AD-774 190

URANIUM ALLOY METALLURGY

AN ANNOTATED BIBLIOGRAPHY

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JANUARY 1974

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URANIUM ALLOY METALLURGY - AN ANNOTATED BIBLIOGRAPHY

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109

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AMMRC MS 74-1	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* URANIUM ALLOY METALLURGY - AN ANNOTATED BIBLIOGRAPHY		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Margaret M. Murphy and David A. Colling		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Army Materials and Mechanics Research Center Watertown, Massachusetts 02172 AMXMR-PL		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS D/A Project: AMCMS Code: Agency Accession:
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Materiel Command Alexandria, Virginia 22304		12. REPORT DATE January 1974 13. NUMBER OF PAGES 112
14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*		15. SECURITY CLASS. *(of this report)* Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Uranium alloys
Uranium
Bibliographies

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

An annotated bibliography is presented of the work reported in the literature in the English language (1957-1973) on fabrication, mechanical and physical properties, physical metallurgy, and corrosion behavior of depleted uranium-base alloys. Also included are testing and preparation techniques and other studies for unalloyed uranium which are applicable to uranium alloys. (Authors)

PREFACE

PURPOSE - Nonnuclear applications of high-density, high-strength uranium-base alloys, exclusive of nuclear applications, have evolved in recent years. Bibliographies covering specific binary uranium-base alloy systems have been published. The purpose of this bibliography is to summarize the literature available on all uranium-base alloys covering the unique metallurgical characteristics, including corrosion behavior, complex phase transformations, and fabrication which must be considered by metallurgists and engineers

SCOPE - The scope of this bibliography includes the fabrication, mechanical and physical properties, physical metallurgy, and corrosion behavior of depleted uranium-base alloys. Testing and preparation techniques and other studies for unalloyed uranium which are applicable to uranium alloys are also included.

Standard bibliographic reference tools including:

CHEMICAL ABSTRACTS
CORROSION ABSTRACTS
DEFENSE DOCUMENTATION CENTER, TECHNICAL ABSTRACTS BULLETIN (TAB)
METALS ABSTRACTS
NASA SCIENTIFIC AND TECHNICAL AEROSPACE REPORTS (STAR)
U.S. ATOMIC ENERGY COMMISSION, NUCLEAR SCIENCE ABSTRACTS
U.S. GOVERNMENT REPORTS ANNOUNCEMENTS (GRA)

were the basic sources of information. Further references were found in texts, especially those publications covering proceedings of conferences in the field.

ARRANGEMENT - The bibliography is arranged in subject areas. References that could have been included in more than one subject area are entered only in the main subject area. Entries are in alphabetical order by author followed by U.S. and U.K. patents.

LIMITATIONS - Because of the vast body of literature on uranium alloy metallurgy in many languages only material published between 1957 and 1973 in the English language has been included.

In instances where the results of a specific research study have been published in the open literature and in report form, only the open literature reference is given.

This bibliography is an attempt to present a comprehensive but not exhaustive study of the literature in the field.

ACKNOWLEDGMENTS - The able assistance and patience of Mrs. A. V. Gallagher and the typing of the manuscript provided by Mrs. M. Gould, Miss J. Romano, Miss J. Caliguri, Miss J. Mc Farlane, Mrs. E. Dugan, and Miss C. Josey are gratefully acknowledged. The assistance of Mr. J. Greenspan in the original planning and scope of this bibliography and the persevering efforts of Miss R. Markus to provide many of the references and her diligent proofreading of the manuscript are also greatly appreciated.

CONTENTS

PHYSICAL AND MECHANICAL BEHAVIOR

PHYSICAL METALLURGY

GENERAL

1. Beck, D., "Uranium-Molybdenum Alloys." Atomic Weapons Research Establishment, Aldermaston, England. Report No. AWRE/LIB/BIB/6, September 1962.

   References to published articles and reports obtained from *Nuclear Science Abstracts* Vol. 12 through Vol. 16, *Review of Metal Literature* 1956 to 1960, and AWRE Library Indexes, including 130 references on U-Mo alloys are listed.

2. Blasch, E. B., Stukenbroeker, G. L., Lusky, R. J., Bonilla, C. F., and Berger, H., "Use of Uranium as a Shielding Material," *Nucl. Eng. Des.*, *13* (1970), 146-82.

   Specific use of U in shielding materials in relation to cost and/or weight savings realized in various designs are discussed. Information concerning commercial grades and forms of U and fabrication methods are included.

3. Chiswick, H. H., Dwight, A. E., Lloyd, L. T., Nevitt, M. V., and Zegler, S. T., "Advances in the Physical Metallurgy of Uranium and Its Alloys." *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy*; *Vol. 6, Basic Metallurgy and Fabrication of Fuels*. Geneva: United Nations (1958), 394-412.

   The dimensional stability and corrosion resistance of U and U-alloys including U-Zr, U-Nb, and U-Zr-Nb were evaluated for use as fuel element materials. Emphasized were: (1) "α-phase" alloys in which relatively low concentrations of alloying addition modify the kinetics of β-or γ-phase decomposition to yield a structure combining random orientation and fine grain size, (2)"γ-phase" alloys in which sufficient concentrations of alloying additions stabilize partially or completely the cubic γ-phase, circumventing the instability of the orthorhombic α-structure. Properties are discussed in relation to constitution, heat treatability, transformation kinetics, and micrographic features.

4. Eichholz, G. G., "Notes on the Safe Handling of Uranium Alloys in Industry." Canadian Department of Mines and Technical Surveys, Mines Branch, Ottawa. Information Circular IC-125, January 1961.

   Physical and chemical properties of U-metal which may have a bearing on the industrial production of U-alloys are summarized. The legal aspects of natural U use are reviewed and some experimental data on airborne U dust obtained during pilot plant tests are presented.

5. Erickson, W. H., "Proceedings of the Uranium Alloy Research Conference at Defence Research Establishment, Valcartier, Quebec, 12-13 February 1970." Defence Research Establishment, Valcartier, Quebec. Report No. DREV-M-2060/71, May 1971. (AD 890 370)

   Collection of 18 papers presented at the conference on the research and development of high - density structural U-alloys. Pertinent papers are annotated in this bibliography with each entry under the name of the specific author.

6. Holden, A. N., Physical Metallurgy of Uranium. Reading, Mass: Addison-Wesley Publishing Company, Inc., 1958.

History, occurrence, preparation, crystallography, physical, chemical, and mechanical properties, and deformation of U are discussed at length. Transformation kinetics of U and U-alloys and diffusion in binary U-alloys are presented.

7. Jackson, R. J., "Uranium-Titanium Alloys: Annotated Bibliography." Dow Chemical Company, Rocky Flats Division, Golden, Colorado. U. S. Atomic Energy Commission Contract Report No. RFP-2005, April 1973.

An annotated bibliography for binary U-Ti alloys complete as of 1 January 1973. The references obtained primarily from Nuclear Science Abstracts have been categorized according to subject within subject groupings.

8. Jackson, R. J. and Johns, W. L., "Explosive Nature of Uranium-Base Niobium Alloys After Immersion in Nitric Acid." Dow Chemical Company, Rocky Flats Division, Golden, Colorado. U. S. Atomic Energy Commission Contract Report No. RFP-1575, 1970.

Study of the explosive behavior of two phase U-Nb alloys after immersion in HNO_3 showed it to be related to finely divided microstructure and to a high C content.

9. Larsen, R. P., "Dissolution of Uranium Metal and Its Alloys," Anal. Chem., 31 (1959), 545-49.

The more common U-alloys and the reagents used to dissolve them are summarized in tabular form. The behavior of U and U-alloys in the common acids, ethyl acetate solutions of Br, HCl, NaOH, Na_2O is described.

10. Lefer, H., "Here's a New Engineering Material," Precis. Metal Molding, 22 (1964), 40-41.

Density, tensile strength, and impact strength of both U and U-Mo alloys are presented. Because of high density, good castability, and mechanical properties of U-alloys, they are considered for applications as aircraft counterweights and radiation shields for high energy sources and nuclear reactors.

11. Nichols, R. W., "Uranium and Its Alloys," Nucl. Eng., 2 (1957), 355-64.

Mechanical, physical, chemical, and metallurgical properties of U and U binary alloys are given and the effects of irradiation, thermal cycling, fabrication techniques, and alloy additions are discussed.

12. Seedhouse, K. G., "Uranium in Industry," Chem. Process. (London), 14 (1968), 30-35.

Wide range of potential industrial, nonnuclear applications of U, U compounds, and U-alloys are described.

13. Semple, C. W., "High-Density Alloys for Shell Fragments," Army Materials Research Agency, Watertown, Massachusetts. Report No. AMRA-TR-64-46, December 1964. (AD 461 787)

High density W, Ta, and U-alloys were fabricated into cubes. Mechanical tests - tensile, compression, hardness, and impact - as well as chemical and metallographic examinations were conducted.

14. Sergeev, G. Ya., and Titova, V. V., "Uranium and Its Alloys," Sov. At. Energy, 6 (1960), 143-49.

Short resume of the results of investigations of the physico-mechanical properties of U and U-alloys is given. The effect of irradiation and, in particular, the phenomenon of gas swelling as well as the effect of elevated temperature on dimensional stability of various α-phase and γ-phase U-alloys are examined. Techniques for metallographic examination of U are given.

15. Sokurskii, Yu. N., Sterlin, Ya. M., and Fedorchenko, V. A., "Uranium and Its Alloys." Translated from the Russian for the Joint Publications Research Service, Arlington, Virginia. Report No. JPRS-57364, October 1972.

Selected reviews of the production methods and properties of U, U-alloys, and U-compounds.

16. Tardif, H. P., "The DREV Uranium Development Programme." Defence Research Establishment, Valcartier, Quebec. Report No. DREV-R-619/70, August 1970. (AD 877 876)

Brief report of work sponsored by DREV on various aspects of the physical metallurgy of U and U-alloys. The work consisted of general studies on the properties of alloys, effects of hot working, vacuum annealing, grain size refinement, and thermomechanical treatments. Some general remarks on cost, availability, health and safety problems, pyrophoricity, and oxidation of the alloys are included. The possibility of making composite alloys and the problems of static and dynamic properties are also included.

17. "Trends in the Use of Depleted Uranium." National Materials Advisory Board, Washington, D. C. Report No. NMAB-275, June 1971.

Report of the Ad Hoc Panel on Depleted Uranium of the Committee on the Technical Aspects of Critical and Strategic Materials. Supply situation, nonenergy consumption, potential uses, metallurgy, chemistry, and effectiveness as a catalyst and alloying element of depleted U are discussed. High density and ability to be alloyed make U a promising material for the development of new nonnuclear applications. Appendixes on metallurgy of U and its alloys are included.

18. "Uranium Alloys for Critical Ordnance Components." Watertown Arsenal Laboratories, Massachusetts. Report No. WAL-MS-19, October, 1961. (AD 609 896)

Proceedings of the Specification Coordination Meeting on Uranium Materials for Davy Crockett and Other Ordnance Programs held at Watertown Arsenal, 7 June 1960.

