crystallized) + quartz
Fithian illite	Illite (broad peak) + quartz	Illite (somewhat better crystallized) + quartz
Green illite	Illite (rather broad peak) + calcite + kaolinite.	Illite (practically unchanged) + kaolinite + calcite (decomposed to about one-half as abundant)
<i>Well-crystallized illites with discrete vermiculite</i>		
Beavers Bend illite	Illite (sharp peak) + quartz + vermiculite + trace chlorite	Illite (sharp peak) + quartz + vermiculite (collapsed) + chlorite (strong 2nd order peak of chlorite appeared)
Indian Red Clay	Quartz + illite + vermiculite + chlorite + feldspars	Quartz + illite (slightly better crystallized) + vermiculite (collapsed) + chlorite (2nd order peak strengthened)
<i>Shales with poorly crystallized illites</i>		
National Test Site ES–S–8A'	Quartz + illite	No obvious changes.
National Test Site ES–S–19A	Quartz + illite (broad peak) + kaolinite + trace chlorite	No obvious changes.
<i>Shales with discrete vermiculite</i>		
Reedsville shale	Quartz + illite (sharp peak) + vermiculite + chlorite + feldspars	Quartz + illite (sharp peak) + vermiculite (collapsed) + chlorite + feldspars
Lewistown shale-sandstone	Quartz + illite + vermiculite + trace feldspars + trace amphiboles	Quartz + illite + vermiculite (collapsed) + trace feldspars

<sup>1</sup> 400°C, 300 bars, 5 weeks.<sup>2</sup> See Table 1.

decrease by hydrothermal treatment of clays and shales.

#### Changes in Cs sorption by hydrothermal treatment

The transformation of micaceous vermiculite to an interstratified mineral in the Cooper sample (Table 2) by collapse of the layers upon hydrothermal treatment resulted in lower Cs sorption (Table 3). Illites containing vermiculite sorb large amounts of Cs before treatment (Table 3) because vermiculite is more selective for Cs than illite where high Cs concentrations are involved (Komarneni and Roy, 1978). Sorption of Cs increased or only slightly decreased in illites interstratified with montmorillonite (poorly crystallized illites), but drastically decreased in the two well-crystallized illite samples containing discrete vermiculite (Table 3). The reason for the increase in Cs sorption in the former case

is probably the creation of wedge zones (Jackson, 1963; Komarneni, 1979b) due to partial collapse of the interstratified montmorillonite as indicated by the presence of sharp illite peaks (Table 2). Hydrothermal treatment for a longer duration might lead to a complete collapse of the layers and result in a loss of Cs sorption even in these minerals. The decrease in Cs sorption in the latter case may be attributed to the collapse of vermiculite components (as tested by XRD) and of wedge zones or frayed edges (Jackson, 1963) in illites. Cs sorption by shales containing poorly crystallized illite or vermiculite decreased, probably due to a collapse of illite and vermiculite layers. Thus, hydrothermal conditions in a shale repository may lead to a reduction in Cs sorption by layer silicate minerals. However, the decrease of Cs sorption seems to be less pronounced in poorly crystallized illites than in well-crystallized illites. The above

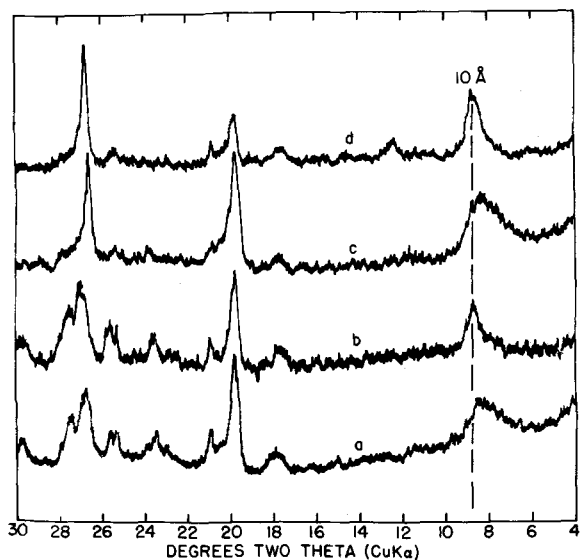


Figure 1. X-ray powder diffractograms of untreated illites and hydrothermally treated illites at 400°C and 300 bars pressure for 5 weeks. (a) Wisconsin illite, untreated; (b) Wisconsin illite showing somewhat well-crystallized illite after hydrothermal treatment; (c) Fithian illite, untreated; (d) Fithian illite showing somewhat well-crystallized illite after hydrothermal treatment.

results point out that some minerals do not lose their sorption abilities by hydrothermal heating and therefore may be used in designing an approximate "over-pack" around the canisters as a back-up barrier in case of a leakage.

