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4-6 REVIEW OF THE IMPLICATIONS OF MICROBIOLOGICAL FACTORS ON THE LONG-TERM MANAGEMENT OF USED NUCLEAR FUEL

EXECUTIVE SUMMARY

D. Roy Cullimore, Ph.D. R.M., Droycon Bioconcepts Inc.

Executive Summary

This review focuses on aspects of used nuclear fuel management that can be impacted by the microorganisms present in the biosphere. While to some this may seem to be an insignificant part of the challenge, there is a growing recognition that single-celled microorganisms do have a major role in the functioning of atmospheric, aquatic and terrestrial systems, including soil and geospheric processes. Traditionally, microorganisms have been viewed by the public as the pathogens causing serious diseases in humans, animals and plants. Less attention has been paid to the other very significant roles that microorganisms play in influencing environmental processes.

In dealing with the long-term management of used nuclear fuel, most studies and proposals have emphasized protecting humans, animals and plants from the potential risks associated with safely storing and disposing of the used nuclear fuel. In the last two decades, there has also been a growing awareness of the need to protect the environment, or more specifically the surface biosphere, from the activities of humans. This perspective has tended to over-simplify and artificially compartmentalize the approaches to used nuclear fuel management. For example, the preoccupation with protecting the surface biosphere from uncontrolled dispersal of radionuclides has led to a definition of used nuclear fuel disposal within the Earth's crust which describes the geosphere as being located below the biosphere. A major flaw in this definition is the lack of recognition that the subsurface biosphere extends into the geosphere. Thus, there is a need to recognize and include factors relating to the subsurface biosphere in the design and establishment of any used nuclear fuel storage or disposal concepts which may be developed.

Clearly, interactions between the geosphere and the subsurface biosphere can be expected to occur. For example, at the disposal site, within the containment envelope, it can be expected that the generation of heat and radiolysis would act as a stimulant to some types of microbial activity, particularly where free liquid water is present, and an inhibitor to other types. For the purposes of this review, the containment envelope is considered to be the used nuclear fuel and all engineered systems for providing protection and support to the fuel within a natural environment. Liquid water for the support of microbial activity within the envelope would occur anywhere from saturation down to 2 percent of the saturation capacity. The form of microbial incursion into the envelope would be dependent not just on available

water, but also available nutrients and the physical conditions relating particularly to pH and the oxidation reduction potential (ORP). Radiolytic effects emanating from the fuel are likely, in the presence of water, to significantly affect the ORP towards oxidative conditions that would be supportive for aerobic (oxygen-utilizing) bacteria. One effect of this would be the focused generation of microbial biomass at the juncture between reductive and oxidative conditions (redox front). Such accumulations would have a multiplicity of implications for the chemical stability, solubility and subsequent mobility of the used nuclear fuel within the containment envelope, including:

- accumulation of metal (commonly with iron dominating) and other chemicals (such as carbonates, oxides and hydroxides) within the biomass that could then cause shielding from the radiolytic affects,
- accumulation in the biomass of escaping radionuclides, increasing corrosion risks to metal and concrete components within the envelope due to products from the biomass (such as hydrogen sulphide and various acidic products of growth),
- changes to the normal hydraulic flows as a result of bio-occlusive processes (plugging),
- gas evolutions from the biomass that could cause fracturing within the porous media components in the envelope and the more rapid movement of water through pneumatic processes, and
- mutagenesis of microbial cells leading to adaptation to growth under more challenging conditions.

Given that the local environment within a containment envelope would likely be too extreme for the activities of plants (i.e., no light source for photosynthesis) and animals (i.e., inadequate oxygen for respiration), the subsurface biosphere is likely to be dominated by microorganisms that have a greater versatility than either plants or animals to function in extreme environments. For plants and animals, the very nature of the complex and sophisticated cellular forms involved render these organisms less adaptable to change and such changes that do occur are intergenerational in their nature. For microorganisms, the simple form of the cell and the nature of cellular organisations, including, in some cases, the coating of the cell with matrices of bound water held in place by a complex network of thread-like molecules (polymers), provide a greater level of adaptability to extreme environments. This adaptability encompasses a variety of different potential challenges, including changes in barometric or hydrostatic pressure, temperature, concentrations of dissolved salts (up to saturation), pH, and ORP. Depending upon the extremity of the parameters applied, microorganisms may either adapt quickly, enter into a transient survival stage that can last for millennia (as can occur with a spore or an ultra-microbacterium), become traumatized and enter a suspended animation state, or be killed if the environment is sufficiently extreme. Given the large number of independent single cells involved (commonly measurable in millions and billions), the impact of any extreme environment has to effectively have killed at least six orders of magnitude of cells before the impact is seen and even then the potential still exists for the survivors to become active. Possibly the simplest validation of the versatility of microorganisms is the fact they dominate the subsurface biosphere and remain active in the geosphere under conditions of increasing pressure, temperature, and salt concentration, and where the ORP falls into highly reductive conditions.

In zoology and botany, it is common to consider each species as occupying a particular range of environmental niches with little ability to adapt beyond those conditions. Microorganisms are distinctly different in two ways: (1) species tend to function in consortia with other species in a mutualistic manner; and (2) component species within the consortium tend to function differently at various places within the consortium. This interdependence means that there is a remarkable ability for these consortia to adapt and locate to functionally significant points (e.g., at the redox front) within the environment where growth can occur. These consortia have the advantage of being able to bioaccumulate chemicals within the bound water around the cells for the purpose of storing future nutrients beyond immediate needs and protecting the cells from possibly harmful chemicals by "locking" them into these extracellular slimes (bound water in a polymer matrix). Should the consortium detach from a surface and move into the flowing liquid water phase, then these slimes (biocolloids) could also carry these excess chemicals, which could include radionuclides moving from the used nuclear fuel due to deterioration in the containment envelope. Once in the biocolloids, then the movement of such entrapped radionuclides would be more a function of the movement of the biocolloid with the ground water systems around the envelope. It could no longer be considered controlled by a first- or second-order reaction, but more by the functional ability of the carrier biocolloid to locate a new attachment point where growth may occur.

A discussion of these various topics is provided in the subsequent chapters of this review. Following an introductory chapter, Chapter 2 gives an overview of the science of microbiology, particularly from the environmental and ecological perspectives. Chapter 3 considers the critical microbiological issues with respect to the storage and disposal of used nuclear fuel. The influences of natural phenomena on microbiological aspects of the containment are addressed in Chapter 4, and Chapter 5 summarizes the potential forms of microbiologically mediated movement of the radionuclides from containment.

The key points arising from this review are that:

- Microbial populations (particularly the Archea) are found throughout the biosphere and several kilometers deep into the geosphere.
- These communities exist anywhere they can exploit an energy gradient (pH gradient, redox gradient,) that may be driven by radiation, temperature, etc.
- The introduction of a used-fuel disposal facility deep into the geosphere will create local gradients that will act as a source of energy for Archea and bacteria capable of exploiting these gradients.
- The consequences of this exploitation could involve increasing the rate at which radionuclides contained in the facility are solubilized, the chemical form of the solubilized radionuclides and as a consequence their potential mobility through the geosphere.
- This in turn may influence the flux of these radionuclides into the receiving surface biosphere where human beings and the ecosystem on which our species depends is adversely affected.
- Any consideration of a concept and associated design for a deep geological repository should include consideration of the effect of microbial processes.