19. "Uranium: Properties - Processes - Controls." Watertown Arsenal Laboratories, Massachusetts. Report No. WAL-MS-55, October 1962. (AD 610 614)

Short history of the development of U as an engineering material and current practices of Watertown Arsenal regarding materials processing, accountability, and health and safety are presented. Several U-alloys having high strength and high density are reviewed.

Phase Diagrams

20. Bauer, A. A. and Rough, F. A., "Uranium Alloy Systems." Progress in Nuclear Energy, Series 5. Metallurgy and Fuels, Vol. 2. Edited by H. M. Finniston and J. P. Howe. New York: Pergamon Press (1959), 600-611.

U-alloy constitutional data are presented in the form of diagrams and crystal structure data for U phases and compounds are tabulated.

21. Carrea, A. J., West, D. R. F., and Ball, J. G., "A Review Paper on the Constitution of Uranium-Molybdenum Alloys," J. Nucl. Energy, 7 (1958), 189-98.

Reports of investigations of the constitution of U-Mo alloys are summarized and differences between the proposed equilibrium diagrams are discussed. It appears that the differences are due partly to the difficulty of establishing equilibrium in the solid state transformations. A compiled equilibrium diagram is presented.

22. Dwight, A. E., "The Uranium-Molybdenum Equilibrium Diagram Below 900°C," J. Nucl. Mater., 2 (1960), 81-87.

The equilibrium diagram for U up to 19w/oMo alloy at < 900° was determined. The eutectoid transformation, $\beta \rightleftharpoons \alpha\ \gamma$, occurred at 639°±5.0°C at 10.5w/oMo - earlier investigations used a maximum of 6a/oMo content. Tetragonality of the δ-phase was confirmed and it was probably formed congruently.

23. Farkas, M. S., Bauer, A. A., and Dickerson, R. F., "The Solid-State Constitution of High-Uranium Alloys of the Uranium-Zirconium-Silicon Systems," Trans. ASM, 53 (1961), 511-21.

Studies of the U-Zr-Si alloys by metallographic, x-ray diffraction, and thermal analysis techniques were used to construct tentative isothermal ternary sections at temperatures from 550°-950°C. Solubility of Si in U-Zr alloy or of Zr in U_3Si was <2a/o but solubility of Zr in U_3Si_2 was fairly extensive and a phase $(U,Zr)_3Si_2$ was formed.

24. Fizzotti, C. and Masperoni, A., "Influence of Heat Treatments on the Structure of Uranium Alloys with a Low Niobium Content." Translated from the Italian for Oak Ridge National Laboratory, Tennessee. U. S. Atomic Energy Commission Contract Report No. ORNL-tr-1695, 1966.

After being continuously cooled at different rates from the γ-phase some U up to 5a/oNb alloys were aged at 550°C and resulting structural change is described. Step annealing in the phase fields $(\beta+\gamma_1)$, $(\alpha+\gamma_1)$, and $(\alpha+\gamma)$ is also described.

25. Friedemann, H. C. and Hausner, H. H., "Bibliography on Uranium Alloys with Binary Phase Diagrams and Selected Data on Properties." Sylvania-Corning Nuclear Corporation, Bayside, New York, 1959.

Bibliography containing 470 references on U-alloys originally prepared for metallurgists and fuel element designers at Sylvania-Corning Nuclear Corporation. Supplements include a collection of phase diagrams of binary U-alloys and tables showing behavior of U-alloys with respect to corrosion and irradiation.

26. Howlett, B. W., "The Alloy System Uranium-Titanium-Zirconium," J. Nucl. Mater., 1 (1959), 289-99.

The U-Ti-Zr alloy system containing up to 40a/oTi and 70a/oZr is reported in nine isothermal sections between 575°-1000°C. Lattice parameters of U_2Ti which vary with composition confirm evidence for the high solubility of Zr in the U_3Ti phase.

27. Howlett, B. W. and Knapton, A. G., "The Uranium-Titanium, Uranium-Zirconium and Uranium-Titanium-Zirconium Alloy Systems." Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy; Vol.6, Basic Metallurgy and Fabrication of Fuels. Geneva: United Nations (1958), 104-10.

U-Ti and U-Zr and U-Ti-Zr alloy systems are described. Alloys were prepared by arc-melting in purified Ar from high-purity materials with <0.5% weight loss. Phase diagrams were determined using dilatometric, metallographic, and x-ray analyses. Isothermal sections of the U-Ti-Zr system are given for temperatures of 575°-850°C.

28. Ivanov, V. E. and Badajeva, T. A., "Phase Diagrams for Certain Ternary Systems of Uranium and Thorium." Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy; Vol. 6. Basic Metallurgy and Fabrication of Fuels. Geneva: United Nations (1958), 139-155.

Brief summary of the results of investigation into alloy structures and phase diagrams of certain ternary systems, including U, Th and their refractory compounds is presented. U-Zr, Nb, Mo, and Cr alloys, first in binary systems then in ternary systems were studied. Emphasis was placed on that section of the phase diagrams which relates to solid state. X-ray and microstructural data were used to plot the phase diagrams.

29. Jackson, R. J., Williams, D. E., and Larsen, W. L., "The Uranium-Rhenium Alloy System," J. Less Common Metals, 5 (1963), 443-61.

The phase diagram of the U-Re alloy is presented. It is of the double eutectic type with the intermediate type having the composition URe_2 which exhibits allotropy at 180°, melts congruently at 2200°, and reacts sluggishly with U solid solutions at <750° to form the peritectoid compound U_2Re. Eutectoid reactions occur at 643°, 681°, 1105°, and 2105° at compositions of 1.4, 6.0, 10.5, and 65.5w/oRe respectively. The maximum stability of Re in α-U is ∿ 0.4w/o at 643°, in β-U ∿ 1.9w/o at 681°, and in γ-U ∿ 7.0w/o at 975°C. Investigation of transformation kinetics of U solid solutions indicated the existence of transition states; one involving γ-phase decomposition and the other the β→α transformation. Sequence of phase changes is discussed.

30. Maxwell, S., Tate, E. F., Harris, D. G., and Stobo, J. J., "γ Lattice Parameters in U-Mo-Nb Alloys," J. Nucl. Mater., 11 (1964), 119-20.

Debye-Scherrer photographs of ternary alloys of γ-U-Mo (up to 30a/o)-Nb (up to 40a/o) were obtained and lattice parameters studied. Parameter measurements and compositions of the alloys are presented in tabular form.

31. Murray, J. R., "Uranium-Thorium System and Some Aspects of the Uranium-Thorium-Zirconium System," J. Inst. Metals, 87 (1958), 94-96.

The U-Th phase diagram is reported a simple eutectic system was formed with a region of liquid immiscibility extending from 0-49a/oTh. Solubility of Th in U is 0.3a/o at 900° and 0.05a/o at 700°C.

32. Park, J. J., "Uranium Phase Diagrams and a Solid Solubility Correlation." Unpublished Ph.D. dissertation University of Maryland, College Park, 1965.

Thermal analysis, x-ray diffraction, and metallographic techniques were used to construct U-Re and U-Rh phase diagrams. Heats of solution for the intermetallic compounds were calculated from activity of U in solution in the liquid phase. Correlation between solid solubility of various elements in γ-U is demonstrated using a model based on atomic radius ratio at the temperature of reaction.

33. Peterson, D. T. and Beerntsen, D. J., "The Uranium-Hafnium Equilibrium System," Trans. ASM, 52 (1960), 763-80.

The addition of 4.5a/oHf to U increased the temperature of $\alpha\to\beta$ transformation on heating from 668° to 676° and lowered the $\beta\to\gamma$ transformation to a eutectoid at 733°. At elevated temperatures, the bcc U and Hf were soluble in all proportions. U-20-65a/oHf alloys quenched from 1100° and above contained a hexagonal δ-phase, a=4.97Å and c=3.04Å with x-ray powder pattern almost identical to that of δ-phase of U-Zr system. It is believed to be a metastable phase which decomposes to U and Hf at equilibrium. U lowered the $\alpha\to\beta$ transformation in Hf to a monotectoid at 1150° and 55a/oHf. At 1425°C the solubility of U in Hf is 2.0-2.3a/o.

34. Pfeil, P. C. L., Browne, J. D., and Williamson, G. K., "Uranium-Niobium Alloy System in the Solid State," J. Inst. Metals, 87 (1959), 204-08.

Metallography, x-ray diffraction, and thermal analysis were used to determine equilibrium diagrams and apparent phase boundaries in U-Nb alloys.

35. Rogers, B. A., Atkins, D. F., Manthos, E. J., and Kirkpatrick, M. E., "Uranium-Columbium Alloy Diagram," Trans. AIME, 212 (1958), 387-93.

The U-Cb phase diagram was determined using x-ray, metallographic, dilatometric, resistivity and melting point measurements.

36. Rough, F. A. and Bauer, A. A., "Constitution of Uranium and Uranium Alloys." Battelle Memorial Institute, Columbus, Ohio. U. S. Atomic Energy Commission Contract Report No. BMI-1300, June 1958.

Compilation written in cooperation with representatives of the U.K. of U and Th constitution diagrams (Supersedes BMI-1000). Both major sections - U alloys and Th alloy - are preceded by a discussion of transformation and melting temperatures of the base metal followed by discussion of the various binary and ternary alloy systems. Crystallographic data, phase diagrams whenever possible, and references to the literature are included for each alloy.

37. Rough, F. A. and Bauer, A. A., Constitutional Diagrams of Uranium and Thorium Alloys. Reading, Mass.: Addison-Wesley Publishing Company, Inc., 1959.

A compilation of U. S. and U. K. constitutional diagrams and data on crystallography of intermetallic compounds including both binary and ternary systems is presented. Melting points and allotropic modification of the base metals are included.

38. Saller, H. A., Rough, F. A., Bauer, A. A., and Doig, J. R., "Constitution of Delta-Phase Alloys of the System U-Zr-Ti," Trans. AIME, 209 (1957), 878-81.

A constitutional diagram of a ternary section, U-74a/oZr to U-35a/oTi, based upon the results of thermal, metallographic, and x-ray analyses of a series of U-alloys ranging in composition between the δ-phases of the U-Zr and U-Ti systems is presented. At all temperatures investigated no evidence for a three phase region or a new phase, not found in the binary system, was indicated.

39. Tate, E. F. and Nicholson, S., "The (β+γ)/γ Phase Boundaries at 675°, 700° and 720°C in the Uranium-Rich Corner of the U-Mo-Nb Diagram," J. Nucl. Mater., 9 (1963), 365-66.

U-Mo-Nb alloys were examined after H_2O quenching from 675°, 700°, and 720° to determine the composition and quantity of γ - and β -phases. The shape of the (α+β)/γ phase boundaries agree with the finding that an increased γ/β ratio can be obtained by step-annealing at 675°-700°C the U-3.6a/oMo-6.9a/oNb alloys.

40. Zegler, S. T., "The Uranium-Rich End of the Uranium-Zirconium System." Argonne National Laboratory, Illinois. U. S. Atomic Energy Commission Contract Report No. ANL-6055, February 1962.

