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Bibliography of Literature on Underground Corrosion of Metals and Alloys Considered for Use in the Construction of Containers for Nuclear Waste

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Center for Materials Science
Materials Chemistry Division
Washington, DC 20234

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BIBLIOGRAPHY OF LITERATURE ON UNDERGROUND CORROSION OF METALS AND ALLOYS CONSIDERED FOR USE IN THE CONSTRUCTION OF CONTAINERS FOR NUCLEAR WASTE

B. T. Sanderson and J. Kruger

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

Bibliography of Literature on Underground Corrosion of Metals and Alloys Considered for Use in the Construction of Containers for Nuclear Waste

by

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Introduction

The citations and annotations from the literature presented in this bibliography consist of articles, papers, talks, books, reports, proceedings of conferences and patents that deal with the corrosion of metallic container materials that are proposed for use for the containment of nuclear waste in underground repositories. Both author and subject indices are provided. The author index is listed by the first author. The subject index uses key words found in the individual bibliography items. This bibliography contains five kinds of metallic corrosion data that is aimed at serving the needs of those who are concerned with the nuclear waste container design:

1. General underground corrosion data of metals that may be applicable to the use of metallic nuclear waste containers. This data describes the performance of metals and alloys that may be used or considered for use in underground environments.

2. Data on corrosion considerations in package design. These data consist of patents and designs of actual corrosion resistant metallic containers for use in underground environments and include provisions to resist corrosion.

3. Data on metallic corrosion in geothermal brines. Since some of the proposed underground environments for buried nuclear waste include salt deposits and deep ocean sediments, a cursory sampling of data pertaining to the corrosion performance of metals and alloys in geothermal brines is included. An effort was made during compilation of this information to concentrate on those metals that might have possible application to the use of metallic nuclear waste containers.

4. Data on the internal corrosion of nuclear waste containers to be used in underground environments. While the primary concern of this bibliography is the compliation of data regarding the interaction of external surfaces of nuclear waste containers with underground environments, the importance of the internal corrosion resistance of the container to its nuclear waste contents is quite obvious. Therefore, some but not a complete set of data concerned with internal corrosion of containers for underground use have been included. Also some of the individual references cited relate to both the anticipated internal corrosion problems as well as the external corrosion problems.

5. Data on external corrosion of nuclear waste containers for underground use. These data concern the reactions between the outer surfaces of a radioactive nuclear waste container and its underground environment such as salt, seabed sediments, rock or soils.

Abstracts are included when available and some lengthy abstracts have been shortened or condensed. When no abstract was abailable or an article was quite brief, key words have been included where possible to better describe the subject material. This compilation was performed utilizing the following computer data bases: National Technical Information Service data base, Engineering Index data base, Department of

Energy data base, and Chemical Abstracts data base. In addition to the computer research, a hard copy search of references was accomplished at the library of the National Bureau of Standards. Another invaluable source of information has been the personal contacts with the individuals at organizations such as the Battelle Pacific Northwest Laboratory, Sandia National Laboratory, Oak Ridge National Laboratory, and the U. S. Bureau of Mines and proved quite helpful. Finally, the 70 odd years of work by NBS in the field of underground metallic corrosion has been utilized extensively.

We gratefully acknowledge the support of the preparation of the Bibliography by the Department of Energy National Waste Terminal Storage Program.

AUTHOR INDEX

[1] Abrego, L., Braithwaite, J. W., Corrosion of Titanium in Saline Nuclear Waste Isolation Environments, 1980 Annual Mtg., American Nuclear Society, Las Vegas, NV, 9-12 June 1980, p. 34.

The corrosion of the Ti alloys Ti-50A and TiCode-12 is being studied to determine their useful lifetime as canister materials for the isolation of nuclear waste. The long-range goal of this program is to qualify a material to survive the first 300 to 600 years of emplacement in a chloride-containing environment. Types of corrosion that could lead to canister failure include uniform attack, stress corrosion cracking, and pitting/crevice corrosion. It was shown in a prior study that the uniform corrosion rates of the above two Ti alloys are extremely small in 250 °C brines (# <0.01 mm/yr) and that pitting attack did not occur. The subject of the present investigation is the crevice corrosion and stress corrosion cracking susceptibility of Ti-50A and TiCode-12 in both nonirradiated and gamma-irradiated saturated brine and sea water environments.

[2] Ahlstrom, P. E., Ceramic and Pure-Metal Canisters in Buffer Material for High-Level Radioactive Waste, Nucl. Chem. Waste Manage., 1(1), 77-88 (1980).

Within the Swedish KBS project, a great effort has been devoted to the development of canisters for the encapsulation of high-level vitrified waste or spent unreprocessed fuel. The canisters will, upon final disposal in deep geological formations, provide an extra engineered barrier against the dispersal of radioactive nuclides in the groundwater. Comprehensive studies have been made on two types of pure metal canisters; i.e., Pb-Ti for the high-level vitrified waste and pure Cu for spent fuel. The final disposal is made in hard crystalline rock, where the waste canisters are embedded in a buffer material--a clay with good long-term stability. For the Pb-Ti canister, a mixture of quartz sand and bentonite is proposed whereas for the Cu canister highly compressed bentonite is preferred. Careful evaluations predicted a lifetime of at least thousands of years for the Pb-Ti canisters and probably tens of thousands of years in the actual environment. For the Cu canister, it is realistic to expect a lifetime of hundreds of thousands of years. Comprehensive studies have also been made of a ceramic canister of alumina for spent fuel. Through hot isostatic pressing, it is possible to make a completely tight and joint-free alumina container. Alumina has a very high chemical and mechanical resistance over very long periods of time. Preliminary studies have also been made of a glass ceramic material of the beta-spodumene type.

[3] Akol'zin, P. A., Tskhvirashvili, D. G., Vardigoreli, O. Sh., Corrosion of Copper and Its Alloys in Geothermal Waters, Prot. Metals., 9(1), 56-58 (1973).

Tests were conducted on specimens from copper and brass tubes, used in water-to-water heat exchangers. The rate of corrosion, initially very considerable, decreased with time and then became stable. No change in the rate of corrosion was observed in half-a-year due to the formation of protective films on tube surfaces. Pure copper samples showed corrosion rates three to ten times greater than copper alloys. To maintain adequate corrosion performance, a water flow rate of about three m/sec is recommended for brass tubing.

[4] Allard, B., Kipatsi, H., Rydberg, J., Radiolysis of Buffer Materials, Kaernbraenslesaekerhet, Rept. No. KBS-TR-56, p. 22 (1977).

The effect of gamma irradiation on the properties of the possible buffer material bentonite (bentonite:quartz, 10:90) has been discussed, mainly in qualitative terms. Changes in ion exchange properties and lattice structure of the clay mixture due to irradiation in an aqueous solution have been studied. The production of gas (hydrogen) due to radiolysis has been determined as a function of the radiation dose. The resistance to corrosion of titanium in a radiation field has been demonstrated.

[5] Anderson, K., Neretnieks, I., Diffusion of Nuclides of Low Solubility From a Copper Capsule After Penetration Through a Hole in the Capsule, Kaernbraenslesaekerhet, Rept. No. KBS-TR-80, p. 11, 1978.

Diffusion of nuclides of low solubility from a copper capsule after its penetration has been computed. It is assumed that by some mechanism the copper has corroded, leaving a hole equal to the inner diameter of the capsule. The uranium oxide is slowly dissolved, and the nuclides diffuse out through the hole. The diffusivity of the uranium ions is taken to be $10^{-10}m^2/S$ in the copper corrosion products, as well as in the porous mass in the capsule UO_2, zircaloy corrosion products, lead corrosion products). The dissolution of the uranium oxide matrix is governed by the solubility of UO_2 and the distance it has to diffuse. The solubility is assumed to be very high--1070g/m^3--which is the value obtained under oxidizing conditions and in a water with very high carbonate content (550 mg/l). Initially, the transport rate of uranium is two g/year. It decreases rapidly as the uranium oxide is dissolved and as the diffusion distance increases. It will take 2.8 million years to dissolve and transport away a mass of uranium oxide in the two meters nearest the assumed hole in the capsule. If this hole has only ten percent of the inner area of the copper capsule, the time increases to 7.1 million years. When 0.2 m of the uranium oxide nearest the hole have been dissolved, the dissolution rate is smaller than the transport from the repository. The rate of diffusion from the capsule may then become the rate determining step.

[6] Angerman, C. L., Rankin, W. N., Durability of Containers for Storing Solidified Radioactive Wastes, Corrosion/77 NACE Mtg., San Francisco, CA, 14 March 1977.

Most concepts for the disposal of highly radioactive waste involve converting the waste to a solid form, like concrete or glass, and storing this solid form in metal containers. Two major factors in the final selection of materials for these containers are the compatibility between waste form and container material and the durability of the material at temperatures and stresses expected during service and possible accidents. Currently, AISI 1020 carbon steel appears to be a better material than other alloys, such as Cor-Ten A, Type 304L stainless steel, or Inconel 600, considered. This choice is based on the results of 10,000 hours of heating tests that showed container compatibility with both concrete and glass waste forms. The selection is also based on: (1) analyses of the strengths and (2) oxidation resistances of the alloys under the conditions expected during 100 year storage in air and in various impact and thermal accidents. The thinner wall thickness required for satisfactory performance of the stronger, more-oxidation-resistant alloys is offset by their higher cost per pound.

[7] Anticorrosion Methods Materials, Article, Buried Nuclear Waste must be Enclosed in Au to Resist Corrosion, Anticorr. Methods Matls., 24(6), 12-13 (1977).

Keywords: Radioactive waste; waste disposal; gold plating; Corrosion Prevention.

[8] Asphahani, A., Corrosion Resistance of High Performance Alloys, Matls. Perform., 19(12), 33-43 (1980).

A review with 88 references on highly alloyed stainless steels, Ni alloys, and Co alloys for the processing industries and pollution control equipment. The resistance to pitting/crevice corrosion is examined, and a ranking of alloys is established. Stress corrosion cracking is examined in the presence of NaCl and/or H_2S.

[9] Baboian, R., Haynes, G. S., Corrosion Resistance of Copper Clad Stainless Steel Cable Shielding Materials, NACE, Intl. Corr. Forum, Chicago, IL, Preprint paper 89, 4-8 March 1974.

Copper clad stainless steel (Cu/430 SS/Cu) and solid copper behave similarly in all soils. Results with panels and shieldings in cables were in good agreement. After extended exposure, copper and copper alloy perforates (such as in acid soils), whereas the stainless steel acts as a corrosion barrier in the Cu/430 SS/Cu shielding, thus preventing corrosion of the inner copper layer and maintaining shielding integrity. Data from potentiodynamic polarization curves in soil water extracts are useful in determining the mechanisms of corrosion in various soil environments.

[10] Banning, L. H., Oden, L. L., Corrosion Resistance of Metals in Hot Brines: A Literature Review, US Bur. Mines, Info. Circ. No. 8601, (1973).

With the ever-increasing demand for energy in all forms, electical energy generated from geothermal resources could become an important energy source in the next few decades. Geothermal fluids, which contain appreciable quantities of dissolved salts and gases, are generally corrosive to materials of construction. Since data on corrosion of materials in geothermal brines is limited, the literature was surveyed through February 1972 to obtain a compilation of information on corrosion resistance of aluminum and its alloys, copper or copper-base alloys, carbon steel and cast iron, stainless steels, chromium-iron alloys, nickel- and cobalt-base alloys, and titanium in heated brines, including sea water.

[11] Bednar, L., Young, J. W., New Corrosion Resistant Material for URD Transformer Cases, Matls. Prot. Perform., 12(3), 21-25 (1973).

