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Project Title: Direct Investigations of the Immobilization of Radionuclides in the Alteration Phases of Spent Nuclear Fuel

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RESEARCH OBJECTIVES

In a moist oxidizing environment, such as in the proposed geological repository at Yucca Mountain, rapid alteration rates are expected for spent nuclear fuel. Laboratory simulations and studies of natural analogues demonstrate that the dominant alteration products of spent fuel under repository conditions will be uranyl phases. There is an inadequate database concerning the effects of the alteration products on the release of radionuclides, but this information is essential to provide a radionuclide-release estimate. It is likely that many of the radionuclides contained in the spent fuel will be incorporated into the uranyl phases that form during alteration, potentially with a profound impact on the future mobility of radionuclides in the repository. Our objective is to develop a theoretically founded and experimentally verified understanding of the incorporation of radionuclides into uranyl phases under repository conditions. The research will permit a more realistic estimate of the release rates of the radionuclides from the near-field environment.

RESEARCH PROGRESS AND IMPLICATIONS

This report summarizes work after 3.5 years of a 6-year project. The project involves a collaboration between the University of Notre Dame, Argonne National Laboratory, and the University of Missouri-Rolla. The emphasis of our research has been geochemical and mineralogical studies intended to improve understanding of the impact of alteration phases on the release of radionuclides from waste forms (especially spent fuel) in a geological repository. The basis of our approach is a detailed understanding of the crystal chemistry of the alteration phases. Components of our research include: (1) structural characterization of the uranyl phases expected to form due to the alteration of spent fuel and borosilicate waste glass, (2) theoretical predictions of incorporation mechanisms of radionuclides into uranyl phases, (3) synthesis of radionuclide-bearing uranyl phases to substantiate theoretical predictions, (4) investigations of the geochemistry of neptunium, (5) investigations of ion exchange of radionuclides with uranyl phases. These components, taken together, provide an enhanced understanding of the impact of uranyl phases on the release of radionuclides during the corrosion of spent fuel in a geological repository.

Structural Characterization of Uranyl Phases: Prediction of incorporation mechanisms of radionuclides into uranyl phases that form due to alteration of spent fuel requires a detailed knowledge of the crystal structures of the uranyl phases. At the outset of this project, the structures and chemical details of many of the uranyl phases relevant to repository performance were either unknown or only poorly characterized. We have placed considerable emphasis on the determination and refinement of the structures of uranyl phases. Laboratory simulations have demonstrated that uranyl oxide hydrates, uranyl silicates, and uranyl molybdates can form as alteration products due to the oxidative dissolution of spent nuclear fuel. Uranyl carbonates may also play a significant role in determining the mobility of actinides under repository conditions. We are also interested in the structures and chemistry of uranyl phosphates, as phosphate-rich backfill additives, such as apatite, may help to minimize actinide migration due to the precipitation of relatively insoluble actinyl phosphates. Full details of these structures, and discussions of their significance to nuclear waste disposal, may be found in the corresponding archival journal publications.

Uranyl oxide hydrates: We have focused efforts on those uranyl oxide hydrates that have been identified as alteration products of spent fuel under conditions similar to those expected in the proposed repository. Our structural studies have included the Na analogue of compregnacite, $\text{Na}_2[(\text{UO}_2)_3\text{O}_3(\text{OH})_2]$ [30]; compregnacite, $\text{K}_2[(\text{UO}_2)_3\text{O}_2(\text{OH})_3]_2(\text{H}_2\text{O})_7$ [13]; agrinierite, $\text{K}_2(\text{Ca},\text{Sr})[(\text{UO}_2)_3\text{O}_3(\text{OH})_2] \cdot 2.4\text{H}_2\text{O}$ [15]; $\text{K}_5[(\text{UO}_2)_{10}\text{O}_8(\text{OH})_9](\text{H}_2\text{O})$

[7]; $\text{Sr}_{2.84}[(\text{UO}_2)_4\text{O}_4(\text{OH})_3]_2(\text{H}_2\text{O})_2$ [6]; $\text{Cs}_3[(\text{UO}_2)_{12}\text{O}_7(\text{OH})_{13}](\text{H}_2\text{O})_3$ [23], and becquerelite, $\text{Ca}[(\text{UO}_2)_6\text{O}_4(\text{OH})_6](\text{H}_2\text{O})_8$ [3].