U-rich end of the Zr alloy system was investigated. Solubilities of Zr in both α- and β-U were found to be 6.21w/o at 662° and 0.41w/o at 693°. The monotectoid decomposition of γ at 693° and the eutectoid decomposition of β at 662°C were confirmed. In alloys containing <150 ppm O the γ and γ phase region boundaries were located at 4.5 and 22.0w/oZr at the monotectoid temperature. Results indicate that O content of 160-355 ppm has a marked effect on phase relations in the γ and γ phase regions.

Testing Techniques

41. Cofield, R. E., "Eddy Current Electrical Conductivity Measurement As an Analysis for Molybdenum in Binary Molybdenum-Uranium Alloys." Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee. U. S. Atomic Energy Commission Contract Report No. Y-1152, February 1957.

Principles involved in the eddy current method of measuring electrical conductivity of a solid are discussed and the meter used is described. The relationships between electrical conductivity and alloy structure, composition, and metallurgical conditions involved in the conductivity analysis of U-2w/oMo alloy are described and results agreed with chemical analysis within ±0.128w/oMo.

42. Jolley, W. G., "Determination of Residual Stress in Uranium with an X-ray Diffractomer," in Papers and Proceedings of the Meeting on Applications of X-ray Diffraction in the Atomic Energy Field held at Richland, Washington, 25-26 February 1965. Hanford Atomic Products Operation, Richland, Washington. U. S. Atomic Energy Commission Contract Report No. RL-REA-2595 (1966), 43-50. (N66-28813)

The techniques and limitations of residual stress analysis of U using an x-ray diffractometer are discussed. A review of the theory and the type of equipment and x-ray geometry are described. Preparation of the standard U plate and the procedure used to standardize x-ray results are presented in detail. Data showing a linear plot of increasing deflections of a U plate vs change in the "d" spacing are given.

43. LeNaour, L., "X-Ray Topography of Uranium Alloys." Translated from the French for Sandia Laboratories, Albuquerque, New Mexico. U. S. Atomic Energy Commission Contract Report No. SC-T-72-2467, 1968.

Data obtained by x-ray diffraction techniques derived from the Berg-Barrett method were used to describe the structure of U-alloys. Exact numerical data concerning the grain and sub-grain size and the distribution of the sizes were obtained. Any disorientation >30 sec of arc can be detected. Observations of internal disorientations were carried out on one- or two-phase U-alloys and compared successfully to high-purity U. Although limited in certain respects the use of x-ray topographies allows a quantitative characterization of the structure.

44. Malcic, S., Mihajlovic, A., Mance, A., and Tepavac, P., "X-Ray Investigation of the Monoclinic Deformation of the α Uranium Lattice in the U-Nb System," J. Nucl. Mater., 30 (1969),314-318.

The transition from orthorhombic to monoclinic structure in quenched U-Nb alloys was investigated by following the changes of ratio between the breadths of a number of selected diffraction lines. The α'-phase represents only the period between the outset of monoclinization and the moment when line-splitting becomes visible on x-ray photographs and it is not justified to regard it as a separate phase.

45. Reeves, C. A. Jr., "Method of Stress Relaxation Testing." Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee. U. S. Atomic Energy Commission Contract Report No. Y-1726, June 1970.

Stress relaxation properties of U-7.5Nb-2.5Zr alloy were determined by two separate series of tests at both room temperature and at elevated temperatures (2500°-3000°F). Only the testing procedure and initial treatment of data are discussed.

46. Twitty, B. L. and Humphrey, H. W., "Gamma Radiography of Uranium Metal." National Lead Company of Ohio, Cincinnati. U. S. Atomic Energy Commission Contract Report No. NLCO-926, September 1964.

Techniques and equipment used at NLCO for γ radiation of U and procedures for handling specimens of various thicknesses are described. The γ-ray source was 15 Ci of Co-60. In addition to γ-radiography, autoradiography, radiography in color, and neutron radiography are discussed.

47. Wiedemann, C. M., "Spark Discharge Machining Method for Preparing Uranium Alloy Specimens for X-Ray Analysis." Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee. U. S. Atomic Energy Commission Contract Report No. Y-DA-1730, April 1967.

A standard method for making U-alloy specimens to study the effect of varying quenching rates by Debye-Scherrer x-ray analysis was developed. The method uses a spark-discharge machine to taper small, square metal rods which are subsequently electropolished to remove the disturbed surface layer of metal remaining after the machining process. Advantages of the method are discussed.

48. Wooden, B. J., House, E. C., and Ogilvie, R. E., "Precision X-Ray Stress Analysis of Uranium and Zirconium." Advances in X-ray Analysis, Vol. 3. Proceedings of the Eighth Annual Conference on Applications of X-Ray Analysis, 12-14 August 1959. Denver: University of Denver (1960), 331-36.

A method for the determination of diffraction peak positions (to a precision of ±0.01°) and their associated precision in U and Zr was developed using x-ray diffraction. It was found that the second-order polynomial provided the best least squares fit within the known precision of the observed data. The stress constant for U was determined to be 1308±110psi/0.01° shift in $\Delta 2\Theta$.

49. Worlton, D. C., "Inspecting Uranium Slugs at Hanford Ultrasonically," Nucleonics, 19 (1961), 80-82.

Ultrasonic testing for grain size, grain orientation, and defects during the various stages of manufacturing in an automated production line are described. Data from the resonant-frequency method and x-ray diffraction are compared and hopefully will lead to a NDT grain-orientation test for fuel specifications.

Metallographic Techniques

50. Ambler, J. F. R. and Slattery, G. F., "New Metallographic Techniques for the Examination of Uranium Alloys and Uranium Dioxide, " J. Nucl. Mater., 4 (1961), 90-99.

An attack-polish reagent consisting of a slurry of H_2O_2 (30w/o) and 5%γ-NH_3 for the metallographic preparation of U-alloys was developed. Polishing was carried out on a polythene lap covered with terylene velvet. A new electrolytic etching technique using bright field illumination for the study *of the grain structure of U and U-alloys* is also described. Results obtained using these techniques with specific metallographic structures as examples are described.

51. Angerman, C. L., "High-Temperature Metallography of Uranium," in Technical Papers of the Fifteenth Metallographic Group Meeting held at Savannah River Laboratory, Aiken, South Carolina, 17-19 May 1961. U. S. Atomic Energy Commission Contract Report No. NMI-4997 (May 1964), 76-84. (N65-36083)

Microstructural changes of U that occurred during heating and cooling through the allotropic transformation were recorded by time-lapse photography. Electropolished U specimens were heated in a hot stage, mounted on a metallograph and evacuated to at least $3x10^{-6}$mm. The original grain structure became visible during heating due to relief caused by the differences in thermal expansion between adjacent grains. The $\alpha \rightarrow \beta$ transformations occurred at a faster rate than the $\beta \rightarrow \gamma$. Grain boundaries of the β and -γ-phases were visible after the respective transformations.

52. Angerman, C. L., "Preparation of Thin Foils of Uranium," in Technical Papers of the Seventeenth Metallographic Group Meeting held at Los Alamos Scientific Laboratory, New Mexico, 21-23 May 1963. U. S. Atomic Energy Commission Contract Report No. NMI-4999 (April 1965), 78-84. (N66-10085)

Foils of U suitable for direct observation in the electron microscope were prepared by electropolishing in a solution containing phosphoric acid, ethylene glycol, and ethyl alcohol followed by a solution containing sulphuric acid, glycerine, and H_2O. Twins, dislocations, and dislocation loops were observed in typical specimens.

53. Angerman, C. L., "Transmission Electron Microscopy of Uranium," J. Nucl. Mater., 9 (1963), 109-10.

Development of techniques for thinning U specimens by electropolishing and removal of the oxide film formed during the electropolishing to enable direct observation of the configurations and movements of dislocations and other crystallographic defects are described. Specimens were heat treated by two methods: (1) annealed for 1hr at 600° to recrystallize the structure, (2) α-transformed for 1hr at 720°C. Observations concerning the nature of dislocations are discussed.

54. Angerman, C. L. and McDonnell, W. R., "Metallography of U-2Wt%Zr Alloy Before and After Irradiation," in Technical Papers of the Fifteenth Metallographic Group Meeting held at Savannah River Laboratory, Aiken, South Carolina, 17-19 May 1961. U. S. Atomic Energy Commission Contract Report No. NMI-4997 (May 1964), 163-83. (N65-36090)

Optical and electron metallography and electron diffraction were used to characterize the response of U-2w/oZr to heat treatment and the effects of irradiation on the alloy. A new technique for isolating the second-phase particles for identification by electron diffraction was developed. Matrix grain size and second-phase distribution were dependent on heat treatment before irradiation. *Retention of the* γ_1*-phase on* quenching from temperature in the $(\beta+\gamma_1)$ region and the formation of a δ-phase instead of γ_2 upon annealing at 650°C were important observations.

55. Bennett, R. K. and Winslow, F. R., "Scanning Electron Microscope Fractography of a U-7.5 Wt. Percent Niobium-2.5 Wt. Percent Zirconium Alloy." Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee. U. S. Atomic Energy Commission Contract Report No. Y-DA-2952, August 1969.

Studies showed that the use of SEM for fractographic study instead of conventional replica techniques in the TEM not only shortened the time necessary to obtain data, but also provided information concerning deep cracks that might have been lost using the replica technique.

56. Bierlein, T. K. and Mastel, B., "Metallographic Studies in Uranium." Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy; Vol. 6, Basic Metallurgy and Fabrication of Fuels. Geneva: United Nations (1958), 14-24.

Conventional metallography, precharacterized surface metallography, and fractography were used to study the nature and extent of reactor-induced microstructural changes in uranium.

57. Bierlein, T. K., Mastel, B., and Leggett, R. D., "Possible Artifacts Associated With Microstructure of Uranium Developed by Ion Bombardment," in Technical Papers of the Sixteenth Metallographic Group Meeting held at Hanford Atomic Products Operation, Richland, Washington, 26-29 March 1962. U. S. Atomic Energy Commission Contract Report No. NMI-4998 (August 1964), 108-23. (N66-11325)

Polished metallographic surfaces bombarded by rare gas ions can be etched due to ejection of surface atoms. Two of several possible artifacts which may result from improper etching conditions were studied by statistical metallography: (1) atoms rejected from a U surface collide with gas atoms and redeposit at preferred sites on the specimen with redeposition increasing with increased gas pressure, (2) small pores, 0.08-1.0 μmd, intersected by the specimen surface become artificially enlarged as a result of selective etching of the pore interior. Techniques used and results obtained are described.

58. Cheney, D. M. and Bauer, A. A., "Impurity Content Determination of Uranium and High-Uranium Alloys by Visual Inspection," in Technical Papers of the Thirteenth Metallographic Group Meeting held at Armour Research Institute of Technology, Chicago, Illinois, 14-15 January 1959. U. S. Atomic Energy Commission, Office of Technical Information, Washington, D. C. Report No. TID-7625 (November 1962), 45-51.

Microscopic inspection using a method similar to grain size determinations was used to obtain relatively accurate estimates of impurity contents in U and U-alloys, UC, UO_2, UN, and UH_3 being the most prominent inclusions.