A composite material, fabricated from a thin layer of stainless steel, metallurgically bonded on each side to a heavy layer of carbon steel, offers high resistance to pitting corrosions and is less expensive than Type 409 stainless. The cathodic corrosion mechanism is evaluated and illustrated sample of corrosive attack of various metals compared with the composite. These materials are used in underground environments.

[12] Bird, J. M., Ringwood, A. E., Container for Radioactive Nuclear Waste Materials, US 4,192,765 (Cl. 252-301.1W; G21F1/08) 11 March 1980, Appl. 878,113, 15 February 1978. Chemical Abstracts, Vol. 93, 1980.

Long-term storage of nuclear reactor wastes in underground rock formations requires container alloys thermodynamically stable against degradation in geochemical environments. Container alloys are proposed on the basis of naturally occurring awaruite and josephinite as stable mineral alloys, which contain Ni 60-90, Fe 10-40, Cu 0-5, and Co 0-5 percent. Their stoichiometric phase is Ni_3Fe.

[13] Boase, D. G., Vandergraaf, T. T., The Canadian Spent Fuel Storage Canister: Some Materials Aspects, Nucl. Tech., 32(1), 60-71 (1977).

Concrete canisters for interim dry storage of spent, irradiated Canadian D-U (CANDU) fuel are being developed by Atomic Energy of Canada, Ltd. The canisters are designed to contain fuel safety for periods of 50 to 100 years in C-steel baskets sealed inside a steel- and Pb-lined concrete shield. A demonstration program at the Whiteshell Nuclear Research Establishment is utilizing four instrumented canisters to establish the canister structural integrity when exposed to the thermal stresses generated by the decay heat of the stored fuel. A review of other potential materials problems identified three areas of concern: corrosion of the fuel basket and canister lining, fuel sheath oxidation, and UO_2 oxidation. Preliminary analysis suggests that the first of these will be minimized by the migration of moisture to the outside of the canister under the influence of the temperature gradient, and the second is predicted to be insignificant for periods $\leq$ 100 years. The third area was less well understood, and a detailed experimental study was, therefore, undertaken. Initial canister designs conceived the use of airfilled fuel baskets, with UO_2 fuel temperatures initially in the 200-300 ° range. Oxidation of the UO_2 in defected fuel could cause contamination of the basket and complicate subsequent fuel retrieval. The rates and mechanisms of UO_2 oxidation were studied using powders, sintered pellets, and intentionally defected fuel elements. In the present demonstration canisters, the possibility of oxidation of the fuel has been eliminated by storing it in He-filled baskets.

[14] Braithwaite, J. W., Molecke, M. A., High-Level Waste Canister Corrosion Studies Pertinent to Geologic Isolation, Conf. on High-Level Radioactive Solid Waste, Denver, CO, 19 December 1978, p. 35.

The compatibility of candidate high-level waste (HLW) canister materials with deep geologic isolation environments is addressed. Results are presented which are applicable to the following repositories or test facilities: bedded and domed salt, sub-seabed sediment, and various types of hardrock. Such studies are an essential portion of the technological basis for terminal waste management. These studies identify HLW canister or overpack materials satisfying appropriate requirements for barrier lifetime. Mechanical properties, as well as constraints on cost and consumption of critically limited materials, are also selection criteria. Lifetime objectives range from a minimum of several years for retrievability constraints up to several hundred years for retardation of near-field interactions (e.g., waste form leaching with potential radionuclide release to the geosphere) during the period of greatest HLW thermal output. A review of present and prior applicable corrosion results is presented. However, emphasis is on the results obtained from current laboratory and in-situ HLW canister/corrosion programs at Sandia Laboratories. The effects of multiple variables on corrosion susceptibility and rates are briefly discussed, and some applicable data are given. It is possible to provide a canister/overpack barrier which can survive geologic isolation environments for periods of several hundred years.

[15] Braithwaite, J. W., Magnani, N. J., Munford, J. W., Titanium Alloy Corrosion in Nuclear Waste Environments, Corrosion/80 NACE Mtg., Chicago, IL, 6 March 1980.

A corrosion study has been conducted on the titanium alloys Ti-50A, TiCode-12, and Ti-Pd to evaluate their suitability as a long lifetime (300 to 600 year) canister material for the isolation of nuclear wastes. TiCode-12, selected as the primary candidate material, is shown to be very resistant to environmental attack. Results of electrochemical, general corrosion, and stress corrosion cracking experiments are presented. These data, including those from severe overtests, have shown that TiCode-12 is a viable candidate material for

long-term waste isolation.

[16] Braithwaite, J. W., Magnani, N. J., Corrosion Considerations for Nuclear Waste Isolation Canisters, Annual Mtg. Matls. Rsch. Soc., Boston, MA, 28 November 1978.

The environments in bedded salt, sub-seabed sediments, and hardrock are described. A corrosion study is being conducted on various candidate overpack alloys in deoxygenated sea water and oxygenated sea water and brine; some rate data are given for 14 to 50 days. Results show that deoxygenated saturated brine is more corrosive than deoxygenated sea water plus sediments, that oxygen increases the corrosion rate, especially in sea water, and that localized attack in deaerated media is minimal, even for 304L stainless steel.

[17] Braithwaite, J. W., Corrosion Behavior of Metals in Terminal Nuclear Waste Storage Environments, NACE Mtg. on Corrosion, Houston, TX, 6 March 1978.

A laboratory and field experimentation program has been undertaken to determine the magnitude of and the remedy for corrosion problems which might be encountered during terminal nuclear waste storage. The investigation has centered upon canister and instrumentation material selection for the following three geologic environments being considered at Sandia Laboratories for terminal storage: (1) bedded salt, (2) deep sub-sea sediments, and (3) hardrock. A wide range of metal alloys are being considered as candidate materials because of the fluidity of the design requirements. Ambient and 90 °C corrosion data have been collected in sea water and saturated brine. However, the depth of burial, along with the residual heat production of each loaded canister, produces a high-temperature, high-pressure, corrosive environment, which can only be simulated or produced in the field (in-situ) or in laboratory autoclaves. Possible corrosion mechanism and rate determinations are being made using an autoclave equipped with internal electrochemical instrumentation capabilities. Preliminary investigations are considering the effects of the following variables on corrosion rate: (1) temperature, (2) pressure, (3) dissolved oxygen concentration, and (4) brine chemistry. Field experiments, using electrically heated canisters, are to begin shortly in two shale formations.

[18] Branch, H. C., Corrosion Resistant Materials for URD Equipment, Matls. Prot. Perform., 12(3), 9-13 (1973).

More economical solutions to underground residential equipment corrosion problems are the use of highly corrosion-resistant alloys to replace cathodic protection and organic coating techniques. Materials evaluated include silicon bronze, copper-nickel, Types 304 and 316 stainless and highly alloyed metals, such as alloys 20 and 825.

[19] Carter, J. P., McCawley, F. X., Cramer, S. D., Needham, P. B., Jr., Corrosion Studies in Brines of the Salton Sea Geothermal

Field, Report RI8350, Bureau of Mines, 1979.

The Bureau of Mines, US Department of the Interior, has conducted in-situ corrosion studies at the Salton Sea Known Geothermal Resources Area (KGRA) in the Imperial Valley, CA, to evaluate and characterize materials of construction for geothermal resources recovery plants. General-, pitting-, and crevice-corrosion characteristics of 13 commercially available alloys were investigated for periods of 15 and 30 days in seven process environments expected to be found in typical geothermal resouces plants. Stainless steel alloy 29-4, Inconel 625, and the Hastelloys G, S, and C-276 were the most resistant to general corrosion, did not pit, and exhibited little susceptibility to crevice corrosion. Stainless steel alloys 430, E-Brite 26-1, and 6X had low general corrosion rates, but pitted and were susceptible to crevice corrosion. Carbon and 4130 steels had high corrosion rates, pitted, and had high susceptibilities to crevice corrosion. The major scale-forming mineral on the corrosion samples in most of the process environments studied was galena mixed with lesser amounts of other minerals.

[20] Carter, J. P., Cramer, S. D., Field Stress Corrosion Tests in Brine Environments of the Salton Sea Known Geothermal Resource Area, Matls. Perform., 19(9), 13-16 (1980).

Stress corrosion tests (30-day) were conducted at the Salton Sea Known Geothermal Resource Area on seven Fe-base and Ni-base alloys in four brine and steam process streams by using wellhead brine from geothermal well Magmammax 1. Transgranular cracking of AISI 316L stainless steel and intergranular and transgranular cracking of AISI 430 stainless steel was observed in all four process streams. E-Brite 26-1 exhibited intergranular and transgranular cracking in three of the four process streams. AISI 1020 carbon steel, Inconel 625, Hastelloy G, and Hastelloy C-276 showed no evidence of stress corrosion cracking.

[21] Carter, J. P., Cramer, S. D., Conrad, R. K., Corrosion of Stainless Steels in the Geothermal Environments of the Salton Sea Known Geothermal Resource Area, Natl. Assn. Corr. Eng. Inter. Forun Toronto, Canada, Apr. 1981.

The U. S. Department of the Interior, Bureau of Mines, in support of its geothermal mineral and metal recovery program, has conducted a series of field corrosion and electrochemical tests in the geothermal environments of the Imperial Valley of California. This paper presents the results of a 45day field corrosion test conducted in 1978 on six stainless steel alloys (>10 Cr) exposed to brine and steam environments of well Magnamax #1 on the Salton Sea field and electrochemical data on fourteen stainless steel alloys (>10 Cr) exposed to wellhead brine. Stainless steels have excellent to good resistance to general corrosion, but are highly susceptible to pitting and crevice corrosion. Type 316 L stainless steel was found to undergo intergranular corrosion and transgranular stress corrosion cracking. Increasing the molybdenum content reduced general corrosion, while higher contents of nickel and molybdenum reduced pitting.

[22] Carter, J. P., Cramer, S. D., Conrad, R. K., An Overview of Materials and Corrosion in Geothermal Systems, NACE Energy Sources, Tech. Conf., New Orleans, LA, 1980.

The Bureau of Mines has been involved in the development of the geothermal mineral resources of the Imperial Valley, CA. The brines produced from geothermal reservoirs in this area are extremely corrosive. Furthermore, the brines readily form complex scales during processing that complicate the corrosion process and interfere with process operations. The Bureau has supported a research program with the objective of identifying optimum materials of construction for geothermal resource recovery plants. This program consists of both laboratory and field studies which include evaluating the corrosion resistance of a wide variety of engineering alloys in typical geothermal process environments, applying electrochemical corrosion measurement techniques in scale-forming geothermal brines, using isokinetic sampling in studying two-phase geothermal fluids, characterizing the kinetics and mineralogy of scale deposition from hypersaline brines, and determining the solubility of oxygen, methane, and carbon dioxide in brines.

[23] Casteels, F., Tas, H., Naets, J., Brabers, M., Corrosion of Materials in a Clay Environment, Sci. Basis Nucl. Waste Manage., 2, 38593 (1980).

Corrosion of canister materials for radioactive waste storage was determined in a clay deposit which may be used for waste disposal. Materials tested included: Al and its alloys, C steel, Cr steel, austenitic and ferritic stainless steels, Ni alloys, Ni superalloys, Ti, and Ti alloys. At high temperatures, S and S compounds are the main corrosive agents in the clay. SO_2 is formed mainly due to the reaction of pyrite in the clay with humidity. Excellent corrosion resistance was found for Hastelloy B.

[24] Christenssen, H., Consideration of Radiolysis of Ground Water, Kaernbraenslesaekerhet, p. 26 (1978).