Uranyl silicates: Uranyl silicates are likely to be common alteration products of spent fuel in the proposed repository owing to the relatively high content of Si in the groundwater. We have focused our studies on uranyl silicates observed as alteration products of spent fuel and actinide-bearing borosilicate waste glass in laboratory simulations. Structures we have reported include boltwoodite, $(\text{K}_{0.56}\text{Na}_{0.42})[(\text{UO}_2)(\text{SiO}_3\text{OH})](\text{H}_2\text{O})_{1.5}$ [12]; weeksite, $\text{K}_2(\text{UO}_2)_2\text{Si}_6\text{O}_{15}(\text{H}_2\text{O})_4$ [24]; haiweeite, $\text{Ca}[(\text{UO}_2)_2\text{Si}_5\text{O}_{12}(\text{OH})_2](\text{H}_2\text{O})_3$ [4]; $\text{KNa}_3(\text{UO}_2)_2(\text{Si}_4\text{O}_{10})_2(\text{H}_2\text{O})_4$ [8]; and $\text{Na}_4(\text{UO}_2)_2(\text{Si}_4\text{O}_{10})_2(\text{H}_2\text{O})_4$ [30].

Uranyl molybdates: Laboratory simulations have demonstrated that uranyl molybdates may be significant phases that retard the release of specific radionuclides during corrosion of spent fuel. We conducted an extensive study of the crystal chemistry of uranyl molybdates, and have solved or refined the structures of umohoite, $[(\text{UO}_2)\text{MoO}_4(\text{H}_2\text{O})](\text{H}_2\text{O})$ [29]; iriginite, $[(\text{UO}_2)\text{Mo}_2\text{O}_7(\text{H}_2\text{O})_2](\text{H}_2\text{O})$ [28]; two polymorphs of $\text{Cs}_2[(\text{UO}_2)_2(\text{MoO}_4)_3]$ [25]; $\text{Na}_6[(\text{UO}_2)_2\text{O}(\text{MoO}_4)_4]$ [26]; $\text{Na}_6[(\text{UO}_2)(\text{MoO}_4)_4]$ [26]; $\text{K}_6[(\text{UO}_2)_2\text{O}(\text{MoO}_4)_4]$ [26]; and $\text{M}_2[(\text{UO}_2)_6(\text{MoO}_4)_7(\text{H}_2\text{O})_2]$ ($\text{M} = \text{Cs}, \text{NH}_4$) [27].

Uranyl carbonates: Our studies of uranyl carbonates have included structure determinations for wyartite, $\text{CaU}^{5+}(\text{UO}_2)_2(\text{CO}_3)_4(\text{OH})(\text{H}_2\text{O})_7$ [11]; bijvoetite, $[(\text{Y}, \text{REE})_8^{3+}(\text{UO}_2)_{16}(\text{CO}_3)_{16}\text{O}_8(\text{OH})_8(\text{H}_2\text{O})_{25}](\text{H}_2\text{O})_{14}$ [34]; $\text{Na}_4(\text{UO}_2)(\text{CO}_3)_3$ [33]; and grimselite, $\text{K}_3\text{Na}[(\text{UO}_2)(\text{CO}_3)_3](\text{H}_2\text{O})$ [31].

Uranyl phosphates: We are studying the structures of a wide variety of uranyl phosphates, including synthetic crystals of the autunite group. We have reported the structure of parsonsite, $\text{Pb}_2[(\text{UO}_2)(\text{PO}_4)_2]$ [5].

Other uranyl structures: As part of our expansion of the structural hierarchy of uranyl phases, we have studied the structures of uranopilite, $[(\text{UO}_2)_6(\text{SO}_4)\text{O}_2(\text{OH})_6(\text{H}_2\text{O})_6](\text{H}_2\text{O})_8$ [2], a variety of uranyl fluorides [14], and a novel NH_4 uranyl framework material [32].