59. Copps, T. P. and Erickson, W. H., "The Topography of the Fracture Surface of Some Uranium Alloys." Defence Research Establishment, Valcartier, Quebec. Research Report No. DREV-TN-1885/70, August 1970. (AD 880 243)

Fracture surfaces of U-2Mo and U-1Mo-1Nb-1Zr alloys during mechanical properties investigation are reported. Examination revealed two predominant modes of fracture: dimpled rupture at the highest hardness levels in the quaternary alloy and quasi-cleavage rupture in the binary alloy at room temperature. The binary alloy tested above room temperature displayed a fracture mode transition. Results suggest that the high hardness of the complex alloy at room temperature is related to a lower "ductile-brittle" fracture mode transition temperature.

60. Cornett, M. H., "Metallography of Uranium: Procedures and Standards." National Lead Company of Ohio, Cincinnati. U. S. Atomic Energy Commission Contract Report No. NLCO-954, March 1966.

Techniques for the preparation of U-specimens for both macro- and microstructure studies are presented. Procedures for sample preparation, etching, and photography are included. Also included are metallographic standards for the evaluation of grain size, recrystallization, and inclusion content of the specimens.

61. Cornett, M. H., "Standards for Metallographic Evaluations of Uranium Metal," in Technical Papers of the Eighteenth Metallographic Group Meeting held at Atomics International, Canoga Park, California, 22-24 June 1964. U. S. Atomic Energy Commission Contract Report No. NMI-5025, Pt. I (August 1965), 97-103.

Visual standards are presented for rating the degree of recrystallization of formed U metal, the inclusion content of as-cast U metal, and the inclusion and stringer content of formed U metal.

62. Davies, A. L., "Specimen Preparation." Electron Microscopy and Microanalysis of Metals. Edited by J. A. Belk and A. L. Davies. New York: American Elsevier Publishing Company, Inc. (1968), 28-51.

Single-stage and two-stage methods of replica preparation are described. Shadowing of replicas with Au and Pd alloys improved contrast. Extraction replicas were prepared for study of metals containing intermetallic compounds and inclusions. Thin films were prepared by deposition, deformation, ion bombardment, dissolution, electrolytic polishing, and chemical polishing. Recommended chemical polishing agents for U and other metals and alloys are given.

63. Dickerson, R. F., "Metallography of Uranium," Trans. ASM, 52 (1960), 748-62.

Paper attempts to summarize the state of the art of U metallography. Conventional preparatory techniques as mechanical and electrolytic polishing methods, etching techniques, and the use of polarized light for the delineation of structure are discussed in detail. Nonconventional techniques such as vacuum-cathodic etching, anodic oxidation, hot-stage microscopy, and strain etching are described and evaluated. The five so-called basic metallographic structures of U: (1) α annealed, (2) α transformed - β quenched, (3) α transformed - β slow cooled, (4) α transformed - γ quenched, (5) α transformed - γ slow cooled are illustrated and described. Techniques for determining grain size of U in different conditions of heat treatment and a discussion of nonmetallic inclusions in U including micrographs are briefly described.

64. Douglass, D. L., "Specimens Preparation for Transmission Electron Microscopy of Alpha Uranium," in Technical Papers of the Seventeenth Metallographic Group Meeting held at Los Alamos Scientific Laboratory, New Mexico, 21-23 May 1963. U. S. Atomic Energy Commission Contract Report No. NMI-4999 (April 1965), 85-86.

A TEM study investigated the effects of cold work on crystallization of α-U. An electropolishing bath, composed of chromic acid, glacial acetic acid, and H_2O was used to prepare thin U films. The standard window technique was used and the thinned specimens were rinsed in anhydrous methanol and dried in a stream of warm air.

65. Duran, J. B. and Fisher, R. E., "Cathodic Vacuum Etching of Uranium Alloys," Microstructures, 2 (1971), 23-24.

Cathodic vacuum etching technique for isothermally treated U-alloys resulted in a very clean etched surface free from an interfering oxide film. The degree of etching was easy to control and the etching parameters - current, gas, pressure, and time - were easy to reproduce. Sharp fine detail in the microstructure and good definition of grain boundaries with somewhat reduced grain contrast were revealed.

66. Estill, W., "Microprobe Analysis of Fractures." Proceedings of the Second Annual Technical Meeting, San Francisco, Calif. 8-10 September 1969. Edited by J. H. Binder and K. A. Johnson. Los Alamos, N.M.: The International Metallographic Society (1970), 85-88.

A scanning electron microprobe method for identifying small particles in fractured surfaces is described. U-7.5w/oNb-2.5w/oZr alloy was analyzed by this method.

67. Ferguson, J. E., "Analytical Applications of Electron Optical Instrumentation." Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee. U. S. Atomic Energy Commission Contract Report No. Y-DA-4818, August 1972.

Paper presented at 16th Conference on Analytical Chemistry in Nuclear Technology, 1972. The use of TEM, SEM, and electron microprobe analysis of small specimens is discussed. TEM examination of thin parts of U-Ti alloy showed an increase in strength due to precipitation of U_2Ti on aging at moderate temperatures. Crystallographic data and microstructure observed in electron micrographs of the U-Ti alloy were correlated. Identification, size, and distribution of carburized U-loaded ion exchange resins were determined by TEM. Results of fractographic study of U-7.5w/oNb-2.5w/oZr alloy using SEM are given.

68. Greulich, F. A., "Method of Producing Foils of Mulberry for Transmission Electron Microscopy." Sandia Laboratories, Albuquerque, New Mexico. U. S. Atomic Energy Commission Contract Report No. SC-DR-69-185, June 1969.

Foils of U-7.5Nb-2.5Zr alloy suitable for TEM were produced by spark cutting and spark planing followed by a final thinning in a dual jet thinner using a solution of 6%$HClO_4$ in CH_3OH. A chemical etch-polishing solution consisting of 35ml HCl, 25ml H_2O, 5ml HNO_3, and 1ml HF was also developed for intermediate thinning to replace spark planing for faster preparation of γ-phase material.

69. Irwin, G. J., "Metallographic Interpretation of Impacted Ogive Penetrators." Defence Research Establishment, Valcartier, Quebec. Report No. DREV-R-652/72, October 1972. (AD 907 367)

U-based and W-based penetrators which had impacted a semi-infinite soft steel target were metallographically studied. The U alloys tend to shear adiabatically at the surface due to: (1) low work-hardening capability, (2) severe stess concentration at the change in penetrator cross section produced during deformation, (3) bending as a secondary influence. Within the bands of adiabatic shear ductile cracks propagate. Martensitic U-2w/oMo alloy is mechanically unstable but the U-1w/oMo-0.7w/oNb-0.7w/oZr alloy shows potential as an alternative to W-Ni-Cu penetrator material when used at >70.76mm/μs impact.

70. Jackson, R. J., "Explosive Behavior of Uranium-Base Niobium Alloys During Metallographic Preparation," Int. Met. Rev., 2 (1973), 11-14.

Explosive behavior of U-Nb alloys after immersion in HNO was found to be related to a finely divided, two-phase microstructure and to a high C content. The HNO_3 selectively attacked the α-U leaving behind a finely divided U-rich γ-phase which can oxidize with explosive violence and NbC inclusions accumulated at the surface and were likewise subject to rapid oxidation. The most violent explosions occurred with slow-cooled, slab-cast, high-C alloys having a scale of UO and UO which the HNO dissolved and a reactive surface layer of finely divided γ-U, Nb_2C, NbC, and $UO_2(NO_3)_2 \cdot 6H_2O$ remained. When this wet or dry layer was sparked or struck a violent decomposition occurred and a residue of UO_2 remained on the surface of the metal.

71. Jackson, R. J., Johns, W. L., and Calabra, A. E., "Simplified Metallographic Techniques for Uranium Alloys and Other Metals." Dow Chemical Company, Rocky Flats Division, Golden, Colorado. U. S. Atomic Energy Commission Contract Report No. RFP-862, January 1967.

Two techniques, one standard (normal) polishing and the other an electrolyte-abrasive slurry on a rotating cathode were developed and were suitable for U-alloys, Be, and stainless steel. It is an economic operation in which mounting and polishing steps are eliminated.

72. Jackson, R. J., Lucas, R. L., and Calabra, A. E., "Macroexamination of Uranium Alloys." Dow Chemical Corporation, Rocky Flats Division, Golden, Colorado. U. S. Atomic Energy Commission Contract Report No. RFP-1744, November 1971.

U-base alloys were macroetched by two procedures; one consisted of electropolishing followed by immersion etching in HNO_3 and is ideal for large nonflat specimens, the other of mechanical grinding followed by a vibratory polish-attack macroetch which is ideal for macropatterns that are difficult to develop. The limitations of the procedure and photomacrographs of U-alloy castings and forgings prepared are presented.

73. Jepson, M. D., Kehoe, R. B., Nichols, R. W., and Slattery, G. F., "Transformation Behaviour of Some Dilute Uranium Alloys." Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy; Vol. 6, Basic Metallurgy and Fabrication of Fuels. Geneva: United Nations (1958), 42-54.

Metallographic and dilatometric data on dilute U-alloys containing one or more of: Al, Cr, Fe, Mo, Nb, Si, Ti, V, and Zr are summarized. Grain refinement results as a whole are considered and general trends in structural effects produced by alloying U are established.

74. Kehl, G. L., Mendel, E., Jaraiz, E. F., and Mueller, M. H., "Metallographic Identification of Inclusions in Uranium," Trans. ASM, 51 (1959), 717-35.

Method for the metallographic identification of common inclusions in U metal - UN, U(C,N), UC, UO, UH_3, UO_2 and U_6F - is described. Identity was established by removing the inclusion by ultrasonic "jack hammer" and subjecting debris created to x-ray diffraction analysis. Metallographic identification was established on the basis of time required to electroplate the inclusions with Cu and on the character of the Cu deposit.

75. Kloepper, H. C., Jr., "Some Observations on the Electron Metallography of Uranium." Mallinckrodt Chemical Works, Uranium Division, Weldon Spring, Missouri. U. S. Atomic Energy Commission Contract Report No. MCW-1501, August 1966.

Thin foil U-specimens suitable for high magnification study with TEM were prepared and metallographic techniques used are described. Studies of three β-quenched, α-annealed U-Si alloys revealed no U_3Si occurred within reasonable annealing times at 500° but at 600° precipitation readily occurred at dislocation sites with the number and size of particles increasing with annealing time. Other studies indicated that the deformation of U-Si alloys at room temperature was by twinning and at 500°C by slip.

76. Makin, S. M., "The Use of Irradiated Extraction Replicas to Identify Inclusions and Precipitates in Metals: A Preliminary Note," Int. J. Appl. Radiat. Isotop., 7 (1960), 258-59.

Note describing the application of extraction replica technique as used in the preparation of electron microscope replicas for the identification of inclusions and precipitates in metals. Stainless steel and U-replicas are presented.

77. Mastel, B., Bierlein, [illegible]. K., and Corey, C. L., "Electron Microscope Studies of Second Phase Particles in Dilute Alloys of Uranium." Battelle Memorial Institute, Pacific Northwest Laboratory, Richland, Washington. U. S. Atomic Energy Commission Contract Report No. BNWL-SA-90, March 1965.