Computer calculations of the radiolysis of ground water have been carried out with regard to the final disposal of highly active waste. Radiolysis of water outside the container of waste encapsulated in glass results in an equilibrium situation after less than 50 h. The equilibrium concentrations of oxygen, hydrogen, and hydrogen peroxide are low on the order of 20, 10, and 20 ppB, respectively. Radical concentrations are much lower, for example, $C(OH) \leq 2 \times 10^{-12}$m. For fuel elements directly deposited in a copper container, the radiolysis of water inside the container has been studied by calculations. The purpose has been to determine whether hydrogen could be formed in concentrations exceeding the solubility limit and also to calculate the amount of copper corrosion. Assuming

that oxygen reacts diffusion controlled with the copper surface, it was found that hydrogen was formed in concentrations far below the solubility limit, even after several million years. Zirconium may possibly react with water below 100 °C, resulting in the formation of hydrogen at a rate of 0.0001 mole/year. The corrosion of copper is less than 50 mg per liter of water present.

[25] Claiborne, H. C., Rickertsen, L. D., Graham, R. F., Expected Environment in High-Level Nuclear Waste and Spent Fuel Repositories in Salt, ORNL/TM-7201, p. 206, Oak Ridge National Laboratories, TN (1980).

The expected environments associated with high-level waste (HLW) and spent fuel (SF) repositories in salt formations are described. These environments include the thermal, fluid, pressure, brine chemistry, and radiation field predicted for the repository conceptual designs. Canistered waste packages containing HLW in a solid matrix or SF elements are emplaced in vertical holes in the floor of the rooms. The emplacement holes are backfilled with crushed salt or other material and sealed at some later time. Sensitivity studies are presented to show the effect of changing the areal heat load, the canister heat load, the barrier material and thickness, ventilation of the storage room, and adding a second row to the emplacement configuration. The calculated thermal environment is used as input for brine migration calculations. The vapor and gas pressure will gradually attain the lithostatic pressure in a sealed repository. A computer code (REPRESS) was developed assuming that these changes occur slowly (equil. conditions). The brine chemical environment is outlined in terms of brine chemistry, corrosion, and compns. The nuclear radiation environment is the stored energy that can be released as a result of radiation damage or crystal dislocations within crystal lattices.

[26] Colombo, P., Neilson, R. M., Jr., Properties of Radioactive Wastes and Waste Containers. Progress Report No. 6, July-September 1977, p. 47 (1978). Brookhaven National Laboratory, Upton, NY.

A survey was made of the available literature on the corrosion of steels in soil environments. The effect of the physical and chemical properties of the soil on the rate and type of corrosion of steels has been evaluated. The corrosion rates of ferrous alloys are influenced primarily by the soil environment; alloy compositional and microstructural considerations are secondary. However, as the steel is made more resistant to uniform corrosion, it becomes more susceptible to pitting corrosion. The various tests and criteria proposed to measure the corrosiveness of soil are reviewed.

[27] Colombo, P., Neilson, R. M., Jr., Kendig, M. W., Analysis and Evaluation of a Radioactive Waste Package Retrieved from the Atlantic 2800 Meter Disposal Site, Report 1979, Brookhaven National Laboratories, NY.

During the 1976 Atlantic 2800 m radioactive waste disposal site survey, the first recovery of a radioactive waste package from a radioactive waste disposal site was performed by the EPA Office of Radiation Programs. The retrieved 80 gal. radioactive waste package was transported to Brookhaven National Lab., where container corrosion and matrix leach rate and degradation studies were conducted.

[28] Cramer, S. D., Carter, J. P., Laboratory Corrosion Studies in Low- and High-Salinity Geobrines of the Imperial Valley, CA., BUMINES-RI-8415, Bureau of Mines, Avondale, MD, 1980.

Corrosion research is being conducted by the Federal Bureau of Mines to determine suitable construction materials for geothermal resource recovery plants. As part of this research, the corrosion resistance of 31 iron-, nickel-, aluminum-, copper-, titanium-, and molybdenum-base alloys was characterized and evaluated in laboratory corrosion studies in low- and high-salinity geobrines representative of those found in the Imperial Valley, CA. General, crevice, pitting, weld, and stress corrosion were measured at 105 and 232 C in deaerated brines and brines containing dissolved O_2, CO_2, and CH_4.

[29] Cramer, S. D., Needham, P. B., Jr., Linear Polarization Measurements at High Temperatures in Hypersaline Geothermal Brines, Rept. #RI-8308, Bureau of Mines, Avondale, MD.

The Bureau of Mines conducted a series of in situ linear polarization measurements in high-temperature, high-pressure hypersaline geothermal brines at the Bureau of Mines Geothermal Test Facility in the Imperial Valley of California. The measurements represented an evaluation of the linear polarization technique for obtaining instantaneous corrosion rates of materials of construction in flowing hypersaline hydrothermal fluids that rapidly form scales on exposed surfaces. A special method was devised for use with the linear polarization technique that resulted in obtaining corrosion rates for 1020 carbon steel, 316 and 430 stainless steel, titanium, various nickelbased alloys, and aluminum 6061 under strong scaleforming conditions. The measurements also provided information on scale-deposition rates in various geothermal environments. Exploratory in situ potentiostatic polarization measurements were made in the flowing brines to qualitatively determine scaledeposition effects on the electrochemical measurements.

[30] Cramer, S. D., Carter, J. P., Corrosion in Geothermal Brines of the Salton Sea Known Geothermal Resource Area, ASTM Special Tech. Publ. 717, Philadelphia, PA, 1981.

Corrosion research is being conducted by the Bureau of Mines, U. S. Department of the Interior, to determine suitable construction materials for geothermal resource recovery plants. High chromium-molybdenum ironbase alloys, nickelbase and titaniumbase alloys, and a titaniumzirconiummolybdenum alloy (TZM) exhibited good resistance to general, crevice, pitting, and weld corrosion and stress corrosion cracking in laboratory tests in deaerated brines of the Salton Sea known geothermal resource area (KGRA) type at 232 °C and in brine containing dissolved carbon dioxide and methane. Only titanium-base alloys were resistant to corrosion in oxygenerated Salton Sea KGRA-type brine. Copper adversely affected the resistance to general corrosion of lowalloy steels in deaerated brine, whereas chromium, nickel, silicon, and titanium improved it. Carbon steel, Type 4130 steel, and Types 410 and 430 stainless steels exhibited poor corrosion resistance in field tests in five brine and steam process streams produced from geothermal well Magmamax No. 1.

These alloys were highly susceptible to pitting and crevice corrosion. General corrosion rates were high for the carbon and Type 4130 steels.

[31] Cramer, S. D., The Solubility of Oxygen in Brines from 0 to 300 °C, I&EC Process Design and Development, April 1980 by the American Chem. Soc. The solubility of oxygen in water, in sodium chloride brines, and in two geothermal brines typical of the Imperial Valley, CA., was determined for temperatures from 0 to 300 °C and for brine concentrations up to 5.69 m in dissolved salts. Measurements were made in a high-pressure, stirred autoclave by the technique of gas extraction. The solubility, expressed in terms of the Henry's Law constant, k, was described with a standard deviation of six percent or less by the empirical equation,

$$\ln k = a_0 + a_1/T + a_2/T^2 + a_3/T^3 + a_4/T^4;$$

where T is the absolute temperature in K, and the coefficients, a_0 through a_4, depend on the concentration of dissolved salts in the brine. A minimum in the solubility occurred in the temperature range 60 to 100 °C. The salting-out coefficient for sodium chloride brines varied by a factor of two over the temperature range 0 to 300 °C with a minimum at 155 °C. The effect of temperature on solubility in the two geothermal brines was different from that in the sodium chloride brines in the mid- and high-temperature ranges.

[32] Davis, R. B., Munir, Z. A., Corrosion Susceptibilities of Various Metals and Alloys in Synthetic Geothermal Brines, J. Matls. Sci., 12(9), 109013 (1977).

The corrosion susceptibilities of various pure metals and alloys were investigated in synthetic geothermal fluids. Rates of corrosion of AISI 1010 steel, types 304 and 316 stainless steels, Monel 400, and nickel were determined at three temperatures (296, 333, and 368 K); and those of the molybdenum, niobium, and titanium were determined at 368 K only. Type 304 stainless steel appears to undergo an active-passive transition at a temperature range between 333 and 368 K. In the passive state, type 304 steel has essentially the same corrosion rate as type 316. At 368 K, the corrosion rate of pure nickel was approximately 2.5 times that of Monel,

which in turn was twice that of type 316 stainless steel. The corrosion rates of Mo, Nb, and Ti were less than one mdd at the highest experimental temperature.

[33] deSoultrait, B., Comparative Study of the Resistance of Al and Cu Alloys to Corrosion for Underground and Open-Air-Mains, Corrosion, Traitements, Protection, Finition, 20(7), 46773 (1972).

Keywords: Aluminum base alloys, corrosion, copper base alloys, corrosion resistance.

[34] Du Pont de Nemours, Waste Management Quarterly Report, July-September 1977, Savannah River Lab., Department of Energy, p. 111, 1977.

Status of the following studies is reported: new reference process for defense waste solidification, sludge washing studies, spray calciner feasibility test, viscosity of glass melts, electrical resistivity of glass melts; tank farm model for Savannah River Plant, pilot-scale offsite tritiated wastes; corrosion of carbon steel by concentrated synthetic nuclear wastes, chemical form of plutonium in groundwater from the burial ground, and groundwater transport of ext 129 I from seepage basins.

[35] Du Pont de Nemours, Waste Management Quarterly Report, April-June 1978, Savannah River Lab., Department of Energy, p. 167, 1978.

The following were studied: environmental impact of longterm management of highlevel radioactive waste at SRP (draft programmatic statement), Defense Waste Solidification Facility, cost analysis of defense waste processing facilities, improved reference process for defense waste supernate clarification, removal of exp 90 Sr from waste supernate, removal of Al from sludges by caustic washing, ion chromatographic determination of nitrite, demonstration of largescale calciner, radiolytic gas production from TRU waste in concrete, incorporation of TRU incinerator ash into glass, improved glass frit, test of smallscale jouleheated melter, evaluation of candidate alloys for incan melting canisters, residual solids from Tank 16 annulus, waste monitors, chemical form of Pu in burial ground soil, alpha waste trench coring, corrosion of buried drums, radionuclide release and migration from buried wastes, groundwater flow pattern from burial ground wells, and radionuclide uptake by pine trees from buried irradiated scrap metal.

[35a] Corrosion Studies on Copper and titanium-lead cannisters-(or Nuclear Waste Disposal. Ekbom, L. B., Hannerz, K,. Henrikson, K. S., (Natl. Def. Res. I,st., Stockhom, Swed.). Underground Disposal Radioact. Wastes, Proc. Symp. 1979. (Pub. 1980). 1, 503-16 (Eng). IAEA: Vienna, Austria. The Nuclear Fuel Safety Project (KBS) has proposed that spent non-processed nuclear fuel shall be disposed of by enclosing it in Cu canisters or alternatively that reprocessed and vitrified waste shall be enclosed in a Ti canister with a Bp lining. The canisters are

to be placed in vertical drill holes in rock, 500 m below ground and embedded in a buffer of sand and bentonite. The purpose of this arrangement is to raise several obstacles against fission products reaching the biosphere. The thick-walled canister is one of these obstacles, which is proposed to be a barrier for a considerable period of time. Corrosion is the limiting factor of the canister durability. The rate of corrosion is dependent on the amt. and transport of corrosion reactants to the surface of the canister. The thermodn. possibilities for various corrosion reactions on Cu and Pb under the prevailing conditions were studied, also with regard to bacterial influence. Entrapped atm. O and S^{2-} by diffusion was calcd., and hence the greatest possible corrosion. The corrosion attack may start as pitting but will penetrate into the thick metal wall at a decreasing rate. An expert group arrived at the conclusion that under given conditions the canisters will last for a very long time (hundreds or thousands of years for Cu canister). To verify the expected high corrosion resistance of Ti, lab. tests were carried out in environments, which must be considered to provide accelerated rather than simulated tests. No localized corrosion or H pick-up was detected, and the oxidn. rate was extremely low, corresponding to a wall-thinning of Ti of only 0.01 μm/yr. The results of potential meausrements during γ-radiation showed that the passivity of Ti is not affected by the radiation.