#### Changes in Cs fixation in Cs-saturated samples by hydrothermal treatment

Hydrothermal treatment at 200°C and 300 bars of all samples saturated with Cs resulted in greater Cs fixation compared to their untreated counterparts (Table 4) because of interlayer collapse as revealed by XRD. The increase in Cs fixation by hydrothermal treatment is greater in illites than in vermiculites because vermiculite with its high layer charge and ideal interlayer spacing collapses even before heat treatment (Sawhney, 1969; Komarneni and Roy, 1978) and "locks up" Cs as indicated by the large percentage of Cs fixed in untreated samples. Hydrothermal treatment of the vermiculites, therefore, results only in a small increase in Cs fixation. Complete Cs saturation of exchange sites of minerals is unlikely under repository conditions because of the presence of several other ions, and, therefore, experimentation with Cs-saturated samples may be unrealistic. However, the main purpose of using the Cs-saturated samples in this study was to detect the formation of any new phases, such as pollucite, formed by the hydrothermal (100°–300°C, 300 bars pressure) interaction of Cs and shales or clays, as pointed out by Komarneni and McCarthy (1978). However, pollucite was not detected in these samples by XRD possibly because of insufficient reaction.

#### Changes in Cs fixation in Cs-sorbed samples by hydrothermal treatment.

To take geothermal gradient into consideration (Komarneni, 1979a) a series of clays and shales were Cs-

Table 3. Hydrothermal effects on cation-exchange capacity and Cs-sorption properties of various minerals and shales.<sup>1</sup>

Sample (<105- $\mu$ m fraction unless otherwise indicated)	Cation-exchange capacity meq/100 g		Cs sorption, Kd <sup>2</sup>	
	Untreated	Treated hydrothermally	Untreated	Treated hydrothermally
<i>Micaceous vermiculite</i>				
Cooper micaceous vermiculite, 1–50 $\mu$ m	101.4	31.0	1432	64
<i>Poorly crystallized illites</i>				
Wisconsin illite	21.5	18.5	51	76
Goose Lake illite	20.7	16.9	41	44
Fithian illite	25.5	9.4	100	63
Green illite	12.3	9.1	31	23
<i>Well-crystallized illites with discrete vermiculite</i>				
Beavers Bend illite	9.9	1.4	206	4
Indian red clay	11.4	7.1	225	15
<i>Shales with poorly crystallized illite</i>				
National Test Site ES-S-8A'	11.5	2.4	27	13
National Test Site ES-S-19A	30.5	21.7	84	25
<i>Shales with discrete vermiculite</i>				
Reedsville shale	10.1	3.8	45	11
Lewistown shale-sandstone	9.2	3.2	225	13

<sup>1</sup> 400°C, 300 bars, 5 weeks.

<sup>2</sup> Kd is defined as the ratio of the amount of Cs sorbed per gram to the amount of unsorbed Cs remaining per milliliter of the solution.

Table 4. Hydrothermal effects on Cs fixation in Cs-saturated minerals.<sup>1</sup>

Sample and particle size	Cs exchanged (meq/100g)	Percent Cs fixed	
		Before treatment	After hydrothermal treatment
Fithian illite, <4 $\mu\text{m}$	12.8	21.4	45.5
Beavers Bend illite, <105 $\mu\text{m}$	9.0	42.2	80.5
Transvaal micaceous vermiculite, 20–125 $\mu\text{m}$	48.9	82.0	89.4
Cooper micaceous vermiculite, 50–177 $\mu\text{m}$	71.5	79.2	90.4
Williams vermiculite, 50–177 $\mu\text{m}$	102.3	86.0	93.6
Poole vermiculite, 50–177 $\mu\text{m}$	112.1	79.6	89.6
K-depleted lepidomelane, 20–250 $\mu\text{m}$	50.4	96.2	99.1
K-depleted phlogopite, 0.2–20 $\mu\text{m}$	76.0	99.4	99.6