Theoretical Predictions of Radionuclide Incorporation Mechanisms in Uranyl Phases: Fission products such as ^{79}Se ($t^{1/2} = 1.1 \times 10^6$ yrs.) and ^{99}Tc ($t^{1/2} = 2.13 \times 10^5$ yrs.) are of considerable significance to geological disposal of spent fuel owing to their long half lives and their potentially high mobility in natural systems. The geochemical and crystallo-chemical retardation mechanisms for ^{79}Se under conditions similar to those expected in the proposed repository at Yucca Mountain have been examined and are reported in Chen *et al.* (1999). In brief, $(\text{SeO}_3)^{2-}$ (selenite) and $(\text{SeO}_4)^{2-}$ (selenate) are the dominant aqueous species under repository conditions. Owing to the high solubility of metal selenites and selenates, and the low adsorption of selenite and selenate aqueous species by geological materials under repository conditions, Se may be highly mobile. However, consideration of the crystal chemistry of uranyl phases that form due to the alteration of spent fuel under repository conditions indicates that the Se may be incorporated into some of these phases in small quantities, thereby significantly reducing Se mobility.

Possible incorporation mechanisms for Tc into the structures of uranyl phases have been examined, with the results given in Chen *et al.* (2000). Under the conditions of spent fuel alteration to uranyl phases, the dominant oxidation state of Tc will be 7+, with the aqueous species being $(\text{TcO}_4)^{-1}$. The bonds within this tetrahedron are very strong. As a result, the anions have most of their bonding requirements met by the bond to Tc, making it very unlikely that the $(\text{TcO}_4)^{-1}$ group shares anions with other cations of high valence in a crystal structure. As such, it seems unlikely that Tc will be incorporated into the uranyl phases that form due to the alteration of spent fuel.

Synthesis of Radionuclide-Bearing Uranyl Phases: The potential for the incorporation of Pu^{4+} and Am^{3+} into uranyl alteration phases has been evaluated using Ce^{4+} and Nd^{3+} as surrogate elements for the actinides. The crystal-chemical behavior of the lanthanides and actinides are expected to be comparable due to the similarity of their valence charges and ionic radii (e.g., Ce^{4+} 0.94 Å vs. Pu^{4+} 0.93 Å; Nd^{3+} 1.04 Å vs. Am^{3+} 1.07 Å). Crystalline phases were synthesized in these experiments by saturating solutions with uranium, plus various combinations of alkali elements, alkaline earths, Si, Ce and/or Nd at temperatures between 90 to 185°C. The phases formed including dehydrated schoepite, $(\text{UO}_2)\text{O}_{0.25-x}(\text{OH})_{1.5+2x}$ ($0 \leq x \leq 0.25$); ianthinite, $\text{U}_2^{4+}(\text{UO}_2)_4\text{O}_6(\text{OH})_4(\text{H}_2\text{O})_4(\text{H}_2\text{O})_5$; becquerelite, $\text{Ca}[(\text{UO}_2)_3\text{O}_2(\text{OH})_3]_2(\text{H}_2\text{O})_8$; sodium-compreignacite, $(\text{Na}_2(\text{UO}_2)_6\text{O}_4(\text{OH})_6(\text{H}_2\text{O})_7)$; and boltwoodite, $(\text{K}(\text{UO}_2)(\text{SiO}_3\text{OH})(\text{H}_2\text{O})_{1.5})$. All of these phases are predicted to form during the oxidative corrosion of spent nuclear fuel.

The K_d values (solid concentration/solution concentration) for cerium in these experiments varied with the different phases present. The highest values were obtained from experiments where ianthinite crystals had formed ($K_d = 146$ to 159), followed by Na-compreignacite ($K_d = 30$ to 96), becquerelite ($K_d = 16$), dehydrated schoepite ($K_d = 5$ to 12), and finally boltwoodite ($K_d = 4$). The wide variation in K_d values for Na-compreignacite may be related

to the formation of a second unidentified crystalline phase in these experiments. In addition to K_d variations with different phases, values were also noted to vary inversely with crystalline grain size. Such a trend suggests that Ce incorporation may be a surface dominated process, with adsorption being favored at high-energy defect sites located at edges and/or surfaces of crystals. In a relatively limited number of experiments conducted with Nd, the K_d values were noted to be highest for tests with boltwoodite ($K_d = 80$), followed by ianthinite ($K_d = 62$), and finally becquerelite ($K_d = 5$).