[36] Escalante, E., Gerhold, W. F., Galvanic Coupling of Some Stainless Steels to Copper Underground, Intl. Corr. Forum on Prot. and Perform. of Matls: Corrosion/75, Toronto, Ont., April 14-18, 1975, p. 10, NACE, Houston, TX, 1975.

This paper is primarily concerned with the effects on the underground corrosion of three types of stainless steels when galvanically coupled to copper. It has been found that the effect on corrosion of galvanically coupling copper to 26Cr-6.5Ni alloy, type 304, and type 409 stainless steels is small. There was no observable increase in the corrosion of the coupled stainless steel compared to the same material uncoupled at any of the six sites after three and four year exposure. In fact, the evidence is that in some instances, the copper protected the stainless steel.

[37] French Patent, 2209983, Confinement Chamber for Radioactive Products or Waste, P29, January 18, 1977.

Keywords: Reinforced concrete and stainless steel, design, tanks, underground disposal, chromium alloys, iron alloys, corrosionresistant alloys, building materials.

[38] French Patent, 2446529, Container for Strongly Radioactive Materials, January 12, 1979.

The title container is made of thick sheet steel cylinders, bolted at the ends and soldered along the sides to make a water-tight unit of several concentric rings with inside diameter ∿ 1.20 m and length 5 m. The innermost cylinder was made rust-proof with a 4 mm thick stainless steel coating. Steel cylinders (5) are fitted one within the other, soldered together along the sides, and bolted at the ends so that none of the fasteners are directly in line with the others.

[39] Gerhold, W. F., Escalante, E., Sanderson, B. T., The Corrosion Behavior of Selected Stainless Steels in Soil Environments, NBS-IR 812243, 1981.

In order to obtain more definitive information regarding the corrosion and stress corrosion of stainless steels in soil environments, NBS in cooperation with the Committee of Stainless Steel Producers, AISI, initiated in 1970 a soil burial program in representative soil environments. Test materials included coated and uncoated sheet specimens in the annealed and sensitized condition, uncoated welded tubing specimens and galvanically coupled and uncoupled stressed and unstressed specimens. To date approximately 10,000 specimens have been buried at six soil test sites. This report contains the results obtained for specimens buried for up to approximately eight years.

[40] Gerhold, W. F., Fink, J. L., Corrosion Evaluation of Underground Telephone Cable Shielding Materials, NBS-IR 812243, 1981.

Corrosion data is given on the performance of base and plastic coated metals intended for use as cable shields for buried telephone cable. The materials investigated on specially prepared specimens were buried for periods up to six years in six different soil environments. Metals tested included homogeneous plasticbonded and metallurgicallybonded laminates. Some specimens were exposed bare (uncoated), while others had plastic coatings or other types of coatings on either one or both sides. Metals studied included aluminum, copper, low carbon steel and stainless steel alloys.

[41] Goldberg, A., Comments on the Use of 316 L Stainless Steel Cladding at the Geothermal Niland Test Facility, UCID17113 University of California, Livermore, CA, 30 April 1976.

[42] Goldberg, A., Geothermal Materials Studies. Metallurgy Division Quarterly Report, April-June 1976. Lawrence Livermore Lab., Livermore, CA.

Progress in evaluating materials for Total Flow Process geothermal energy conversion systems, particularly materials for a 100 KW, brine-tolerant turbine, is reported. In the Total Flow Process, the total flow of the wellhead is expanded through converging-diverging nozzles to obtain lowtemperature, high-velocity streams of two-phase fluids for driving impulse turbines. The turbine materials must be corrosion resistant to the high salinity acid brines and exhibit resistance to erosion caused by the impingement of high velocity brine droplets and entrained materials. Programs for studying erosion in nozzle and turbine materials, stress corrosion cracking in turbine materials; e.g., Ti-, Fe-, Ni-, and Co-base alloys, and corrosion and erosion failures in wellhead casing and surface pipes are

summarized.

[43] Gray, L. W., Donnan, M. Y., Okamoto, B. Y., Chemical Characterization of SRP Waste Tank Sludges and Supernates, Savannah River Lab., p. 141 (1979).

Most high-level liquid wastes at the Savannah River Plant (SRP) are by-products from plutonium and enriched uranium recovery processes. The high-level liquid wastes generated by these separations processes are stored in large, underground, carbon-steel tanks. The liquid wastes consist of: supernate (an aqueous solution containing sodium nitrate, nitrite, hydroxyl, and aluminate ions), sludge (a gelatinous material containing insoluble components of the waste, such as ferric and aluminum hydroxides, and mercuric and manganese oxides), and salt cake (crystals, such as sodium nitrate, formed by evaporation of water from supernate). Analyses of SRP wastes by laser-Raman spectrometry, atomic absorption spectrometry, spark-source mass spectrometry, neutron activation analysis, colorimetry, ion chromatography, and various other wet-chemical and radiochemical methods are discussed. These analyses are useful in studies of waste tank corrosion and of forms for long-term waste storage.

[44] Haijtink, B., Corrosion of Potential Materials for Containers and Repository Structures for the Disposal of Highly Radioactive Waste in Geological Formations, Workshop on Radioactive Waste Management, Brussels, Belgium, June 12, 1979, 2(2), p. 597-617, 1980.

Under the R & D programme on "Radioactive Waste Management and Storage" (indirect action 1975-1979) of the Commission of the European Communities, the Commission participates in various studies concerning the corrosion aspects of potential materials to be used in the conditioning, storage, and disposal of radioactive waste. The materials to be used for the containers, borehole casings, and repository linings must be to a high degree resistant to different corrosive media under a wide range of conditions concerning temperature, pressure, humidity, etc. and for long periods (500-1000 years). Special criteria are being established for the selection of materials and programmes to test corrosion behavior in laboratories, as well as *in situ*, are planned or already started.

[45] Haynes, G. S., Baboian, R., Comparative Study of the Corrosion Resistance of Cable Shielding Materials, Matls. Perform., 18(2), 45-56 (1979).

Data are given on the three year performance of Al, solid Cu, and copper clad stainless steel (Cu/430 stainless steel/Cu) at four sites with varying resistivities. Data are given also on six year results from a Rural Electrification Administration--National Bureau of Standards test program involving cable shielding materials with and without various dielectric coatings.

Effects of resistivity, pH, aeration, and dissolved salts are discussed. Data are presented on weight loss, perforations, and galvanic effects. In general, localized corrosion of aluminum occurred due to differential aeration, even when plastic coatings were applied. Copper corroded at predicted rates, but the copper clad stainless steel provided additional protection due to the stainless steel barrier mechanism.

[46] Hehemann, R. F., Troiano, A. R., AbuKhater, B., Ferrigno, S., Hydrogen Sulfide Stress Corrosion Cracking in Materials for Geothermal Power, Electrochem. Soc. Mtg., Las Vegas, NV, October 17, 1976, p. 34.

Studies to evaluate the performance of alloys used in geothermal power systems are reported. Alloys which are commercially available and those which have modified metallurgical structures and/or composition modifications were tested to determine the corrosive effects of the H_2S and thermal environments in geothermal fluids. Hydrogen embrittlement and sulfide stress corrosion cracking were tested. Test results showing the effects of alloy composition, tempering temperatures, fluid temperature, and salt content, and aging on sulfide stress cracking are tabulated.

[47] Henrikson, S., de Pourbaix, M., Corrosion Testing of Unalloyed Titanium in Simulated Disposal Environments for Reprocessed Nuclear Waste, Kaernbraenslesaekerhet, Rept. # STUDSVIK/El-79/83, p. 34 (1979). Stockholm, Sweden.

On the commission of the Nuclear Safety Project (KBS), corrosion tests have been carried out on unalloyed titanium, which is planned to be used as an outer corrosion resistant canister for reprocessed nuclear waste. Tests were conducted for 300 days in a corrosive medium of modified Baltic water at 100 and 130 °C with high (eight ppm) or low (< 10 ppb) oxygen content. The tests at low oxygen content and 100 °C were continued for 600 days. Very low oxidation rates (0.01-0.1 mu m/year) were obtained, corresponding to a lifetime of ten to hundred thousands of years for a six mm thick titanium canister. In spite of the considerably more severe corrosive conditions (higher temperature, higher chloride, and fluoride contents, as well as lower pH) compared with those estimated for the final disposal, no signs of localized corrosion were found, nor could any hydrogen pick-up be detected.

[48] Henriksson, S., Pettersson, K., Suitability of Titanium as a Corrosion Resistant Canister for Nuclear Waste, Kaernbraenslesaekerhet, p. 55 (1977). Stockholm, Sweden.

A literature study and inventory of experience has been carried out, aimed at assessing the possibilities of unalloyed and Pd-alloyed titanium withstanding corrosion for 1000-10000 years in contact with Baltic Sea water at 100 °C and pH 4-10. The following assessment can be made: (1) Pitting, crevice corrosion, stress corrosion cracking, and corrosion fatigue constitute no problem if the canister is made of unalloyed titanium corresponding to ASTM Grade 1; (2) linear extrapolation of reported corrosion rates for oxidation and general corrosion gives a life of between 1000 and 10000 years for a five mm thick canister; and (3) Hydrogen embrittlement resulting from hydrogen pick-up from the deposition environment should not occur. Delayed failure caused by a redistribution of the hydrogen initially present in the titanium can be avoided if its concentration is maximized to 20 ppm.

[49] Hoffman, T. L., Corrosion Monitoring of Storage Bins for Radioactive Calcines, Matls. Perform., 15(1) (1976).

Corrosion coupons exposed in aluminum and zirconium calcined radioactive waste from nuclear reactors using highly enriched /SUP 235/U have been withdrawn and average losses calculated. Calculated corrosion losses for 500 years are 4, 5, 20, and 35 mils for AISI types 304L, 304, and 405 and 1025 carbon steel, respectively, in aluminum calcinate and 5, 7, 40, and 50 mils, respectively, for the same materials in Zr calcinate. Revision of coupon withdrawal invervals to 10, 100, 250, and 450th year is contemplated. Types 304LC and 405 bins are underground in concrete vaults with provision for monitoring leakage from or into the bins and vaults.

[50] Hoffman, T. L., Corrosion Evaluation of Stainless Steels Exposed in ICPP High-Level Radioactive Waste Tanks, Corrosion/75, Toronto, Ont., April 14-18, 1975, p. 15.

Corrosion studies were conducted on welded stainless steel types 304L, 316, 316ELC, and 348 and unwelded type 304L in five different waste solutions from the reprocessing of nuclear fuels at the Idaho Chemical Processing Plant, ICPP. Corrosion rates were determined by evaluation of test specimens of the various stainless steels immersed in the actual waste tanks for periods of up to 19 years. As part of the over-all surveilance program on the ICPP Waste Tank Farm, the corrosion of some of these tanks has been monitored at five different times.

[51] Holzworth, M. L., Girdler, R. M., Costas, L. P., Rion, W. C., How to Prevent Stress-Corrosion Cracking of Radioactive Waste Storage Tanks, Matls. Protect., 7(1), 36-38, (1968).

Keywords: Carbon steel, corrosion, storage tanks, corrosion, stress corrosion cracking, stress relieving, radioactive waste, corrosion prevention.

[52] Johnson, A. B., Jr., Spent Fuel Storage Experience, Nucl Tech., 43(2), 165-73 (1979).