<sup>1</sup> 200°C, 300 bars, 2 months.

sorbed at 45°C. The fixation of Cs by these materials before and after hydrothermal treatment is given in Table 5. Cs fixation was considerably greater for the hydrothermally treated samples compared to the untreated samples (Table 5) as a result of collapse of the expandable layers in all the samples. However, layer collapse does not appear to be complete as evidenced by XRD analysis under the present hydrothermal conditions so as to fix all the sorbed Cs. Hydrothermal treatment for a longer time or higher temperature may

further increase the Cs fixation by these minerals and shales. Thus, hydrothermal conditions in a repository may be beneficial after radioactive Cs ions migrate from breached containers and after they are taken up by minerals.

## CONCLUSIONS

Hydrothermal treatment of clay minerals and shales leads to a notable decrease in their cation-exchange capacities and Cs-sorption abilities. Thus, the elevated

Table 5. Hydrothermal effects on Cs fixation in Cs-sorbed minerals and shales.<sup>1</sup>

Sample (<105- $\mu\text{m}$ fraction, unless otherwise indicated)	Cs sorbed at 45°C (meq/100 g)	Percent Cs fixed	
		Before treatment	After hydrothermal treatment
<i>Vermiculites</i>			
Williams vermiculite, 1–50 $\mu\text{m}$	15.8	69.5	86.6
Poole vermiculite, 1–50 $\mu\text{m}$	22.6	81.4	94.2
<i>Illites</i>			
Fithian illite	0.630	28.3	44.4
Goose Lake illite	0.398	15.6	29.6
Morris illite	0.425	13.6	22.4
Wisconsin illite	0.440	16.8	29.5
Wisconsin glauconite	0.468	13.9	30.8
Beavers Bend illite	0.767	76.0	94.1
Ouachita illite	1.138	91.4	95.3
Illitic clay	0.404	15.1	24.0
Indian red clay	0.884	75.7	96.7
Green illite	0.362	18.2	43.4
Green mica	0.136	14.7	27.9
<i>Shales and Slates</i>			
Eleana shale	0.404	14.6	37.9
National Test Site ES–S–16	0.738	57.6	74.1
National Test Site ES–S–8A'	0.362	17.7	49.2
National Test Site UEIL–2931	0.611	18.2	41.4
National Test Site ES–S–19A	0.644	48.3	68.6
McAvoy shale	0.546	27.3	68.9
Conasauga shale	0.503	17.7	46.7
Reedsville shale	0.398	32.7	63.1
Lewistown shale-sandstone	0.847	71.2	92.7
Black slate	0.221	26.2	92.3
Weathered slate	1.157	89.5	100.0

<sup>1</sup> 200°C, 300 bars, 2 months.

temperatures developed in the immediate vicinity of buried radioactive waste containers might, over a period of many years, reduce the Cs-sorption capabilities of shales and clays.

Hydrothermal treatment of Cs-sorbed or Cs-saturated clays and shales, however, resulted in an increase in their Cs fixation. This indicates that hydrothermal conditions might be beneficial if they persist after the leaked radioactive Cs ions are taken up by clays in shale repositories.

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**Резюме**—Изучалось воздействие гидротермических условий на сорбцию и фиксацию цезия разными глинистыми минералами и сланцами. Гидротермическое нагревание, которое можно ожидать в хранилище радиоактивных отходов, изменяло глинистые материалы и сланцы и привело к понижению их катионной обменной способности. При гидротермической обработке при 400°C и давлении 300 бар благодаря полному разрушению слоев резко понизилась сорбция цезия в слюдистом вермикулите и в хорошо кристаллизованных иллитах, содержащих вермикулит. Однако, плохо кристаллизованные иллиты, нагретые в тех же условиях, показали или незначительное повышение, или слабое понижение в сорбции Cs из-за частичного разрушения слоев. Эти исследования показывают, что в хорошо кристаллизованных иллитах понижение сорбции Cs значительнее, чем в плохо кристаллизованных иллитах при аналогичной обработке в гидротермических условиях. Гидротермическое нагревание сорбированных и насыщенных Cs образцов увеличило количество фиксированного Cs во всех минералах и сланцах, как следствие разрушения слоев. Например, образец Конасуговского сланца зафиксировал перед обработкой только 18% сорбированного Cs, но зафиксировал 47% после гидротермической обработки при 200°C и давлении 300 бар. Таким образом, гидротермические условия в сланцевом хранилище могут быть благоприятными, поскольку после утечки радиоактивных ионов Cs они впитываются глинистыми минералами в сланцах. [N. R.]