Studies of neptunium geochemistry: Work at Argonne on synthesizing uranyl compounds has continued, with additional effort being made towards synthesizing and characterizing pure Neptunium (Np) compounds and Np-containing uranyl compounds. Np-containing U(VI) compounds are especially relevant to understanding the potential geochemical behavior of Np in the presence of U, such as expected where spent UO_2 fuel undergoes aqueous corrosion in a high-level nuclear-waste repository. Effort during the past year consisted primarily of synthesizing and characterizing several new Np-bearing compounds, including preparation of a pure Np nitrate, a mixed Np/U nitrate, several mixed Np/U oxides and oxyhydroxides, and two mixed Np/U silicates, as well as developing enhanced capabilities for analyzing samples containing multiple actinides by EXAFS.

Synthesis of a new Np(VI) nitrate: A Np(VI) nitrate has been prepared by evaporating aqueous solutions to dryness at approximately 100°C in air, which produces macroscopic crystals. The oxidation state of Np in this nitrate is Np(VI), as determined by optical-absorption spectroscopy. The composition of the Np(VI) nitrate is still being investigated, but preliminary results indicate a Np-to-nitrate ratio of 1:3; the compound is hydrated, with an undetermined number of H_2O groups. Crystals are bright red, deliquescent, and alter readily in air, presumably by hydrating further (although this remains to be demonstrated). These properties are consistent with a synthetic amorphous Np nitrate reported in the literature. Our synthetic Np(VI) nitrate is crystalline, however, and may be a new compound. X-ray diffraction data collected from the compound do not match any known Np nitrates listed in the latest Powder Diffraction File (International Center for Diffraction Data). Most XRD patterns collected so far suggest a mixture of two or more phases in variable proportions.

Synthesis and characterization of Np-doped U oxides: Mixed Np/U anhydrous oxides have been synthesized with a range of Np:U ratios, and these are currently being analyzed by XRD and EXAFS/XANES. Initial results indicate several structural modifications as a function of the Np:U ratio, including a change in the local Np coordination environment (indicated by EXAFS) and an apparent phase transformation (indicated by XRD). Results are preliminary and examination of these oxides is continuing.

Synthesis and characterization Np-doped U oxyhydroxides: Several Np-bearing U(VI) and pure Np oxyhydroxides have been synthesized. XRD data indicate only slight changes to the unit-cell parameters with increasing Np concentrations in the U(VI) oxyhydroxides, up to approximately 20 mole % Np. This is consistent with a solid solution between U(VI) oxyhydroxides and the isostructural Np(VI) oxyhydroxides, and suggests that the Np occurs as Np(VI) in these solids. These solids have not yet been analyzed by EXAFS/XANES, which should unambiguously determine the Np valence in these solids.

Synthesis and characterization pure Np silicates: Two Np-bearing silicates were prepared by evaporating aqueous solutions to dryness at approximately 100°C in air. One of the solids prepared by this method is crystalline and, based on preliminary XRD data, may be structurally related to the uranophane group minerals; a second solid prepared in a similar fashion is amorphous, although chemically homogeneous. The Np oxidation state in both silicates appears to be Np(VI), as suggested by XANES; however, these results are somewhat ambiguous and more complete characterization is required.

Despite repeated efforts to synthesize pure Np silicates by more conventional hydrothermal methods known to successfully prepare uranyl silicates, no positive results have yet been obtained.

EXAFS of lanthanide-bearing silicate: Lanthanides are useful, nonradioactive chemical analogues of many actinides of environmental concern, so we have also been examining solid-state structural effects of lanthanide substitutions in synthetic crystals of zircon (ZrSiO_4). A major part of this effort is aimed at developing our capabilities for collecting EXAFS data from compounds with elements that may experience absorption-edge interferences from neighboring elements, as is the case for many actinides and lanthanides. Furthermore, nonradioactive lanthanides provide useful surrogates for examining structural changes induced by substitutions into crystalline materials, such as ZrSiO_4 . Recent efforts at Argonne have focused on examining REE substitutions by XRD and XAS.