Particle size and density distribution in dilute U alloys were studied by TEM and results agreed with those derived from replica electron micrographs. High resolution in TEM permitted inclusion of particles usually too small to be resolved by replica methods.

78. Miglionico, C. J., "Electron Fractographic Study of the Uranium Alloy, Mulberry." Proceedings of the Second Annual Technical Meeting, San Francisco, California, 8-10 September 1969. Edited by J. H. Bender and K. A. Johnson. Los Alamos, N.M.: The International Metallographic Society (1970), 223-42.

Results of preliminary fractography on U-7.5w/oNb-2.5w/oZr alloy and comparison of the topographics by SEM and replica microscopy are presented. From various laboratory experiments six types of failure were identified: (1) fatigue from a fatigue pre-crack Charpy specimen, (2) dimple rupture from tensile specimens, (3) intergranular, (4) quasi-cleavage, (5) intergranular and dimple rupture mixed mode, (6) intergranular and quasi-cleavage mixed mode. All tests were conducted in various corrosive environments and proved that the alloy was sensitive to environment and susceptible to both stress corrosion and H embrittlement types of failure.

79. Moore, D. A. and Walker, D. E. Y., "The Metallographic Preparation of Uranium-Silicon Alloys," Prakt. Metallogr., 7 (1970), 698-706. (Text in English and German)

Methods of polishing and etching U-1.8-4.0w/oSi alloys are described and the results obtained with the most satisfactory techniques are described. α-U, U_3Si_2, and U_3Si can be distinguished by normal etches but a line etch is required to show the microstructure of the U_3Si.

80. Porter, I. T. and Ruckman, J. C., "Electron Metallography of Uranium and Some Uranium Alloys." Atomic Weapons Research Establishment, Aldermaston, England. Report No. AWRE-0-52/68, September 1968.

Thin foils (<2000Å) of U and U-Mo and U-7.5w/oNb-2.5w/oZr alloys produced by electropolishing using both the "window" and "jet polishing" techniques were studied by TEM. Larger quantities of material were produced by the "window" technique but it is slower, involves more preparation, and examination of areas from the fractured end of a tensile test piece is more difficult than with "jet polishing" technique.

81. Robins, L. and Garufi, M. F., "Decreasing the Electropolishing Time for Uranium," in Technical Papers of the Fourteenth Metallographic Group Meeting held at Nuclear Metals, Inc., Concord, Massachusetts, 5-6 April 1960. U. S. Atomic Energy Commission Contract Report No. NMI-4996 (January 1964), 27-35e. (N65-36029)

The times required for preparing satisfactory metallographic specimens were determined by studying the behavior of mechanically polished U during electropolishing. Specimens suitable for preferred orientation and microstructural examination were obtained after 10mins in an orthophosphoric acid-ethyl alcohol-ethylene glycol solution. Evaluations were based on x-ray diffraction and microscopic observations.

82. Schaich, E. L., "The Identification of Inclusions in Uranium Metal by Color Metallography," in Advances in Metallography. Technical Papers of the Twentieth Metallographic Conference, Denver, Colorado, 18-20 May 1966. Edited by R. J. Jackson and A. E. Calabra. Dow Chemical Company, Rocky Flats Division, Golden, Colorado. U. S. Atomic Energy Commission Contract Report No. RFP-658 (October 1966), 18-25.

Techniques for the optical identification of various phases and inclusions in U-metal by controlled oxidation or heat tinting were developed. In this method the various phases assume characteristic colors by which they can be identified. At present UC, U_6Fe, U_3Si, and UAl_2 particles can be distinguished. Sample preparation, heat tinting procedures, and identification are discussed.

83. Thomas, G. J. and Miglionico, C. J., "Scanning Electron Microscopy of an Ion Etched Uranium Alloy." Electron Microscopy and Structure of Materials. Proceedings of the Fifth International Materials Symposium held at University of California, Berkeley, 13-17 September 1971. Berkeley: University of California Press (1972), 339-46.

Ion-etching technique and SEM were used to study U-7.5w/oNb-2.5w/oZr alloy. Inclusions exposed in relief by etching were studied by energy-dispersive x-ray analysis and samples were examined for microstructural changes within grains after various aging treatments and after mechanical deformations.

84. Wise, W. N., "Metallography of Uranium at Elevated Temperatures," in Technical Papers of the Sixteenth Metallographic Group Meeting held at Hanford Atomic Products Operation, Richland, Washington, 26-29 March 1962. U. S. Atomic Energy Commission Contract Report No. NMI-4998 (August 1964), 48-56. (N66-11320)

Electropolished U samples of varying thermal, chemical, and fabrication histories were studied in a vacuum heating stage. Microstructural changes resulting from the allotropic transformations were recorded. Dilute U-base alloys were prepared and their inclusions examined in situ with an electronprobe x-ray microanalyzer. The effect of α annealing on the precipitation of U_6Fe from a dilute solution of Fe in U is shown.

PROCESS METALLURGY

85. Dayton, R. W., "The Metallurgy and Fabrication of Uranium-Alloy Fuel Elements." Fuel Elements Conference, Paris, 18-23 November 1957. U.S. Atomic Energy Commission, Washington, D.C. Report No. TID-7546, Book 1 (March 1958), 302-65.

Unique characteristics which dictate the processing methods for U-3-7w/oNb and Zr (α'), U-10-20w/oNb or Mo (γ), and U-3.8w/oSi and U-40-80w/oZr (ε) alloys for use as fuel elements are discussed. Induction and arc melting for alloy preparation and brazing, roll banding and pressure bonding for cladding are discussed but for U-Zr alloys discussion is limited to cladding with metallurgical bonding. Detailed metallurgical characteristics of the materials which affect the fabrication operations are provided in the Appendix.

86. Henry, C. R., "Plutonium and Uranium as Engineering Materials." University of California, Lawrence Radiation Laboratory, Livermore. U.S. Atomic Energy Commission Contract Report No. UCRL-12427, February 1965.

Mechanical and physical properties of Pu and U and their principal alloys are summarized. Fabrication and joining techniques including forging, plating, machining, and welding are presented. The peculiar difficulties and hazards of packaging and handling assemblies containing these materials are discussed.

87. Jackson, R. J. and Wickland, C. E., "Electrocleaning of Uranium Alloys." Dow Chemical Company, Rocky Flats Division, Golden, Colorado. U.S. Atomic Energy Commission Contract Report No. RFP-1596, March 1971.

The types of surface oxidation on U-alloys, the chemical pickling procedures for the removal of the surface oxides, and a proven electrochemical prodedure for the removal of the scale surface are presented and discussed.

88. London, R. V. and Edelman, R. E., "Manufacture of Uranium-8.5% Molybdenum Balls." Frankford Arsenal, Philadelphia, Pennsylvania. Research Report No. FA-TM-M65-3-1, July 1964. (AD 448 999)

Fabrication of high density components is evaluated, using the example of 0.20 in d. balls weighing 20 gms. The problem of fabricating a smooth wire, free from kinks and surface imperfections was undertaken. Processing phases - casting, heat treating, forging, rolling, annealing, swaging, and testing - are described. A cold head technique followed by grinding was used to study the manufacture of production quantities of U-balls. The methods of pressing the material, rill filling, and tumbling are described.

89. "Special Fabrication Techniques," React. Mater. 13, (1970), 92-105.

Fabrication techniques for reactor materials reported are: (1) powder metallurgy methods, (2) melting, casting, and fabrication of cast structures including U-[illegible] alloy, (3) welding and brazing, (4) nonelectrolytic chemical plating including electroless Ni plating of U to form U-Ni alloy at the interface, (5) electroplating, (6) explosive metalworking, (7) NDT with emphasis on ultrasonic techniques. For each technique reported the location of where the work is or has been done is included.

90. Wilkinson, W. D., Uranium Metallurgy, Vol. I: Uranium Process Metallurgy.
New York: Interscience, 1962.

Metallurgical processing of U-ores and metals and safe practice in U metallurgy are presented. Some aspects of processing U-alloys are included.

91. U.S. Patent No. 2,789,072. April 16, 1957. Heat Treated Uranium Alloy and Method of Preparing Same. Donald W. White, Jr. to U.S. Atomic Energy Commission.

Method of preparing dimensionally stable U-Cr alloys by adding 0.1-10a/oCr to U and heating to a temperature above the $\beta \rightarrow \alpha$ transformation temperature, quenching to α-phase, and holding at this temperature until transformation to α-phase crystals is complete.

92. British Patent No. 943,942. December 11, 1963. Improvements In or Relating to Uranium Alloys. Commissariat a l'Energie Atomique.

Method of preparing U-1-3w/oMo fuel alloys by vacuum melting the two metals in a graphite crucible, coated with a reducing cement, casting and cooling the ingots at a rate of 10°-80°C/min. The microstructure is characterized by grain size of 20-80μm, with no preferred orientation, making them superior to unalloyed U with respect to creep, traction, and cycling resistance.

93. British Patent No. 950,163. February 19, 1964. Improvements In or Relating to Uranium-Molybdenum Alloys. Jeanne Lehmann and Henri Ollier to the Commissariat a l'Energie Atomique.

Method of preparing U-3-6w/oMo fuel alloys by vacuum melting the two metals in a graphite crucible, coated with a reducing cement, casting, heating the ingots to 675°-800°, quenching to 550° in a fused salt bath, and finally cooling at a rate of 20°-60°C/min. Alloys have microstructure with no preferred orientation and grain size of 60-80μm making them superior to unalloyed U with respect to creep, traction, and thermal cycling resistance.

94. British Patent No. 1,138,949. January 1, 1969. Improved Uranium-Based Alloys Employed as Fuel Elements in Nuclear Reactors and Process for Making Same. SNAM-S.p.A., Milan, Italy.

Method of making U-0.05-0.3w/oCr-0.5-3.0Nb alloys for use as nuclear fuels present in which U is present in the form of a fine-grained dispersion of γ-phase U in fine-grained (<40μm) α-phase, which is stable and free from preferred orientation. Alloy is cooled from the γ-phase 300°-50°C/min, then reheated to the β-phase, maintained for a period <3 hrs, cooled to room temperature at a rate of 400°-4°C/min and subsequently reheated in the α-region.

Melting and Solidification

95. Avery, J. G., "Induction Melting and Casting of U-2.2wt.%Nb and U-0.75wt.%Ti." Dow Chemical Company, Rocky Flats Division, Golden, Colorado. U.S. Atomic Energy Commission Contract Report No. RFP-1948, February 1973.

Process for obtaining sound, segregation-free ingots of U-2.2w/oNb and U-0.75w/oTi by induction melting is described and casting parameters are discussed.

96. Baird, J. E. and Carson, N. J., "Melting and Casting of Uranium, Zirconium, Niobium Alloys." Nuclear Metallurgy, Vol. 4. A Symposium on Uranium and Uranium Dioxide. IMD Special Report Series No. 4. New York: The Metallurgical Society of AIME (1957), 31-37.

Development work and production experience of induction melting and casting, of U-5w/oZr-1.5w/oNb alloy for coil materials in nuclear reactors are described. Furnace design, crucible materials Zr dissolution, and ingot soundness are discussed.