**Resümee**—Die Auswirkungen hydrothormaler Bedingungen auf die Adsorption und Fixierung von Cäsium an verschiedene Tonminerale und Tonschiefer wurden untersucht. Hydrothermales Erhitzen, wie man es in Lagergebieten für radioaktiven Abfall erwarten kann, verändert die Tonminerale und Tonschiefer und führt zu einer Abnahme ihrer Kationenaustauschkapazität. Wegen des Zusammenbrechens der Schichten verringert sich die Adsorption von Cäsium im glimmerigen Vermiculit und in gut kristallisierten Illiten, die Vermiculit bis zu einer hydrothermalen Behandlung auf 400°C bei 300 bar enthalten. Schlecht kristallisierter Illit, der ebenso erhitzt wurde, zeigte jedoch aufgrund des teilweisen Zusammenbrechens der Schichten entweder eine geringe Zunahme oder eine geringe Abnahme in der Cs-Adsorption. Diese Untersuchungen zeigen, daß die Abnahme der Cs-Adsorption bei gut kristallisierten Illiten größer ist als bei schlecht kristallisierten, wenn sie auf ähnliche Weise unter hydrothermalen Bedingungen behandelt wurden. Hydrothermales Erhitzen von Cs-adsorbierten und Cs-gesättigten Proben vergrößert die Menge des fixierten Cäsium in allen Mineralen und Tonschiefern, bedingt durch das Zusammenbrechen von Schichten. So bindet z.B. eine Probe des Conasauga Tonschiefers vor der Behandlung nur 18% des adsorbierten Cs, aber nach der hydrothermalen Behandlung auf 200°C und 300 bar wurden 47% gebunden. Aus diesem Grund könnten hydrothermale Bedingungen in einem Tonschiefer-Lager nützlich sein, nachdem radioaktive Cs-Ionen von den Tonmineralen im Tonschiefer aufgenommen wurden. [U. W.]

**Résumé**—Les effets des conditions hydrothermales sur la sorption et la fixation de césium par certains minéraux argileux et argiles shisteuses ont été étudiées. L'échauffement hydrothermal, auquel on peut s'attendre dans un repository de déchets radioactifs, a altéré les minéraux argileux et les argiles shisteuses et a mené à un amoindrissement de leur capacité d'échange d'électrons. La sorption de césium a beaucoup amoindri dans la vermiculite micacée et dans les illites bien cristallisées contenant de la vermiculite sous traitement hydrothermal à 400°C et 300 barres de pression à cause d'un affaissement de couche complet. Les illites pauvrement cristallisées cependant, échauffées comme ci-dessus, ont montré soit un léger accroissement ou seulement un petit amoindrissement de sorption de Cs à cause d'un affaissement de couche partiel. Ces études montrent que l'amoindrissement de sorption de Cs est plus fort dans les illites bien cristallisées que dans les illites pauvrement cristallisées lorsqu'elles sont traitées de la même manière sous des conditions hydrothermales. L'échauffement hydrothermal d'échantillons sorbés de Cs et saturés de Cs a augmenté la quantité de fixation de Cs dans tous les minéraux et dans les argiles shisteuses résultant de l'affaissement des couches. Un échantillon d'argile shisteuse de Conasauga, par exemple, n'a fixé que 18% du Cs sorbé avant le traitement, mais a fixé 47% après le traitement hydrothermal à 200°C et 300 barres de pression. Ainsi, les conditions hydrothermales peuvent bénéficier à un repository d'argile shisteuse après que des ions radioactifs de Cs échappés sont pris par les minéraux argileux des argiles shisteuses. [D. J.]