Investigations of Ion Exchange of Radionuclides with Uranyl Phases: Using single crystals of natural boltwoodite, we demonstrated the exchange of Cs into the interlayer [10]. This was the first demonstration of ion exchange in single crystals of a uranyl phase, and has significant implications for the mobility of Cs under repository conditions. Additional experiments performed using synthetic boltwoodite demonstrated ion exchange of Cs into the structure where Cs was present in solution at concentrations of ~100 ppm. We have also demonstrated ion exchange of Cs into single crystals of compreignacite, even when Cs is present in the solution in concentrations of only tens of ppm. These results indicate that minerals such as boltwoodite and compreignacite are likely to incorporate ^{135}Cs into their structures as they grow under repository conditions. Such phases are also likely to exchange ions with solutions that contact them after they grow, and may either sequester Cs or release it, depending upon the relative concentrations of different ions in the solution.

INFORMATION ACCESS

Archival Journal Publications concerning this project

1. Buck, E.C., **Wronkiewicz**, D.J., Finn, P.A., and Bates, J.K., "A new uranyl oxide hydrate phase derived from spent fuel alteration", *Journal of Nuclear Materials* 249, 70-76 (1997).
2. **Burns**, P.C. (2001): A new uranyl sulfate chain in the structure of uranopilite. *Canadian Mineralogist* (accepted).
3. **Burns**, P.C. & Li, Yaping (2001): The structures of becquerelite and Sr-exchanged becquerelite. *American Mineralogist* (submitted).
4. **Burns**, P.C. (2001): A new uranyl silicate sheet in the structure of haiweeite and comparison to other uranyl silicates. *Canadian Mineralogist* (accepted).
5. **Burns**, P.C. (2000): A new uranyl phosphate chain in the structure of parsonsite. *American Mineralogist* 85, 801-805.
6. **Burns**, P.C. & Hill, F.C. (2000): Implications of the synthesis and structure of the Sr analogue of curite. *Canadian Mineralogist* 38, 175-182.
7. **Burns**, P.C. & Hill, F.C. (2000): A new uranyl sheet in $K_5[(UO_2)_{10}O_8(OH)_9](H_2O)$: New insights into sheet anion-topologies. *Canadian Mineralogist* 38, 163-174.
8. **Burns**, P.C., Olson, R.A., **Finch**, R.J., Hanchar, J.M. and Thibault, Y. (2000): $KNa_3(UO_2)_2(Si_4O_{10})_2(H_2O)_4$, a new compound formed during vapor hydration of an actinide-bearing borosilicate waste glass. *Journal of Nuclear Materials* 278, 290-300.
9. **Burns**, P.C. (1999): The crystal chemistry of uranium. *Reviews in Mineralogy* 38, 23-90.
10. **Burns**, P.C. (1999): Cs boltwoodite obtained by ion exchange from single crystals: Implications for radionuclide release in a nuclear repository. *Journal of Nuclear Materials* 265, 218-223.
11. **Burns**, P.C. & **Finch**, R.J. (1999): Wyartite: crystallographic evidence for the first pentavalent-uranium mineral. *American Mineralogist* 84, 1456-1460.
12. **Burns**, P.C. (1998): The structure of boltwoodite and implications of solid-solution towards sodium boltwoodite. *Canadian Mineralogist* 36, 1069-1075.
13. **Burns**, P.C. (1998): The structure of compregnacite, $K_2[(UO_2)_3O_2(OH)_3]_2(H_2O)_7$. *Canadian Mineralogist* 36, 1061-1067.
14. Cahill, C.L. & **Burns**, P.C. (2001): Building unit and topological evolution in the hydrothermal DABCO-U-F system. *Inorganic Chemistry* 40, 1347-1351.
15. Cahill, C.L. & **Burns**, P.C. (2000): The structure of agrinierite: A Sr-containing uranyl oxide hydrate mineral. *American Mineralogist* 85, 1294-1297.
16. Chen, Fanrong, **Burns**, P.C. & Ewing, R.C. (2000): Near-field behavior of ^{99}Tc during the oxidative alteration of spent nuclear fuel. *Journal of Nuclear Materials* 278, 225-232.
17. Chen, Fanrong, **Burns**, P.C. & Ewing, R.C. (1999): ^{79}Se : Geochemical and crystallo-chemical retardation mechanisms. *Journal of Nuclear Materials* 275, 81-94.
18. Fayek, M., **Burns**, P.C., Guo, Y.X. & Ewing, R.C. (2000): Micro-structures associated with uraninite alteration. *Journal of Nuclear Materials* 277, 204-210.
19. **Finch**, R.J. & Murakami, T. (1999): Systematic mineralogy and paragenesis of uranium minerals. In: *Uranium: Mineralogy, Geochemistry and the Environment*, by P.C. Burns and R.J. Finch Eds. *Reviews in Mineralogy* 38, 91-179 (Mineralogical Society of America, Washington, D.C.).
20. **Finch**, R.J., Hanchar, J.M., Hoskin, P.W.O. & **Burns**, P.C. (2001): Rare earth elements in synthetic zircon. 2. A single-crystal X-ray study of xenotime substitution. *American Mineralogist* 86, 681-689.
21. Hanchar, J.M., **Finch**, R.J., Watson, E.B., Cherniak, D. (2001): Rare-earth elements in zircon. Part 1. Synthesis and rare-earth element and phosphorous doping. *American Mineralogist* 86 (in press).
22. Hawthorne, F.C., Krivovichev, S.V. & **Burns**, P.C. (2000): The crystal chemistry of sulfate minerals. *Reviews in Mineralogy and Geochemistry* 40, 1-112.
23. Hill, F.C. & **Burns**, P.C. (1999): Structure of a synthetic Cs uranyl oxide hydrate and its relationship to compregnacite. *Canadian Mineralogist* 37, 1283-1288.
24. Jackson, J. M. & **Burns**, P.C. (2001): A re-evaluation of the structure of weeksite, a uranyl silicate framework mineral. *Canadian Mineralogist* 39, 187-195.
25. Krivovichev, S.V., Cahill, C.L. & **Burns**, P.C. (2001): Synthesis and crystal structures of two topologically related modifications of $Cs_2[(UO_2)_2(MoO_4)_3]$. *Inorganic Chemistry* (submitted).
26. Krivovichev, S.V. & **Burns**, P.C. (2001): Crystal chemistry of uranyl molybdates. III. New structural themes in $Na_6[(UO_2)_2O(MoO_4)_4]$, $Na_6[(UO_2)(MoO_4)_4]$ and $K_6[(UO_2)_2O(MoO_4)_4]$. *Canadian Mineralogist* 39, 207-214.