97. Binstock, M. H. and Stanley, J. A., "Casting Development for Uranium-Molybdenum Alloy Shapes." Atomics International, Canoga Park, California. U.S. Atomic Energy Commission Contract Report No. NAA-SR-4030, November 1959.

U-Mo shapes of varying sizes and thicknesses were cast from a molten charge using specifically designed graphite distributors and molds. Solid cylinders, hollow cylinders, and flat plate shapes were cast in gang molds. All castings had smooth surfaces and the solid shapes were cast to 0.006in tolerance on all dimensions except length.

98. Britton, W. H. and Haynes, W. B., "Arc Melting of Uranium-Rich Alloys." Nuclear Metallurgy, Vol. 4. A Symposium on Uranium and Uranium Dioxide. IMD Special Report Series No. 4. New York: The Metallurgical Society of AIME (1957), 63-66.

Consumable and non-consumable arc-melting techniques have been successfully used in production melting of U-12w/oNb and U-12w/oMo alloys. Control of macro-segregation and removal of contaminants are the major problems that have been encountered. Arc-melting techniques have been limited but possible future developments are considered.

99. Carson, H. J., "Induction Melting of Uranium Base Alloys." Nuclear Metallurgy, Vol. 4. A Symposium on Uranium and Uranium Dioxide. IMD Special Report Series No. 4. New York: The Metallurgical Society of AIME (1957), 23-29.

The techniques and equipment for induction melting of binary U alloys containing Nb, Zr, Mo, Si, Cr, and Al with melting points <1600°C are described. The use of coated graphite and other materials as crucibles and molds are discussed.

100. Chandley, G. D. and Fleck, D. G., "Structural Uranium Alloy Melting, Casting and Heat Treating Techniques," Mod. Cast., 40 (1961), 56-64.

Processing techniques including melting, casting, and heat treatment for making structural U-base alloys having high strength and good corrosion resistance are described.

101. Chandley, G. D. and Fleck, D. G., "Uranium Foundry Practice," Foundry, 88 (1960), 76-79.

Foundry practice suitable for casting U parts of exceptional soundness and uniformly high mechanical properties is described. Vacuum melting and pouring are required, and the casting produced must be kept under high vacuum until cooled to ~1200°F.

102. Chandley, G. D., Fleck, D. G., and Crocker, B. W., "First Success with Cast Uranium," Mod. Cast., 40 (1961), 41-44.

Mass production application of U-8%Mo alloy for "spotting rounds" for atomic warhead firing of weapons using a coaxial melting-casting process with a refractory mold is reported.

103. Coughlen, C. P., Evans, P. A., and Townsend, A. B., "Homogenization Evaluation of a Cast Uranium-Molybdenum Alloy." Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee. U.S. Atomic Energy Commission Contract Report No. Y-1696. October 1969. (AD 918 540L)

Studies to determine the method and parameters of heat treatment for homogenization of a U-10w/oMo alloy were conducted. The specimens were tensile tested and metallographically examined. The as-cast material indicated evidence of coring, heat treatment homogenized the material, and the wrought material indicated evidence of chemical inhomogeneity.

104. Crompton, C. E., Davis, J. O., and Guay, A. E., "Casting of Uranium Alloys." Reactive Metals. Metallurgical Society Conferences, Vol. 2. Edited by W. R. Clough. New York: Interscience (1959), 147-70.

Practical methods for producing tonnage quantities of U-Mo, Nb, and Zr alloys and dilute alloys of Si, Fe, and C are reviewed. Comparative data on grain size and grain refinement by alloying additions of static and centrifugally cast, rolled, and heat treated sections are presented.

105. Edelman R. E. and Saia, A., "Coring Blind Holes in Small Uranium Castings," Mod. Cast., 54 (1968), 82-84.

A method of casting blind holes, having a ℓ/d ratio of 5:1, into a small U-8.5%Mo alloy shape is described. A rammed bentonite-bonded graphite mix was used for both the core and the mold. Castings were sound and possessed satisfactory properties.

106. Finucane, J. S., "The Viscosity of Uranium Metal and Some Uranium-Chromium Alloys." Unpublished Ph.D. dissertation University of California, Berkeley, 1969.

An oscillating crucible viscometer capable of precise vicsocity determinations at >1000°C was constructed. The operating details were developed and the viscosities of U and two U-Cr alloys were measured.

107. Foster, E. L., Jr., Fletcher, B. L., Franklin, C. K., Lechler, A., and Dickerson, R. F., "Experimental and Theoretical Studies of the Solidification of Uranium Castings." Battelle Memorial Institute, Columbus, Ohio. U.S. Atomic Energy Commission Contract Report No. BMI-1390, October 1959.

Large cylindrical U ingots cast in graphite molds were studied using a mathematical model and a digital computer. Heat flow during solidification is described.

108. Frank, J. W. and Macherey, R. E., "Casting Uranium-5% Zirconium 1.5% Niobium Alloys Into Zirconium and Zircaloy-2 Containers." Argonne National Laboratory, Illinois. U.S. Atomic Energy Commission Contract Report No. ANL-5442, July 1958.

U and U-5%Zr-1.5%Nb were cast with Zr and Zircaloy-2 molds of various sizes and shapes. Provided the molds were out-gassed at elevated temperature before use and proper preheating precautions were observed, the castings made in cans of circular cross section were well bonded and sound.

109. Guichard, C. and Soret, J. C., "Vacuum Experimental Castings of Uranium-Tests of Solidification Rate Control," Vacuum, 19 (1969), 175-77.

Equipment and procedure for vacuum melting and casting of low-alloyed U into tubes weighing ~40kg each. The method is recommended for metals with a high gas content or high vapor pressure which are unsuitable for electron beam melting. Test results are presented and important design parameters are derived.

110. Hayashi, C., Kashu, S., and Tsuchiya, T., "A Skull Furnace and Its Operation." 1961 Transactions of the Eighth National Vacuum Symposium Combined with the Second International Congress on Vacuum Science and Technology, Vol. 2. Edited by Luther E. Preuss. New York: Pergamon Press, Inc. (1962), 744-48.

U, U-3.6%Zr, and U-1.0%Nb alloys were melted and cast in a skull furnace by using bottom pouring crucibles incorporated with a centrifugal casting device. Eight pieces of 1/2 in o.d. x 6 in ℓ rods were cast in vacuum (<1 torr) using U-alloy consumable electrodes and there was no contamination or segregation in the cast shape but density was slightly less than theoretical value which may be improved by heating up the mold.

111. Healy, G. J. and Shore, A., "Vacuum Melting and Casting Uranium Molybdenum Alloys." Defence Research Establishment, Valcartier, Quebec. Report No. DREV-M-2060/71 (May 1971), 32-55. (AD 890 370)

Vacuum induction furnaces of 180, 350, 3000lbs. working capacity with ceramic crucibles were used for the melting and casting of U-Mo alloys, with specifications on Mo and C content. Mo is easily held to within ±5% of requested target analysis but C is very difficult to control. The types of furnace and crucible used depended on C level that must be maintained.

107. Foster, E. L., Jr., Fletcher, B. L., Franklin, C. K., Lechler, A., and Dickerson, R. F., "Experimental and Theoretical Studies of the Solidification of Uranium Castings." Battelle Memorial Institute, Columbus, Ohio. U.S. Atomic Energy Commission Contract Report No. BMI-1390, October 1959.

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112. Hueston, F. H. and Barclay, R. S., "Some Problems in the Melting and Casting of Uranium and Its Alloys," Can. Mining Met. Bull., 60 (1967), 795-98.

Crucible materials for melting U and U-alloys were evaluated. Depending on the application ZrO_2 fused 97% MgO, and graphite have been found to be the most suitable. Ceramic-type molds are superior to graphite for small sections (<4sq in) and those shaped castings which prohibit the economic use of machined graphite molds. Heating cycles, addition mechanisms, and furnace conditions for melting are discussed.

113. Jackson, R. J., "Metallographic Study of Segregation in Uranium-Base Niobium Alloys," Metallography, 6 (1973), 347-59.

Three types of Nb segregation occur in U-Nb alloys: (1) dendritic coring, (2) macrobanding, (3) gross-ingot segregation. The origin and nature of these inhomogeneities and the optical and x-ray metallographic techniques for their identification are discussed. Half-height peak widths, peak intensity ratios, hardness, and optical microstructure measurements are related to segregation. Procedures for minimizing segregation are described.

114. Jaynes, G. E., Taub, J. M., and Doll, D. T., "Development of Casting Techniques for Uranium and Uranium Alloys." Nuclear Metallurgy, Vol. 4. A Symposium on Uranium and Uranium Dioxide. IMD Special Report Series No. 4. New York: The Metallurgical Society of AIME (1957), 1-15.

U and U alloys were cast into slugs ranging in weight from 1 to 1800 kg in various size vacuum furnaces with either micarta tube or steel tank construction. Graphite was used for crucibles and molds which were coated with a ceramic to prevent metal-graphite contact. The use of uncooled Cu induction coils, induction stirring, and castable refractories are described. Neither Cu nor glass provided any advantage when compared with graphite.

115. Katz, N. H. and Binstock, M. H., "Casting of Long and Thin Plates of Uranium-Molybdenum Alloys." Atomics International, Canoga Park, California. U.S. Atomic Energy Commission Contract Report No. NAA-SR-6227, November 1961.

Vacuum-induction casting of U-Mo alloys into both thin (0.01-0.10in) and long (36in) plates is described. Melting and casting cycles and casting techniques are explained. The plates were evaluated by radiographic and metallographic examination and by chemical analysis.

116. Kinsey, H. V., "The Production of Titanium-Uranium and Iron-Uranium Master Alloys in the Consumable-Electrode Vacuum-Arc Furnace." Canadian Department of Mines and Technical Surveys, Mines Branch, Ottawa. Report No. NP-10771, January 1961.

U-base alloys containing Ti and Fe were prepared using consumable-electrode vacuum-arc melting. Electrode and ingot production are described.

117. London, R. V. and Edelman, R. E., "Chill Effect on Cast Uranium -8.5 Per Cent Molybdenum Plates," Mod. Cast., 45 (1964), 233-37.

U-8.5w/oMo alloy plates were investment cast in a vacuum induction furnace using a bottom pour technique. Three specimens (5in, 4in, 3in) were chill cast and one (5in) remained unchilled. Tensile properties, ductility, and grain size of the cast plates were determined.

118. Loveland, C. W. and Owen, J. E., "Production of Molybdenum-Uranium and Zirconium-Uranium Alloys." Union Carbide Corporation, Paducah Plant, Kentucky. U.S. Atomic Energy Commission Contract Report No. KY-348, August 1960.

Coreduction method of producing U-3, 6, 10, 14w/oMo and U-2w/oZr alloys at the Paducah Metals Plant is described. Various ratios of Mo powder and MoO_3 were blended with UF_4 and Mg and charged into refractory lined (MgF_2) bomb shells for reduction. Surface impurities were removed from the resultant alloy debris by roasting at 1200°F for ∿2 hrs, followed by a H_2O quench, melted under vacuum in an induction furnace, and cast into ingots (3in d.). The U-Zr alloy debris were also produced by the coreduction of UF_4, ZrF_4 and Mg.