Irradiated nuclear fuel has been stored in water pools at essentially all nuclear reactors, beginning with the earliest plants in 1943. Fuel from water-cooled power reactors is clad either with Zircaloy or with stainless steel. Zircaloy-clad fuel has been stored in the US pools since 1959. Some experimental stainless-steel-clad fuel was stored for 12 years in the US before reprocessing. Canadian Zircaloy-clad fuel has been stored since 1962. There has been no evidence that the fuel has degraded during pool storage, based principally in visual observations and radiation monitoring of pool air and water. However, several fuel rods have been subjected to metallographic examination after pool exposures up to 11 years, also with no evidence that the fuel cladding has degraded in the pool. The favorable storage experience, demonstrated technology, successful handling of fuel with reactor-induced defects, benign storage environments, and corrosion-resistant materials offer sufficient bases to proceed with expanded storage capacities and extended fuel storage until questions regarding fuel reprocessing and final storage of nuclear wastes have been resolved. Some surveillance is justified to detect degradation if it becomes significant. Surveillance programs are already under way in several countries.

[53] Jorda, R. M., Ellis, R. C., State of the Art in Well Completion Technology as Applied to Geothermal Development. Preliminary Report, Including: Part I. Corrosion and Metal Problems. Part II. Scale Deposition and Control. Part III. General Production Interval Completion Techniques. Part IV. All-Liquid Heat Recovery System Model, Completion Technology Co., Houston, TX, p. 160 (1977).

The preliminary phase of a state of the art report concerning well completions for geopressured and geothermal energy source and injection wells is presented. The report covers corrosion and metal problems, scale deposition and control, general production interval completion techniques, and a model of an all-liquid heat recovery system. Both hot water geopressured source wells and water disposal (injection) wells are discussed in some detail. Areas for further development and study with regards to United States Gulf Coast geopressured well completions are identified.

[54] Kaernbraenslesaekerhet, Corrosion Resistance of Copper Canisters for Final Disposal of Spent Nuclear Fuel, p. 165 (1978. Stockholm, Sweden.

The Nuclear Fuel Safety Project (KBS) has proposed that spent non-processed nuclear fuel can be disposed of by enclosing in copper canisters with 200 mm thick walls. The canisters are to be placed in vertical drill-holes in rock 500 m below ground, and embedded in a buffer of compacted bentonite. The thermodynamic possibilities for various corrosion reactions on copper under prevailing conditions were studied, also with regard to bacterial influence. Oxygen entrapped in the buffer material at the closing of the storage was found to be the oxidant of major importance for the corrosion. Sulphide in the ground water was found to be another reactant of importance. The supply of oxygen and sulphide mainly by diffusion was calculated, and hence the greatest possible corrosion of copper.

[55] Kaernbraenslesaekerhet, Estimation of the Corrosion Resistance of Materials Intended for Enclosure of Nuclear Fuel Waste, P. 154 (1977). Stockholm, Sweden.

Within the KBS project, the Swedish Corrosion Institute has got the task to evaluate the corrosion resistance of different materials proposed to be used in canisters for nuclear waste. For this purpose, the Institute appointed a reference group of specialists, mainly within the fields of corrosion and material. KBS has proposed three different alternatives of canisters: (1) titanium lined with lead as a canister material for reprocessed and vitrified waste, (2) copper as a canister material for direct disposal of spent fuel, and (3) Alumina as a canister material for direct disposal of spent fuel. For further evaluations, the Institute point out the need of complementary investigations; e.g., on variations in ground water composition at a depth of 500 m, especially the content of oxygen, chloride, nitrite, sulfate, and organic matter.

[56] Kaernbraenslesaekerhet, Corrosion Resistance of Titanium Canisters Lined With Lead for Final Disposal of Reprocessed and Vitrified Waste From Nuclear Reactors, p. 80 (1978) Stockholm, Sweden.

The nuclear Fuel Safety Project (KBS) has proposed that reprocessed and vitrified waste from nuclear reactors would be disposed of by enclosure in titanium canisters with six mm thick walls and a 100 mm thick lead lining. The canisters are to be placed in vertical drill-holes in rock, 500 m below ground, and embedded in a buffer of 80-90 percent sand and 10-20 percent bentonite. On estimation of the life of the titanium sheath, a general corrosion rate of 0.25 mu/year has been taken as a conservative value, which would lead to a life of at least ten thousand years. Pitting and crevice corrosion have been considered very unlikely at the foreseen temperatures and salt contents. Further, the risk of delayed fracture, due to hydrogen up-take, is considered as small but cannot be completely excluded at the present state of knowledge. For this reason, the titanium sheath cannot absolutely be guaranteed an appreciable lifetime. If the titanium sheath were penetrated due to mechanical damage or localized corrosion, the exposed lead could suffer localized attack. The corrosion rate would then be determined by the supply of oxygen from the surrounding buffer to the canister surface. Conservative calculations have shown that perforation of the 100 mm thick lead lining would take about 4500 years. In any case, the life of the lead lining was estimated to at least a thousand years. In total, a titanium canister with a lead lining was estimated to have a life of at least a thousand years and probably tens of thousands of years. The expert group was unanimous in its judgement, with the exception of Prof. Goesta Wranglen, who has delivered a statement of his own.

[57] Kaernbraenslesaekerhet, Handling of Final Storage of Unreprocessed Spent Nuclear Fuel. 2. Technical, p. 325 (1978). Stockholm, Sweden.

In this report, the various facilities incorporated in the proposed handling chain for spent fuel from the power stations to the final repository are described. Thus, the geological conditions which are essential for a final repository are discussed, as well as the buffer and canister materials and how they contribute towards a long-term isolation of the spent fuel. Furthermore, one chapter deals with leaching of the deposited fuel in the event that the canister is penetrated, as well as the transport mechanisms which determine the migration of the radioactive substances through the buffer material. The dispersal processes in the geosphere and the biosphere are also described together with the transfer mechanisms to the ecological systems, as well as radiation doses. Finally, a summary is given of the safety analysis of the proposed method for the handling and final storage of the spent fuel.

[58] Kamrowski, J., Jakobs, J., Corrosion of Zn Coatings in Underground Conditions in Cu Mines, Ochr. Przed Koroz, 20(12), 310-12 (1977).

Keywords: Galvanized steels, corrosion, chlorides, environment underground corrosion, underground mining, inhibitors.

[59] Khanlarova, A. G., Aliev, Ch. A., The Corrosion Resistance of Aluminum Alloys in Stratal Water, Korroz. Zashch., 8 (1979).

Corrosion tests of 500 h duration of stressed (0.9 YS0.2) and unstressed welded specimens of various Al alloys were made in a stratal water of pH 5.4-6.3 contg. C- 0.096, S024- 0.0011, HC0-3 0.0018, Ca2+ 0.007, Mg2+ 0.007, and Na+l K+ 0.085 g. equiv. /100 g, with and without H2S 500 g/l. The alloys included 1911 Zn 4.5, Mg 1.4, Mn 0.3, Zr 0.2. 1915 .3.5:2.0 Zn-Mg, D16T .Cu 3.8-4.9, Mn 0.3-0.9, Mg 1.2-1.8, and AMg3, AMg5, and AMg6 .contg. Mg3, 5, and 6 percent resp... The Al-Mg alloys, stressed or unstressed, were the most corrosion resistant to H2Scontg. stratal water. The AlZnMg alloys were subject to significant corrosion and their use in these environments is not recommended. The use of D16T alloy in oil industry equipment should be limited because of a tendency to conceal subsurface corrosion.

[60] King, F. D., Baker, W. H., Interim Storage of Spent Fuel Assemblies, Intl. Symp. on Mgmt. of Waste From the LWR Fuel Cycle, Denver, CO, July 11, 1976.

Spent fuel discharged from light water reactors (LWR) is cooled at the reactor sites for at least five months to allow shortlived radioactive isotopes to decay. Recently, spent fuel has been considered as a possible waste form suitable for

interim storage or even ultimate disposal. Several alternatives have been demonstrated or proposed for retrievable storage of spent fuel for periods of up to 100 years. These include storage in watercooled basins, aircooled vaults, concrete surface silos, geologic formations, or nearsurface heat sinks. Watercooled sotrage of spent fuel in nearsurface cells of heavily reinforced concrete lined with stainless steel has been proven by about 30 years of operating experience at reactor sites and fuel reprocessing plants. Nearsurface storage with forceddraft air cooling of HTGR (High Temperature Gas Reactor) fuels is being used by INEL (Idaho National Engineering Laboratory) and is feasible for unpackaged LWR fuel that has been out of the reactor at least three to four years. Natural-draft cooling of spent fuel has also been proposed, and demonstration programs are in progress for CANDU (Canadian Deuterium Uranium) fuel. Spent fuel assemblies are sealed in thick lowcarbon steel containers and placed in large cylindrical concrete housings (silos) located outdoors. The cooling is completely passive, requiring little maintenance and only minimal surveillance. Recent studies comparing the economics of interim storage of spent fuel (throwaway fuel cycle) with prompt chemical reprocessing conclude that disposal as fuel decreases the Nation's natural resources significantly and is not cost justified if both plutonium and uranium are recycled in the nuclear fuel cycle.

[61] Kobayashi, K., Corrosion-Resistant Composite Material for Radioactive Waste Disposal, Japan, Kokai Tokyo Koho, 79, 112,927, September 1979.

A composite material consists of an amorphous alloy and hydraulic cement compounds and is resistant to corrosion, leaching or cracking.

[62] Kopczynski, C., Corrosion of Cu, Al, and Zn in Subsoil Waters of the "Machow" S Mine, Ochrona Przed Korozka, 15(10), 270-72 (1972).

Keywords: Copper base alloys, corrosion, aluminum base alloys, zinc base alloys, tanks.

[63] Koplik, C. M., Oston, S. G., Pentz, D. L., Talbot, R., Information Base for Waste Repository Design. Vol. 3. Waste/Rock Interactions, Rpt. No. TASC-TR-1210-1-Vol-3, p. 137 (1979). Analytic Sciences Corp. Reading, MA.

This report is Volume 3 of a seven volume document on nuclear waste repository design issues. This report describes the important effects resulting from interaction between radioactive waste and the rock in a nuclear waste repository. The state-of-the-art in predicting waste/rock interactions is summarized. Where possible, independent numerical calculations have been performed. Recommendations are made pointing out areas which require additional research.

[64] Krysko, W. W., Lead as a Material for Atomic Waste Containers. Analysis of the Corrosion Behavior Based on Archaeological Finds, Metall., 34(5), 433-36 (1980). Germany

From archaeological finds, it has been observed that grain size and shape is the factor governing the corrosion durability of lead. For long-term corrosion stability, the grain size should not exceed 0.5 mm grain diameter. On the basis of an investigation of 2000 year old Pb artifacts, conclusions are drawn, and manufacturing conditions for Pb containers for the burial of high-level atomic waste are recommended.

[65] Landry, B., Curry, D. M., Cox, J. E., Disposal of Thermal/ Radioactive Wastes in Permafrost Ground Areas, Paper No. 73-WA/HT-8, ASTM Mtg., November 11-15, 1973, p. 12.

Thermal wastes, either hot fluids or radioactive materials, present a disposal problem in permafrost areas due to the delicate thermal balance in the environment. A numerical technique is developed to simulate the heat transfer characteristics for two aspects of the underground disposal problem: (a) hot fluid injection down a wellbore into a porous reservoir; and (b) storage of a radioactive heat source. Temperature fields and permafrost melting-front locations are presented graphically. Parametric studies include the effects of variable thermal properties, depth of disposal region, etc.

[66] Leidheiser, H., Jr., Corrosion of Copper, Tin, and Their Alloys, John Wiley & Sons., Inc., NY, 1971, p. 411.

Keywords: copper base alloys, tin base alloys, underground corrosion, stress corrosion cracking.