27. Krivovichev, S.V. & **Burns**, P.C. (2001): Crystal chemistry of uranyl molybdates. IV. The structures of $M_2[(UO_2)_6(MoO_4)_7(H_2O)_2]$ ($M = Cs, NH_4$). *Canadian Mineralogist* 39, 215-226.
28. Krivovichev, S.V. & **Burns**, P.C. (2000): Crystal chemistry of uranyl molybdates. II. The crystal structure of iriginite. *Canadian Mineralogist* 38, 847-851.
29. Krivovichev, S.V. & **Burns**, P.C. (2000): Crystal chemistry of uranyl molybdates. I. The structure and formula of umohoite. *Canadian Mineralogist* 38, 717-726.
30. Li, Yaping & **Burns**, P.C. (2001): The structures of two sodium uranyl compounds relevant to nuclear waste disposal. *Journal of Nuclear Materials* (submitted).
31. Li, Yaping & **Burns**, P.C. (2001): The crystal structure of synthetic grimselite, $K_3Na[(UO_2)(CO_3)_3](H_2O)$. *Canadian Mineralogist* (accepted).
32. Li, Yaping, Cahill, C.L. & **Burns**, P.C. (2001): Synthesis and structural characterization and topological rearrangement of a novel open framework U-O material: $(NH_4)_3(H_2O)_2\{[(UO_2)_{10}O_{10}(OH)][(UO_4)(H_2O)_2]\}$. *Chemistry of Materials* (accepted).
33. Li, Y., Krivovichev, S.V. & **Burns**, P.C. (2001): The crystal structure of $Na_4(UO_2)(CO_3)_3$ and its relationship to schröckingerite. *Mineralogical Magazine* 65, 285-292.
34. Li, Y. & **Burns**, P.C. (2000): A new rare-earth element uranyl carbonate sheet in the structure of bijvoetite-(Y). *Canadian Mineralogist* 38, 153-162.
35. Li, Y., Krivovichev, S.V. & **Burns**, P.C. (2000): The crystal structure of thornasite, $Na_{12}Th_3[Si_8O_{19}]_4(H_2O)_{18}$: a novel interrupted silicate framework. *American Mineralogist* 85, 1521-1525.
36. **Wronkiewicz**, D.J. and Buck, E.C., "Uranium mineralogy and the geologic disposal of spent nuclear fuel", in *Uranium Mineralogy*, (R.J. Finch and P.C. Burns eds.) Reviews in Mineralogy Series, Mineralogical Society of America, vol. 38 Washington D.C., pp. 475-498 (1999).