119. Mahaffey, J. W., "Control of Carbon Pickup in Uranium Metal by Induction Furnace Tuning." National Lead Company of Ohio, Cincinnati. U.S. Atomic Energy Commission Contract Report No. NCLO-768, February 1959.

Coreless induction furnaces may be effectively standardized by tuning the high-frequency by adjusting the variable capacitator banks to obtain a standard impedance of 3.3-3.6Ω. Correct time-power control also controls the C pickup.

120. Murray, J. R. and Williamson, G. K., "Techniques Used in Alloy Investigations at Temperatures Above 1200°C," J. Less-Common Metals, 1 (1959), 73-76.

Problems related to U and Th and their alloys, because of their high reactivity, are presented. Data on thermal analysis, the use of the arc furnace for casting various shapes, and determination of melting points are included.

121. Roland, E. H., "Calculated Equilibrium Constants for Metal-Oxygen Reactions in Molten Uranium Alloy." Westinghouse Electric Corporation, Bettis Atomic Power Laboratory, Pittsburgh, Pennsylvania. U.S. Atomic Energy Commission Contract Report No. WAPD-TM-99, November 1957.

This study provided preliminary qualitative information on two important points regarding oxidation reactions occuring in molten U-alloys: (1) relative ability of various elements to deoxidize U, (2) relative stability of the oxides formed as a result of deoxidation. Ideas have been proposed regarding the extent to which U can be purified by conventional melting techniques.

122. Schaffer, P. S., "Some Theoretical and Practical Considerations in Vacuum Induction Melting of Uranium Alloys." Watertown Arsenal Laboratories, Massachusetts. Report No. WAL-MS-33, 1961. (AD 610 003)

Melting, refining, and casting procedures of depleted U-alloys using vacuum induction melting techniques, a hand-rammed commercially pure MgO crucible, and a phosphate-bonded ZrO_2-SiO_2 mold are dicussed. Casting with ductile qualities in the as-cast condition and a reduction of residual gas concentration in the alloy resulted.

123. Shuck, A. B., "Centrifugal Casting of U-Zr Alloy Rods." Nuclear Metallurgy, Vol. 4. A Symposium on Uranium and Uranium Dioxide." IMD Special Report Series No. 4. New York: The Metallurgical Society of AIME (1957), 39-50.

Design, development, and experimental evaluation of multiple mold centrifugal casting machine with precision Cu molds used in conjunction with high-vacuum induction heated melting and pouring to produce U-2w/oZr alloy fuel rods or slugs is described.

124. Stanley, J. A. and Binstock, M. H., "Development and Production of Uranium 10wt,%Molybdenum As-Cast Slugs for HNPF Physics Experiment." Atomics International, Canoga Park, California. U.S. Atomic Energy Contract Report No. NAA-SR-4874, April 1960.

U-10Mo alloys were cast into slugs ∿0.16in/d. and 12in/ℓ using a multicavity mold. The alloys were vacuum induction melted in $MgZrO_3$ coated graphite crucibles and cast into coated graphite molds. The graphite used is an important variable in the process. The homogeneity, surfaces, and dimensional tolerances of the 3850 slugs of as-cast U-10w/oMo met all the requirements for nuclear fuel materials.

125. Stoddard, S. D. and Harper, W. T., "Refractories for Melting and Casting Uranium and Other Metals," Bull. Amer. Ceram. Soc., 36 (1957), 105-08.

Various pure oxide refractories used for melting and casting of U, U-alloys and other metals are discussed. The purity and methods of fabrication of the refractories, coating materials, and methods of applying them to molds and crucibles are considered. A typical vacuum furnace for melting U and U-alloys is described.

126. Swarts, E. L., "The Action of Molten Uranium on Graphite," Trans. Met. Soc. AIME, 215 (1959), 553-54.

A continuous carbide layer was formed when molten U contacted graphite. The layer clads the graphite and probably protects the graphite against rapid corrosion. The layer itself is not stable toward U.

127. U.S. Patent No. 3,343,947. September 26, 1967. Ternary Uranium Alloys Containing Molybdenum with Niobium or Zirconium for Use with Nuclear Reactors. Carlo Fizzotti, Guglielmo Colobianchi, Benito Dalmastri, and Alberto Masperoni to Comitato Nazionale per l'Energia Nucleare.

Specifications are given for methods of preparing and heat treatment of U-Mo-Nb and U-Mo-Nb-Zr alloys for reactor fuels that are stable, fine grained, and free from preferred orientation or distortion as-cast.

128. British Patent No. 950,163. February 19, 1964. Improvements In or Relating to Uranium/Molybdenum Alloys. Jeanne Lehmann and Henri E. Ollier to Commissariat a l'Energie Atomique.

Process for preparing a U-0.3-0.6w/oMo alloy by melting under vacuum in a graphite crucible covered with a reducing cement as Al_2O_3 or $CaZrO_3$, maintaining the product in a molten state and pouring it into molds in the form of bars or tubes, heat treating at 675°-800°, followed by a stepped tempering with the main tempering 550° for 15 min and cooling to the ambient temperature at a rate of 20°-60°C/min to produce a microstructure with grains of 60-80µm.

129. British Patent No. 981,956. February 3, 1965. Improvements In or Relating to Uranium Alloys. Malcolm Stevens to the United Kingdom Atomic Energy Authority.

Method of preparing U-0.4-0.55w/oMo and U-0.15-0.25w/oMo 0.1-0.15w/oAl alloys having fine as-cast grain structures after being subjected to accelerated cooling in the range of 75°-300°C/min.

130. British Patent No. 1,183,635. March 11, 1970. Improvements in Casting Processes. Michel Manet and Jean Noel Ach to Commissariat a l'Energie Atomique.

Process for casting U-alloys in which specially designed mold and metal are first brought to a temperature higher than the solidification point of the U-alloy and then cooled by bringing into contact with the mold a cooling material which is initially at a temperature below the solidification point of the casting metal.

Power Metallurgy

131. Bufferd, A. S., Zwilsky, K. M., and Grant, N. J., "Dispersion Strengthening in the Uranium-Alumina System," ASM Trans. Quart., 60 (1963), 508-12.

Dispersion strengthened U was prepared by the mechanical mixing of UH_2 and Al_2O_3, compacting in vacuum, dehydriding in vacuum at 260°, and extruding at 620°C. The resulting dispersions were very fine and the creep-rupture properties were superior to hot rolled U.

132. Hausner. H. H. and Zambrow, J. L., "Powder Metallurgy of Uranium." Powder Metallurgy in Nuclear Engineering. Cleveland, Ohio: American Society for Metals (1958), 73-81.

Powder production, compacting, and sintering techniques for shapes consisting of U, U-alloys, and U-compounds are described. U samples prepared by hot pressing are high in hardness and tensile strength and low in ductility. Special heat treatments of the sintered product are necessary to increase ductility and lower hardness.

133. Kalish, H. S., "Uranium Alloys by Powder Metallurgy." Powder Metallurgy in Nuclear Engineering. Cleveland, Ohio: American Society for Metals (1958), 141-48.

U-base binary alloys containing 0.5-5.0w/oMo, Nb, Si, Cr, Zr, or V (fine powder ∿325 mesh) may be fabricated by powder metallurgy: cold pressing and sintering, hot pressing, or powder rolling. Cold pressing, being the most straightforward approach, was used. Mo was the most successful alloying addition, increasing ductility and controlling grain size. The smaller the Mo addition, the larger the grain growth, and grain growth can be eliminated at ∿3.0-3.5w/oMo. In thermal cycling, additions of >1.0w/oMo showed excellent stability.

134. Kalish, H. S. et al., "Uranium Alloys." Reactor Handbook, 2d ed; Vol. 1, Materials. Edited by C. R. Tipton, Jr. New York: Interscience (1960), 147-210.

Preparation by powder metallurgy, melting and coreduction, fabrication, heat treatment, physical and mechanical properties, corrosion, and irradiation effects of U-alloys are included in this chapter. Also included are 198 references and a Selected Reading List.

135. Kieffer, R. and Sedlatschek, K., "Uranium Alloys Prepared by the Powder-Metallurgical Infiltration Process." Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy; Vol. 6, Basic Metallurgy and Fabrication of Fuels. Geneva: United Nations (1958), 96-103.

Infiltration processes for the manufacture of U-alloys, U-pseudo-alloys and combinations of U-compounds with metals are described. A metal powder or liquid was infiltrated into a porous body by means of capillary action at 750°-1250°C. Strength of infiltrated materials can be increased by incorporating metallic reinforcements (rods, nets, coils, etc.) into the skeleton prior to infiltration.

136. Myers, R. H. and Robins, R. G., "Uranium-Alloy Powders by Direct Reduction of Oxides." Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy; Vol. 6, Basic Metallurgy and Fabrication of Fuels. Geneva: Nations (1958), 91-95.

The feasibility of producing U-Ni, Cr, Mo, Nb alloy powders by direct reduction of compound oxides and mixed oxides by Ca was studied. Reduction usually begins at ∿630°C after which bomb temperature is rapidly raised to above the liquidus of the alloy. Compound oxide reduction resulted in high heats of reaction, low yields, irregular particle size, and inhomogeneous composition. The mixed oxide process was superior, in all respects, except particle-to-particle composition variation.

137. Rabin, S. A., Lotts, A. L., and Hammond, J. P., "Swaging of Uranium-Molybdenum Alloy Powders Containing 10 to 15 Wt% Molybdenum." Oak Ridge National Laboratory, Tennessee. U.S. Atomic Energy Commission Contract Report No. ORNL-TM-455, September 1963.

U-10-15w/oMo alloy rods were fabricated by hot, rotary swaging both U-Mo powder mixtures and prealloyed powders contained in Inconel tubing with a Mo barrier. Densities >95% of theoretical were obtained with reductions in area of 55% at 1050°-1100°C. Alloy homogeneity was good for prealloyed powders, but traces of Mo-rich, γphase persisted in rods made from elemental mixtures.

138. Saller, H. A. and Rough, F. A., "Alloying by Powder Metallurgy." Powder Metallurgy in Nuclear Engineering. Cleveland, Ohio: American Society for Metals (1958), 120-40.

Powder metallurgy processes in reactor metallurgy and atomic energy work are emphasized. Experimental applications included the use of powder metallurgy in determining phase diagrams for various alloy systems and also studying homogenization or diffusion specimens.

139. Sari, C., "Preparation of Zirconium Powders, Zirconium Alloys and U-Mo Alloys." Translated from the French for United States-Euration Joint Research and Development Program. Report No. EURAEC-1390, May 1965.

Powders of Zr, Zr-alloys, and both α-U-4%Mo and γ-U-12%Mo alloys were produced by the hydride method or by a direct comminution of selected turnings. A fluidized bed process was developed for the reduction of the hydride. Results of a study on hydriding kinetics are presented.

140. Stewart, J. H., Jr., "Quantitative Analysis of Micrometer Size Uranium Alloy Powders Using the Electron Microprobe X-ray Analyzer." Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee. U.S. Atomic Energy Commission Contract Report No. Y-1745, September 1970.