[67] Lovachev, V. A., Criteria for the Protection of Trunk Pipelines Laid in Saline Soils, Tr. Vses. Nauchno-Issled. Inst. Stroit. Magistral'n. Truboprovod., 41, 40-56 (1977).

Abstracted from Russian Ref. Zh.; R.-Z. (Kor.) 81OK213. Experimental data from a study of the effectiveness of cathodic protection of underground trunk pipelines in saline soils established that the corrosion rate of pipeline steel could reach 0.6 mm/year and the pit depth, 2.4 mm/year. Parallel specimens in approximately the same conditions could have corrosion rates differing by an order from these values and similar effects obtained for specimens at the same cathodic protection potential. The maximum danger of corrosion was at defects in the coatings on the lowest one-third of the pipe. Temporary disconnection of cathodic polarization, or even a reduction in the potential value, could increase the corrosion rate. It is concluded that the potential of -0.9 V ($Cu/CuSO_4$ electrode) guaranteed protection in soils only in certain cases and that, for maximum reliability, a value of -1.0 V should be used.

[68] McCawley, F. X., Corrosion of Materials and Scaling in Low-Salinity East Mesa Geothermal Brines, Rpt. No. BUMINES-RI-8504, Bureau of Mines, p. 24 (1980).

The Bureau of Mines, in pursuing its goal of extending the life span of strategic materials, conducted field corrosion studies at the East Mesa Known Geothermal Resources Area (KGRA) in the Imperial Valley, CA, to determine the optimum materials of construction for use in geothermal mineral energy resource recovery plants. These studies included characterization of geothermal environments and in-situ corrosion testing. The corrosion resistance of ten alloys exposed to five brine and steam process environments was evaluated using the low-salinity, high-temperature brine from geothermal well Mesa 6-1.

[69] McCright, R. D., Corrosion Behavior of Materials Exposed to Hypersaline Geothermal Brine, The Intl. Corrosion Forum Sponsored by the National Association of Corrosion Engineers, April 1981, Toronto, Canada.

The corrosion rate and corrosion attack characteristics were determined for thirteen commercially available materials exposed in a geothermal production well for three months. The materials included carbon steels, CrMo alloy steels, martensitic and ferritic stainless steels, highnickel alloys, and titanium. The environment at the 1800 ft. (600 m) depth of exposure was a single phase high salinity brine. The prevailing temperature was 260 C and the prevailing pressure was 630 psi (4.0 MPa) during the exposure period. Results indicated that the carbon steels suffered intense generalized and localized corrosion. Addition of Cr and Mo to steels imparted significant improvement in the corrosion performance in this aggressive environment. Of the stainless steels tested, the most resistant were those containing a few per cent molybdenum.

[70] Mack, J. E., Lackey, W. J., Angelini, P., McCoy, H. E., Jr., Corrosion Testing of Candidate Canister Materials With Alternative Waste Forms, Trans. Ann. Conf., Can. Nucl. Soc., 1, 60-1 (1980).

The program of corrosion testing of metal alloy canisters to determine their compatibility with immobilized radioactive waste forms during geological storage is discussed.

[71] Magnani, N. J., Braithwaite, J. W., Corrosion Resistant Metallic Canisters for Nuclear Waste Isolation, Sci. Basis Nucl. Waste Mgmt., 2, 377-84 (1980).

Studies were made to assess the ability of a canister alloy to survive > 300 years in a repository environment. TiCode-12 and stainless steel 304 were tested in deoxygenated brines and seawater at 250-300 °. The 304 stainless steel was susceptible to localized corrosion and stress corrosion cracking in Cl-plus water-containing environments. TiCode-12 was corrosion-resistant in bedded salt and sealed environments. No pitting or crevice corrosion was observed at ≤ 300 °. Uniform corrosion rates were 1-10 μm/yr.

[72] Mattson, E., McCarthy, G. J., Corrosion Resistance of Canisters for Final Disposal of Spent Nuclear Fuel. Scientific Basis for Nuclear Waste Management, Ann. Mtg. Matls. Rsch. Soc., Boston, MA, 1978, p. 271-81.

A group of Swedish scientists have evaluated, from the corrosion point of view, three alternative canister types for final disposal of waste from nuclear reactors in boreholes in rock 500 m below ground. Titanium canisters with a wall-thickness of six mm and 100 mm thick lead lining have been estimated to have a life of at least thousands of years, and probably tens of thousands of years. Copper canisters with 200 mm thick walls would last for hundreds of thousands of years. The third type, *alpha*-alumina sintered under isostatic pressure, is a very promising canister material.

[73] Mattsson, E., Localized Corrosion, Br Corros. J., 1978, 13 (1), 512.

Keywords: Steels, corrosion, aluminum base alloys, copper, corrosion pitting, underground corrosion, corrosion prevention.

[74] Mecham, W. J., Seefeldt, W. B. Steindler, M. J., An Analysis of Factors Influencing the Reliability of Retrievable Storage Canisters for Containment of Solid High-Level Radioactive Waste, ANL, 76-82, August 1976.

[75] Merz, M. D., Zima, G. E., Jones, R. H., Westerman, R. E., Materials Characterization Center Workshop on Corrosion of Engineered Barriers, p. 72 (1981). Battelle Pacific NW Laboratory, Richland, WA.

A workshop on corrosion test procedures for materials to be used as barriers in nuclear waste repositories was conducted August 19 and 20, 1980, at the Battelle Seattle Research Center. The purpose of the meeting was to obtain guidance for the Materials Characterization Center in preparing test procedures to be approved by the Materials Review Board. The workshop identified test procedures that address failure modes of uniform corrosion, pitting and crevice corrosion, stress corrosion, and hydrogen effects that can cause delayed failures. The principal areas that will require further consideration beyond current engineering practices, involve the analyses of pitting, crevice corrosion, and stress corrosion, especially with respect to quantitative predictions of the lifetime of barriers. Special techniques involving accelerated corrosion testing for uniform attack will require development.

[76] Miller, R. L., Results of Short-Term Corrosion Evaluation Tests at Raft River, p. 95 (1977).

Four categories of short-term materials evaluation tests were conducted in geothermal fluid from Raft River Geothermal

Experiment, Well No. 1, to obtain corrosion data relevant to the design of the Raft River Thermal Loop Facility. Test programs are described and the testing philosophies are discussed. All materials and configurations which were tested are identified and details of post-test visual examinations are presented. The materials are then assigned to appropriate performance categories on the basis of test behavior, and the possible service limitations are appraised.

[77] Molecke, M. A., Gas Generation From Transuranic Waste Degradation, Symp. Sci. Basic Nucl. Waste Mgmt., Boston, MA, November 26, 1979, p. 9.

Based on experimental data, the relative quantities of gas generated by individual mechanism for existing forms of TRU-contaminated wastes under expected WIPP environmental conditions are ranked in order as: (1) BACTERIAL (greatest potential, but large variability); (2) THERMAL (at 40 °C, probably insignificant at 25 °C);
(3) RADIOLYSIS (most predictable, potential short-term risks);
(4) CORROSION (under the dry conditions expected in WIPP); and
(5) ALPHA DECAY (insignificant). Results indicate that waste processing to minimize such gas generation is not technically required.

[78] Molecke, M. A., Degradation of Transuranic-Contaminated Wastes under Geologic Isolation Conditions, Rept. No. CONF8006112, Intl. Symp. on the Management of Alphacontaminated Wastes, Vienna, Austria, June 1980.

An extensive experimental study of the degradation of existing forms of defenserelated, transuraniccontaminated (TRU) wastes is being conducted by and for Sandia Labs. Studies have been performed under environmental conditions expected for deep geologic isolation in the Waste Isolation Pilot Plant (WIPP), a beddedsalt TRU waste repository planned for southeastern New Mexico. A primary purpose of this program has been to support the US Dept. of Energy in establishing waste acceptance criteria for TRU wastes for isolation in the WIPP. TRU waste forms investigated include cellulosics (paper, rags, wood), plastics, rubbers, mixed organic composite, bitumen, a developmental concreteTRU ash matrix, mild steel, and inorganic process sludges. This review includes laboratory and field results for waste degradation under a range of conditions, resultant gas generation rates, gas compositions, corrosion rates, and microbial formation and degradation of chelating agents.

[79] Molecke, M. A., Abrego, L., Status of Sandia HLW Canister/Overpack Program Studies, SAND802191C. Presented at 1980 NWTS Annual Infor. Mtg., Columbus, OH, December 1980.

[80] Nathan, J. B., Jr., Evaluation of Materials for Underground Exposure in Extreme Environments, SAMPE Tech. Conf. & Exhibit, Palo Alto, CA, October 17-19, 1972, p. 37-48.

Results of an investigation are reported which was carried out to define those materials most suitable for fabricating containers protecting electronic hardware that can withstand long-term burial in all geographic locations. The investigation was conducted in the four phases. Two-year underground exposure testing in Minnesota and North Carolina substantiated laboratory selections of 316 stainless steel, Sn63 or 55/45 Bi-Pb solder, flexible sealants, and a bituminous epoxy coating.

[81] Needham, P. B., Jr., Cramer, S. D., Carter, J. P., McCawley, F. X., Corrosion Studies in High-Temperature, Hypersaline Geothermal Brines, Paper No. 59, Corrosion/79, NACE, Houston, TX.

Results for laboratory corrosion studies of 23 metals and alloys in high-temperature, high-pressure hypersaline brines are reported. These include the effects of O_2, CH_4, and CO_2 additions to the brines on general, crevice, pitting, and weld corrosion, and stress-corrosion cracking. The results of in-situ corrosion tests at a geothermal well are reported.

[82] Neretnieks, T., Transport of Oxidants and Radionuclides Through a Clay Barrier, Kaernbraenslesaekerhet, p. 31 (1978). Stockholm, Sweden.

The mass transfer rate for oxidants to, and radionuclides from, a capsule in a repository has been computed. The capsule which is 0.75 m in diameter is surrounded by Montmorillonite clay. The hole is 1.5 m in diameter. For one capsule about 1220 g, copper will corrode due to oxygen corrosion in 10,000 years. If the fissures in the rock nearest the hole are filled with clay, the corrosion will decrease significantly. This is valid for a case where the ground water is in equilibrium with oxygen of 0.2 bar pressure (normal air pressure). Measurements of the oxygen content in ground water at large depths show a more than 1000 times smaller values. The transport rate will then be correspondingly smaller. Corrosion due to sulfate/sulfide corrosion may reach some 590 g in the same time if there is ten mg/l of the least abundant component. The radionuclides Sr^{90}, Cs^{137}, Am^{241}, and Am^{243} will decay totally in the clay barriers. Pu^{240} will be seriously hindered. The total dissolution of the uranium oxide in a capsule takes at least 1.8 million years. Nuclides with high solubilities decrease in about 2000 years to half their original concentration. The sodium in the Montmorillonite clay in the fissures is exchanged for calcium in about 20,000 years. The exchange of the sodium in the clay in the hole takes millions of years.

[83] Neretnieks, I., Note on the Consequence of Hydrogen Production in the Repository. Some notes in connection with the KBS Studies of Final Disposal of Spent Fuel, Sept. 1978, p. 1619. KBS Rept. # TR120.

Hydrogen may be produced in the copper capsule by zircalloy-corrosion and by radiolysis. Hydrogen diffuses slowly in compacted bentonite. If the production of hydrogen is fast it will not have time to escape by diffusion at the same rate at which it is produced. A gas bubble may form. In the present work, it is concluded that no grave consequences are expected if escaping hydrogen opens a channel in the clay and in the rock.

[84] Nomi, M., Transportation and Disposal of Radioactive Wastes, FAPIG, 80, 31-37 (1976). Japan.