Symposium Proceedings and Conference Abstracts

1. **Burns**, P.C. (2001): Structures of uranyl minerals and compounds containing tetrahedrally coordinated hexavalent cations. *Goldschmidt Conference*, Hot Springs, Virginia (invited).
2. **Burns**, P.C. (2000): Mineralogy: where we are and where we're going. *Geoscience 2000* (Calgary).
3. **Burns**, P.C., Hill, F.C., **Finch**, R.J. & Olson, R.A. (1999): Radionuclide retardation in uranyl silicate forming in a geological repository for nuclear waste. *GSA* (Denver).
4. **Burns**, P.C. & **Finch**, R.J. (1999): The structure of wyartite: Crystallographic evidence for the first pentavalent-uranium mineral. *GAC-MAC* (Sudbury).
5. **Burns**, P.C. (1998): Topological aspects of uranyl mineral structures. *IMA* (Toronto).
6. Cahill, C.L., Krivovichev, S.V. & **Burns**, P.C., (2000): Novel open-framework uranyl molybdates. Abstracts of Papers of the American Chemical Society, 220: 463-INOR.
7. Cahill, C.L. & **Burns**, P.C. (1999): The structure of agrinierite: a K-Ca-Sr uranyl oxide hydrate sheet of the α - U_3O_8 type. *GSA* (Denver).
8. Chen, F., **Burns**, P.C., & Ewing, R.C. (1998): ^{79}Se : Geochemical and crystallo-chemical retardation mechanisms. *The Scientific Basis for Nuclear Waste Management XX*. MRS Proceedings, 556, 1115-1122.
9. **Finch**, R.J., Kropf, A.J. & Hanchar, J.M. (2001): XAFS spectra of HREE in zircon. Goldschmidt Conference Special Session on Accessory Minerals: Equilibrium and Kinetic Properties and Applications. Roanoke, Virginia, May 20-24, 2001. *Invited*.
10. **Finch**, R.J., Hanchar, J.M., Hoskin, P.W.O. & **Burns**, P.C. (1998): Rare earth elements in synthetic zircon: the roles of P and Li. *GSA* (Toronto).
11. **Finch**, R.J. *et al.* (2000): Accessory minerals and the alteration of nuclear-waste forms: Insights and comparisons. American Geophysical Union Spring Meeting, Washington, D.C. *Invited*.
12. **Finch**, R.J. *et al.* (2000): Actinide and lanthanide host phases formed during the corrosion of nuclear-waste forms. American Chemical Society National Meeting, San Francisco. *Invited*.
13. **Finch**, R.J., & Buck, E.C. (1998): Synthesis and characterization of $Ba[(UO_2)_5MoO_6(OH)_6] \cdot nH_2O$. Materials Research Society, Boston, MA, November 30 - December 4, 1998. MRS 1998 Fall Meeting Abstracts volume 25, 723 (abstract)
14. Hanchar, J.M., **Finch**, R.J., Watson, E.B. & Hoskin, P.W.O. (2001): Towards a better understanding of rare earth element partition coefficients in zircon. European Union of Geochemistry; Special Session on Accessory Minerals: Equilibrium and Kinetic Properties and Applications. Roanoke, Virginia. *Invited*.
15. Hill, F.C. & **Burns**, P.C. (1999): Cs ion exchange in boltwoodite. *GSA* (Denver).

16. Hill, F.C. & **Burns**, P.C. (1999): The importance of uranyl silicates for the disposal of nuclear waste. *GAC-MAC* (Sudbury).
17. Hill, F.C. & **Burns**, P.C. (1998): Investigations of the crystal chemistry of uranyl oxide hydrates. *IMA* (Toronto).
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