The fuel for CANDU reactors in Canada is natural uranium. It is burnt up to about 7500 MWD/T in heavy water reactors, then it is technologically stored for about 100 years. After that, it is disposed or reprocessed. Zircaloy clads will endure corrosion in water or in air for about 100 years, and effective disposal means will be found within 100 years. The fuel for light water reactors is enriched uranium, and reprocessing must be carried out. When mixed FP waste liquid can be directly disposed into underground structure, it is solidified and stored intermediately, then it is disposed. The separation of transuranic elements and extinction treatment cannot be forecase at present, but they are the promising final disposal for future. For solidifying high-level wastes, calcination and vitrification are conceivable. France adopts vitrification and storage, while in the USA, high-level wastes are calcined and contained in canisters. Technological storage must be adopted for the time being until the method of final disposal and the mode of solidification will be established. The planning and investigation of retrievable surface storage facility are in progress, and the facility is classified into water basin concept, air-cooled concrete vault concept, and sealed storage cask concept. National Academy of Sciences, USA, has made recommendations on the storing method.

[85] Paige, B. E., Siedenstrang, F. A., Niccum, M. R., Evaluation of Hazards and Corrosion of Buried Waste Lines in NRTS (Nuclear Reactor Testing Station) Soils, Report 1972, ICP-1013, p. 247. Allied Chem. Corp., Idaho Falls, Idaho.

The corrosion of carbon steel, cast iron, and stainless steel is compared for different types of NRTS soil. Detection of leaks at the ground surface and infiltration of liquid from corrosion-type leaks are described. Encasements, which protect highly radioactive waste lines from external corrosion and provide monitoring capabilities, are discussed. Cathodic protection and existing systems and means of upgrading them are described.

[86] Parsons, Brinckerhoff, Quade, and Douglas, Inc., Savannah River Plant Bedrock Waste Storage Project--Status Report, Deep Shaft Studies, p. 71 (1972).

A study is being made to determine problems and evaluate solutions for the construction of deep shafts passing through a major public water supply aquifer and designed to support the 1000 year positive containment of radioactive wastes 2000 ft. underground. It is shown that safety and ventilation requirements dictate two shafts connected at storage level, the first or pilot shaft to have an I.D. of 12 ft., the second (for tunnel excavation) to have an I.D. of 16 ft. The longevity requirement and site conditions dictate that only natural materials (wood and bitumen) and basic manufactured materials (stainless steel and concrete) be used on the project. Seismic effects are shown to be negligible. The requirement for 1000 years of waste isolation with possibly unattended conditions dictates a watertight shaft sealed internally from the storage tunnel complex and constructed in such a manner that no potential external flow paths are created. Protection of the public water supply aquifer dictates external sealing rings, one immediately below the equifer, another a short distance above the tunnels leading to the storage zones, to prevent any upward fluid migration. Provision must be made for any long-term differential movement between soil and shaft. A presently preferred solution is outlined.

[87] Pitman, S. G., Griggs, B., Elmore, R. P., Evaluation of Metallic Materials for Use in Engineering Barrier Systems, Ann. Mtg. Matls. Rsch. Soc., Boston, MA, November 17, 1980, p. 8.

Conclusions of this work are as follows: Inconel, Incoloy, Hastelloy C-276, and titanium alloys all had excellent corrosion resistance in all postulated repository environments tested. Further work will be required to evaluate the pertinent enviro-mechanical properties of these materials; the mechanical properties of Grade 2 titanium are better than those of Grade 12 titanium, except the tensile and yield strengths. These properties include fatigue-crack-growth rate, environmental fatigue-crack-growth rate, fracture toughness, impact toughness, and dynamic fracture toughness; there is no evidence in the current data to indicate that the simulated repository environment is aggressive to Grade 2 or Grade 12 titanium. This includes data from corrosion-fatigue, crevice corrosion, wedge-loaded cracked specimens, and residual-stress specimens.

[88] Posey, F. A., Palko, A. A., Bacarella, A. L., Corrosivity of Geothermal Brines. Progress Report for Period Ending September 1977. Final Report, p. 53 (1978). Oak Ridge National Lab., TN.

Results of studies carried out principally during FY-76 and FY-77 on the corrosion of ferrous materials in synthetic geothermal brines are summarized. A survey of prior work on electrochemical aspects of the corrosion of iron and carbon steel in chloride solutions is presented, and some of the

results of these investigations are summarized. The principal results of the present studies are then recapitulated. Included are measurements of the corrosion potential, corrosion rate, and polarization behavior of iron and carbon steel in deaerated four M NaCl over the pH range from one to 11 at temperatures up to 100 °C in a conventional Pyrex electrochemical cell. The effect of pH on hydrolysis, precipitation, and electrochemical reactivity of ferrous and ferric ions in four M NaCl at 25 °C is presented, and implications for plant operation are discussed. Details of a refreshed, stirred titanium autoclave system are described; the system permits electrochemical measurements to be made up to at least 200 exp 0 in corrosive aqueous saline media. The effect of pH (from pH equals seven to pH equals two) and temperature from 25 °C to 200 °C on the corrosion rate of type A212B carbon steel in deaerated four M NaCl is described. A relatively simple numerical correlation describes the data over the entire temperature and pH range. The spontaneous corrosion potentials and pitting potentials of types 304 and 316 stainless steel were measured in deaerated four M NaCl at pH equals five from 25 °C to 200 °C, and the data demonstrate the borderline stability of austenitic stainless steel for brine service. Finally, conclusions and recommendations for further studies are presented.

[89] Rankin, W. N., Canister Compatibility with Carlsbad Salt, Sci. Basis Nucl. Waste Mgmt., 2, 395-402 (1980).

Corrosion by solid NaCl from the Carlsbad (New Mexico) deposit was studied for the following canister steel: (a) Cor-Ten A oxidation-resistant grade, (b) low-C steel grade 70 of ASTM A-516, and (c) AISI 304L stainless steel. No reaction by contact was found at $\leq$ 5000 h for sealed capsules and at $\leq$ 10,000 h for open capsules, at 80 or 225 °C. After 5000 h, at 600 °C, the low-C steel showed attack 20 mils deep. The canister steels are evaluated for storage of solidified radioactive waste in the salt bed.

[90] Rankin, W. N., Compatibility Testing of Vitrified Waste Forms.

This paper describes an experimental program to evaluate candidate metals for use in the fabrication of canisters for long-term storage of vitrified radioactive wastes. The long-term compatibility of the candidate metal, both with the contained vitrified radioactive waste and with the external environments expected in possible final storage locations, will be determined. Three canister materials were chosen for testing, based on their oxidation resistance and cost: Cor-Ten A, Type 304L stainless steel, and Inconel 600.

[91] Rennerfelt, J., Composition of Ground Water in Deep Layers of Bedrock, Kaernbraenslesaekerhet, p. 23 (1977). Stockholm, Sweden.

The effect of different types of dissolved solids in ground water on corrosion and leaching is discussed. A suitable composition of water for leaching tests is indicated. The technique for sampling of water in bedrock at large depths is discussed. Water analyses from different investigations are presented and a probable interval of water composition, as well as some maximum values, are given. Very low oxygen concentrations, relatively high Fe exp 2+ concentrations, and low levels of organic substance can be expected. Leaching of bentonite can increase the concentration of organic substance.

[92] Romanoff, M., National Bureau of Standards Circular 579, 1957, p. 227, NITS PB168350 1LLC.

The Circular is a report on the studies of underground corrosion conducted by NBS from 1910 to 1955. Up to 1922, the studies were confined to corrosion due to stray-current electrolysis and its mitigation. After it became apparent that serious corrosion occured in soils under conditions that precluded stray-currents as an explanation, a field burial program was initiated, in order to obtain information pertaining to the effect of soil properties on the corrosion of metals. More than 36,500 specimens, representing 333 varieties of ferrous, nonferrous, and protective coating materials, were exposed in 128 test locations throughout the US. During this time, the electrical and electrochemical aspects of underground corrosion have been continuously studied in the laboratory. Results from both field and laboratory investigations are presented.

[93] Romben, L., Tuutti, K., Final Storage in Concrete of Activated Metal Parts, Kaernbraenslesaekerhet, p. 42 (1978). Stockholm, Sweden.

A part of the medium-level nuclear waste problem is the disposal of metal parts which have been activated during use in nuclear reactors. Some alloys contain Ni-59 with a half-life or 75,000 years. A proposed method for final disposal consists in storing the waste in rock tunnels at a depth of 300-500 m inside containers which are surrounded by a buffer consisting of compacted quartz-bentonite mixture. This paper deals with the possibilities to use containers made of concrete and designed as cubic boxes enclosing the waste material cast and incorporated into cement mortar matrix. Special regard is given to the containment problem in relation to the mechanical and chemical processes that are operating. A calculation of the rate of release of Ni^{59} through the walls of a container has given a figure of about ten^{-5} kg Ni per year for undeteriorated container walls. In six appendices, the sizes of different quantities describing the mechanical and chemical processes which are operating in this containment problem are given.

[94] Sanderson, B. T., Romanoff, M., Performance of Commercially Pure Titanium in Soils, Proc. 25th Conf. Ntl. Assoc. Corr. Eng., Houston, TX, March 10-14, 1969, pp. 2-5.

This paper reports the corrosion behavior of specimens of commercially pure titanium tubes with welded seams after exposure underground for eight years. Excellent corrosion resistance shown by specimens in different atmospheric environments, sea water and underground is attributed to the formation and maintenance of a stable and passive oxide film over the surface. All details of soil test corrosion test are tabulated.

[95] Sandia Ntl. Labs., State of the Art in Well Completion Technology As Applied to Geothermal Development, Prelim. Rpt., Part I. Corrosion and Metal Problems. Part II. Scale Deposition and Control. Part III. General Production Interval Completion Techniques. Part IV. All-Liquid Heat Recovery System Model, SAND-78-7008, p. 160 (1977).

[96] Sandia Ntl. Labs., Corrosion of Some Pure Metals in Basaltic Lava and Simulated Magmatic Gas at 1150 exp 0 C, p. 77 (1979). Sand791981.

[97] Schulz, W. W., Kupfer, M. J., Solidification and Storage of Hanford's HighLevel Radioactive Liquid Wastes, Natl. Mtg. of the Amer. Chem. Soc., 31 Mar. 1974, Los Angeles, CA.

When the present Hanford waste management program is completed in 1980. Approximately 140 million liters of solid salt cake, produced by evaporation of aged radioactive liquid waste will be stored in underground mild steel tanks. Additionally, megacuries of Sr^{90} and Cs^{137} will have been removed from Hanford waste solutions, converted to solid $Sr^{90}F_2$ and $Cs^{137}Cl$, and stored underwater in doubly encapsulated metallic containers. Several alternative modes for longterm storage/disposal of these highlevel wastes are presently being evaluated. For some of these modes conversion of the solids to immobile silicates of low water solubility may be desirable. Laboratory-scale studies of both low and high temperature processes for preparation of silicate minerals and glasses are in progress; status of the work is reviewed.

[98] Schutz, R. W., Covington, L. C., Titanium Applications in the Energy Industry, Pamphlet, Metallurgical Soc., AIME (1981).

Because of its freedom from corrosion in a wide range of aggressive environments, Ti is a leading candidate for the material of construction in many of the new processes being developed in the energy industry. Its use has cut maintenance and downtime costs in many plants and, in some cases, has made new processes practical that were previously limited by availability of suitable corrosion resistant materials. A few examples discussed are its use in heat exchangers for prototype OTEC units, geothermal brine testing, pressure vessels and piping for ocean mining processes, applications as condenser tubing in sea water-cooled surface condensers, as pressure vessels in hydrometallurgical mining processes, and utilization in nuclear waste disposal canisters.

[99] Science Applications, Inc., Technical Support for GEIS: Radioactive Waste Isolation in Geologic Formations. Vol. 22. Nuclear Considerations for Repository Design, p. 203 (1978). Oak Ridge, TN.

This volume is one of a 23 volume series which supplements the "Contribution to Draft Generic Environmental Impact Statement on Commercial Waste Management: Radioactive Waste Isolation in Geologic Formations", Y/OWI/TM-44. The series provides a more complete technical basis for the preconceptual designs, resource requirements, and environmental source terms associated with isolating commercial LWR wastes in underground repositories in salt, granite, shale, and basalt. Wastes are considered from three fuel cycles: uranium and plutonium recycling, no recycling of spent fuel, and uranium-only recycling. Included in this volume are baseline design considerations such as characteristics of canisters, drums, casks, overpacks, and shipping containers; maximum allowable and actual decay-heat levels; and canister radiation levels. Other topics include safeguard and protection considerations; occupational radiation exposure, including ALARA programs; shielding of canisters, transporters, and forklift trucks; monitoring considerations; mine water treatment; canister integrity; and criticality calculations.

[100] Scott, T. A., Issues Relevant to Nuclear Waste Canister Materials, Corrosion/80, NACE Mtg., Chicago, IL, March 6, 1980, p. 38.

This paper focuses on the canister as a component of multibarrier systems for the containment and isolation of high-level radioactive wastes and spent fuel from nuclear reactor burning. It provides perspective for the role of canisters in the overall nuclear fuel cycle with special emphasis on the multibarrier concept of waste isolation. Attention is given to the chemical composition of wastes, waste forms, interim storage environments, and geologic isolation repository environments; these will all have to be considered in canister materials selection. In addition, other factors, such as mechanical loads, radiation effects, and radioactive decay-heat generation rates, are cited. The paper culminates with a summary of the author's opinion of the technical issues which need to be resolved before the canisters can be considered viable components of a multibarrier system for geologic waste isolation.

[101] Shannon, D. W., The Role of Chemical Components in Geothermal Brines on Corrosion, Paper No. 57, Corrosion/78, NACE, Houston, TX, March 6-10, 1978.

[102] Shannon, D. W., Morrey, J. R., Smith, R. P., Use of a Chemical Equilibrium Code to Analyze Scale Formation and Corrosion in Geothermal Brines, Proc. Intl. Symp. Oilfield and Geothermal Chemistry, June 27-29, 1977, p. 21.

[103] Shannon, D. W., Corrosion of Iron-Base Alloys Versus Alternate Materials in Geothermal Brines, Interim Report--Period Ending October 1977, p. 37 (1977).

A series of 30 refreshed autoclave tests and one field test were performed to define how various chemical components in geothermal brines affect uniform corrosion of 35 materials. The data indicate uniform corrosion rates of carbon steels will be satisfactory for most major components of a geothermal power plant for low salinity, neutral to alkaline pH reservoirs, when 20 mpy (mils per year) corrosion allowances are permitted. Corrosion rates of carbon steels probably will be excessive under the following conditions: carbon dioxide saturated, low pH (less than pH six) brines at ambient to 100 exp 0 C temperature, and CO_2 saturated steam condensate system; applications near 250 exp 0 C and above in salinities above five to ten percent; thin sections, such as heat exchanger tubes (may fail by pitting); or applications where any oxygen may be present, such as steam condenser and waste injection systems. While some minor alloy effects were observed among the ten carbon steels tested, the alloy composition of the carbon steel was a second order effect compared with important brine chemistry variables, such as pH, salinity, and temperature. Acidification of East Mesa geothermal brine to pH 4.8 increased carbon steel corrosion three to four times in agreement with lab tests. The corrosion rates of carbon steels were found to be largely controlled by the composition and structure of the corrosion product film that formed on the metal. A number of alloys were found in the screening tests that showed negligible corrosion under all conditions tested up to 250 exp 0 C and 22 percent salinities. Alternate materials to carbon steels include: high chromium alloys above 23 percent Cr, including E-Brite 26-1, 446, 29 Cr-4 Mo, 29 Cr-4 Mo-2 Ni, 26 Cr-1 Mo-1 Ti, Al 6X; nickel alloys Hastelloy C276, Inconel 625, Incoloy 825; four titanium alloys; and zirconium.

[104] Slansky, C. M., Radioactive Waste Management, Chem. Tech., 160-64 Mar (1975).

High-level radioactive waste is produced at Idaho Chemical Processing Plant (ICPP) during the recovery of spent highly enriched nuclear fuels. Liquid waste is stored safety in doubly contained tanks made of steel. The liquid waste is calcined to a solid and stored safely in a retrievable form in doubly contained underground bins. The calcine can be treated further or left untreated in anticipation of ultimate storage. Fluidized bed calcination has been applied to many kinds of high-level waste. The environmental impact of high-level waste management at the ICPP has been negligible and should continue to be negligible.

[105] Slansky, C. M., Review of Materials of Construction in Nuclear Fuel Reprocessing and in Radioactive Waste Treatment, Paper No. 78, Corrosion/77, NACE, Houston, TX, March 14-18, 1977, p. 78.

This paper presents a brief description of the development of fuel reprocessing and waste management with reference to the choice of metals and alloys used in the construction of the various plants. Recovery processes in use employ equeous technology, i.e., the fuels are dissolved in mineral acids and the uranium and plutonium separated from each other and from fission products by a solvent extraction separation process using tributyl phosphate (TBP) as a selective solvent. The Purex process is used to recover irradiated LWR fuel and utilizes 30 percent TBP.

[106] Slansky, C. M., Review of Corrosion and Materials Selection in Radioactive Waste Handling, Rev. Coat. Corr., 3(2-3), 79-103 (1979).

Materials of construction are reviewed for the handling of radioactive waste. Topics covered include corrosion and materials selection in the storage of acidic and neutralized high-level liquid waste and the storage of intermediate-level liquid waste; in the transport of liquid waste at the spent fuel processing plant and of all waste by air, rail, and truck; in the treatment of waste by evaporation, digestion, ion exchange, calcination, and pyrometallurgy; in the storage of solid calcined waste, transuranic waste and miscellaneous wastes; and a commentary on materials for the storage of waste in geologic formations (Ni-base superalloys and stainless steels).

[107] Slate, S. C., Maness, R. F., Corrosion Experience in Nuclear Waste Processing at Battelle-Northwest, Paper No. 81, Corrosion/77, NACE, Houston, TX, March 14-18, 1977, p. 81.

Most of the canister corrosion work has been conducted in support of the In-Can Melter (ICM) vitrification system. The corrosion effects of the melt, furnace atmosphere, and water basin on stainless steel canisters are insignificant or can be controlled. Corrosion due to the melt or its vapor is not significant for most of the examined materials. Protection methods will be needed to protect the canister from oxidation, such as using an inert cover gas or surface coatings. Stress corrosion cracking can be prevented in 304L canisters by maintaining the chloride content of the water below one ppm chloride and the pH in the range of nine to 12 by adding ammonia.

[108] Smyrl, W. H., Stephenson, L. L., Braithwaite, J. W., Behavior of Candidate Canister Materials in Deep Ocean Environments, Paper No. 85, Corrosion/77, NACE, Houston, TX, March 14-18, 1977, p. 85.

This paper described preliminary results of tests undertaken to evaluate the compatibility of radioactive waste storage canister materials with the external environments of ocean water and sediments. Bottom ocean water from the North Pacific and sediments with supernatant sea water from the Atlantic

were used. The materials tested were base alloys of titanium, zirconium, and nickel. All showed corrosion rates that were very low, even at the highest test temperatures.

[109] Sokol, J., Cooper, M., Radioactive Waste Management--the Need for Multiple Barriers, Proc. 15th DoE Nucl. Air Clean Conf., Boston, MA, August 7-10, 1978, pp. 998-1004.

Isolation criteria for the disposal of high-level radioactive waste are critically examined. The results indicate that the essential period for isolation of high-level waste is about 1000 years. Multiple barriers, such as a solidified, leach-resistant waste form, a corrosion-resistant outer container, and a stable geological formation, which limit the transport of radioactivity into the human food chain are recommended. The multiplicity of barriers allows for the unlikely event of failure in one or two of the barriers while still providing adequate isolation of the waste.

[110] Syrett, B. C., MacDonald, D. D., Shih, H., Wing, S. S., Corrosion Chemistry of Geothermal Brines, Ntl. Sci. Found., Grant No. AER 76-00713, pp. 16-18 (1977). Washington, D. C.

[111] Toney, S., Cohen, M., Cron, C. J., Metallurgical Evaluation of Materials for Geothermal Power Plant Applications, Geotherm. Energy, 5(9), 8-38 (1977).

The performance of some materials used for the manufacture of conventional steam turbine power plants can be adversely affected by contaminants, particularly sulfide and chloride, in geothermal steam. Equally important, the chemical composition of geothermal is known to be site dependent. For these reasons, on-site metallurgical evaluation of materials for geothermal power generation equipment is often desirable. This investigation is concerned with the determination of the chemical composition of geothermal steam. An evaluation is made about the effect of geothermal steam exposure on the corrosion, stress-corrosion cracking, and fatigue behavior of selected turbine and heat exchanger materials.

[112] Tskhrirshvili, D., On Corrosion of Metals in Geothermal Power Plants, Geothermics, 1(3), 113 (1972).

[113] Tylecote, R. F., Durable Materials for Sea Water: The Archaeological Evidence, Report 314(R), Brit. Nucl. Fuel. Ltd., 1977.

[114] Wethe, P. I., Appendix to Chapter 6: Radioactive Waste and Transport. Vedlegg til Utredningen 'Kjernekraft og Sikkerhet', p. 171-300 (1978). Oslo, Norway.

The appendices are here edited into a homogeneous treatment of the whole question of high-level radioactive wastes originating from nuclear fuel and its reprocessing, and from low and medium level radioactive wastes arising from operation of

nuclear facilities. The Swedish AKA (1976) and KBS (1977) reports are directly quoted at length on a number of specific subjects. The nature and amounts of the wastes, costs, responsibilities; processing; solidification and vitrification of high-level wastes; after-heat generation and cooling requirements; intermediate storage and final disposal, both underground in geologically stable formations and marine; transmutation; encapsulation and corrosion and leaching, with associated hazard evaluation are some of the principal items discussed. The Oklo phenomenon is discussed in connection with radionuclide migration. The final sections are devoted to discussion of transport, containers and regulations.

[115] Yamazaki, H., Materials for Geothermal Power Plants, Chinetsu Gijutsu 2(1), 39-47 (1977). Japan.

A study was made on corrosion and abrasion resistance of stainless steels in acidic hot solutions for development of geothermal power plant materials. In a corrosion test in 0.1 M H_2SO_4 containing 0.001-0.01 M H_2S, the corrosion loss of SUS 304 was smaller than that of SUS 309 and SUS 310 and corrosion products were mainly FeS, FeS_2, and Fe_7S_8. SUS 304 and SUS 316 had excellent abrasion resistance in an abrasion test in H_2SO_4 acidic (pH 1-2) and H_2S-saturated solution.

[116] Zastrow, O. W., Copper-Corrosion in Moderate and High Resistivity Soils, Matls. Perf., 13(8), 31-36 (1974).

Keywords: Copper, corrosion, underground corrosion, corrosion tests.

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This bibliography consists of references pertaining to the corrosion of metallic container materials for nuclear waste disposal. Five kinds of corrosion data are presented - general underground corrosion data that may apply to metallic nuclear waste containers; corrosion considerations in package design; metallic corrosion in geothermal brines; internal corrosion of nuclear waste containers for underground use; and external corrosion of nuclear waste containers for underground environments. Abstracts are provided for most references, and key words are included when there is no abstract. One hundred and sixteen references are presented.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

alloys; corrosion; corrosion data; containers; geothermal brines; metals; nuclear waste; underground

13. AVAILABILITY

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