The electron probe was used in the quantitative analysis of individual microparticles of U-Mo and U-Nb-Zr alloys. The characteristic x-ray intensities of the alloyed metals excited by the electron beam for absorption were corrected by a computer program. A simplified specimen preparation and handling procedure was devised. The accuracy of the method is comparable to that of the conventional chemical analysis of bulk samples.

141. Zambrow, J. L., "Powder Metallurgy of Uranium and Uranium Alloys." Nuclear Metallurgy, Vol. 4. A Symposium on Uranium and Uranium Dioxide. IMD Special Report Series No. 4. New York: The Metallurgical Society of AIME (1957), 117-21.

Processing of uniformly porous U and U-alloy components by hot pressing of powders is described. Closed porosity is encountered which decreases with increasing porosity U-Mo, Si, Nb, Cr, Zr, V densification and grain sizes are tabulated.

Thermomechanical Processing

142. Brook, G. B. and Iles, R. F., "Thermomechanical Treatment of Uranium Alloys Containing Molybdenum and Vanadium." Defence Research Establishment, Valcartier, Quebec. Report No. DREV-M-2060/71 (May 1971), 309-68. (AD 890 370)

γ-forming and isoforming treatments were investigated as a means for producing fine grained α structure in U-2-5w/oMo, U-4-5w/oMo - 1 w/oV, and U-2w/oNb-2w/oZr alloys. γ-forming had little or no effect on the shear transformation to α'_b or α''_b but fine grain α structures with some compressive ductility were produced. Additions of V to U-Mo raised the eutectoid temperature so that isoforming could be performed at higher temperatures. Hardening was caused by high isoforming deformation, usually at 525°C and by reheating prior to final deformation.

143. Davis, T. F., "Extrusion of Uranium, Uranium Alloys, and Uranium Compacts - A Literature Search." U.S. Atomic Energy Commission, Office of Technical Information, Washington, D. C. Report No. TID-3563, June 1961.

A literature survey including unclassified reports appearing in Nuclear Science Abstracts and also journals, patents, books, and other published material on the subject of extrusion of U, U-alloys, and U-compacts covering the period 1951-1961. A subject index is included.

144. Edelman, R. E., "The Backward Extrusion of Uranium - 8.5% Molybdenum Alloy Cores." Frankford Arsenal, Philadelphia, Pennsylvania. Research Report No. FA-R-1887, April 1968. (AD 834 662)

Method of producing a blind hole in U-8.5%Mo alloy core of a 15mm spotter round by hot reverse extrusion is described. Parts had smooth surfaces and were within specified concentricity requirements. It is believed other U-alloys could be used.

145. Fellows, J. A., "Bomb Reduction, Forging and Extrusion of Uranium and Uranium Alloys." Fuel Elements Conference, Paris, 18-23 November 1957. U.S. Atomic Energy Commission, Washington, D. C. Report No. TID-7546, Book 1 (March 1958), 46-74.

U and high-purity binary U-alloys were developed by thermite bomb reduction of massive charges. Remelting step to convert to ingot forms is not required. Press forging and extrusion procedures are discussed. Examples of structure and the influence of alloy additions on both forming characteristics and product quality are illustrated.

146. Foster, E. L., ed., "Production Uranium Residual Stresses, Internal Friction, and Modulus." Battelle Memorial Institute, Columbus, Ohio. U.S. Atomic Energy Commission Contract Report No. BMI-1658, December 1963.

Levels and distribution of residual stresses encountered in specimens from the manufacture of hollow U fuel elements were determined. To obtain data, an electrochemical procedure was developed and used for removal of metal from the bores of the specimens. Residual stresses in H_2O quenched specimens was $\sim$60,000 psi and in the oil-quenched specimens $\sim$12,000 psi. In the final production step earlier stresses are almost cancelled; the final stresses were 15,000-20,000 psi. After various mechanical and thermal treatments, measurements of internal friction and Young's modulus went through a maximum and minimum, respectively, with increasing severity of quenching from a β temperature.

147. Grigorovich, V. K. and Golovkina, N. E., "Deformation of Binary Alloys of Uranium Containing 0-20 at % Mo, 0-30 at % Nb and 0-100 at % Zr When Subjected to Cyclic Heating up to 600°-900°C." Translated from the Russian for University of California, Lawrence Radiation Laboratory, Livermore. Report No. UCRL-Trans-10453, 1970.

Shape stability and the tendency toward surface hummock formation on cyclic heating of U- up to 20a/oMo, U- up to 30a/oNb, and U- up to 100a/oZr alloys were studied. Specimens were forged, quenched from 800°, and annealed at 500°C for 24 hrs. It was found that shape stability after cyclic heating increases as the alloying additive is increased to 20-30a/o. Residual deformations increase at the upper temperature limits of the heating cycles and the shapes that undergo $\alpha \rightarrow \beta$ transformation are sharply changed.

148. Kinas, E. N. and Rizzitano, F. J., "Evaluation of Co-Reduced Depleted Uranium Alloy." Watertown Arsenal, Massachusetts. Research Report No. WAL-TR-420.5/1, March 1963. (AD 401 158)

U-8Mo and U-8Mo-1Ti alloys were investigated to determine the advantage of forging depleted U components directly from co-reduced dingot stock eliminating remelting and alloying operations. Upset forging and cogging hot-working methods were used and improved the mechanical properties, especially ductility and Charpy V-notch impact.

149. Perry, J. A., "Laboratory Extrusion of Uranium Alloys." Defence Research Establishment, Valcartier, Quebec. Report No. DREV-M-2060/71 (May 1971), 76-95. (AD 890 370)

Practical problems experienced in extruding U-alloys in a laboratory are described and suggestions for handling these problems in a production situation are given. Mechanical aspects of the thermomechanical working of U alloys are discussed in the Appendix.

150. Russell, R. B., "Textures in Extruded Uranium." Advances in X-Ray Analysis, Vol. 3. Proceedings of the Eighth Annual Conference on Applications of X-Ray Analysis. Edited by William M. Mueller. Denver: University of Denver (1960), 315-30.

Effects of extrusion variables - prior texture, billet and linear temperature, reduction in area, and ram speed - on textures were examined by crystallographic pole figures for extruded U rods and tubes. In general, increase in extrusion temperature and increase in reduction ratio have similar effects. Final texture can be deeply effected by prior texture. Ram speed has no important effect between 13 and 10in/min, and temperature effects the development of a strong 110 axial texture at temperatures > ~525°, a strong 010 axial texture at <400°, and a mixture of both at intermediate temperatures. A 900°C, γ-phase extrusion is shown to have a mild 100, 010, 021, 001 texture.

151. Sengupta, P. K. and Rezek, J., "Thermomechanical Processing of U-3 Mo." Defence Research Establishment, Valcartier, Quebec. Report No. DREV-M-2060/71 (May 1971), 277-308. (AD 890 370)

The effect of thermomechanical processing on the hardness and grain morphology of U-3Mo alloy was studied. The hardness was increased when deformation occurred as an intermediate step below the $\gamma \rightarrow \alpha$ transition temperature. Maximum hardness (Rc 62) was attained by heating at 760°, followed by a H_2O quench and further deformation at room temperature and also by aging at 380°C for 2 hrs. There was no significant variation in grain size or systematic variation of hardness with grain size.

152. Smith, E. J., Jr., "Fabrication of Uranium and Uranium-Base Alloy Tubes and Rods." Battelle Memorial Institute, Columbus, Ohio. National Lead Company Subcontract Report for the U.S. Atomic Energy Commission. Research Report No. BMI-X-294, June 1964.

A rolling study in which as-extruded or β-heat treated U and U-base alloys were fabricated in the form of tubes and rods was made. Roll separation force, mill powder input, time of rolling, and specimen temperature for each specimen and pass values were recorded using the necessary instrumentation. Data for each specimen and pass were tabulated. As-extruded U in either tube or rod form was easiest to fabricate and U alloyed with Fe, and most difficult with Si and Al.

153. Stohr, J., "Fabrication of Uranium. Influence of Fabrication on the Microstructure and Mechanical Characteristics of Uranium and of Slightly Alloyed Uranium." Translated from the French for the U.S. Atomic Energy Commission, Office of Technical Information, Washington, D. C. Report No. AEC-TR-6519, 1962.

Microstructure and mechanical properties of technically pure and lightly alloyed U after fabrication or after fabrication followed by tempering or heat treatments were studied. The quality of U and characteristics of the alloys, and fabrication by casting and plastic deformation, are evaluated. Results obtained from each method are compared.

154. Tardif, H. P., "Preliminary Observations in Hot-Worked Uranium Alloys." Defence Research Establishment, Valcartier, Quebec. Report No. DREV-TN-1942/71, June 1971. (AD 891 497)

Preliminary studies of the mechanical properties of both hot-worked and as-cast U-alloys containing 2-3w/oMo, Nb, V, and/or Zr are reported. Commercially produced alloys with differences in composition, processing variables, and heat-treatment temperatures showed no significant differences in properties between the cast and wrought alloys. Results of all tests are presented in tabular form. Further studies using split heats are suggested.

155. Tardif, H. P. and Erickson, W. H., "Thermomechanical Treatment of High Density Uranium Alloys." Defence Research Establishment, Valcartier, Qeubec. Report No. DREV-R-624/71, April 1971. (AD 890 364)

The results of work on the thermomechanical treatments of U-2-6w/oMo and other U-alloys (minimum hardness Rc 54) containing γ soluble elements are summarized. Results indicate that the significant changes expected in strength and ductility were not produced. Low temperature γ-phase forming and isoforming were investigated. Some grain refinement and increase in hardness was achieved by γ working and it is considered that controlled deformation of the stable γ-phase could produce improved properties.

156. Uhlmann, W., "Preferred Orientation and Recrystallization in Fabricated Zirconium, Uranium, and Their Alloys." Information Office, Scientific and Technical Information, Stockholm, Sweden. Report No. VDIT-46, November 1961.

Bibliography consisting of 29 annotated references to articles appearing in Nuclear Science Abstracts, 1957-1961; The Review of Metal Literature, 1960-1961; and The Atomic Industry Reporter.

157. Whitlow, G. A., "Resistance to Deformation of Some Uranium-Molybdenum Alloys - Its Dependence on Temperature and Rate of Deformation." Atomic Weapons Research Establishment, Aldermaston, England. Report No. AWRE-0-66/64, August 1964.

A cam plastometer was used to determine the resistance to deformation of U-1, 2, and 5w/oMo alloys at several strain rates. In general, the deformation resistance decreased with increasing temperature. Results have been applied to the formation of hot rolled schedules for the U-1-2w/oMo alloys.

Joining And Machining

158. Bertossa, R. C., "Feasibility Study on the Diffusion Bonding of Uranium." University of California, Lawrence Radiation Laboratory, Livermore. U.S. Atomic Energy Commission Contract Report No. UCRL-13075, October 1962.

The use of pure Au as a catalyst appeared to have promising characteristics for catalyzing diffusion bonding reaction of joining U to itself. Phase diagrams for U alloyed with Au, Cr, Co, Cu, Fe, Mn, and Ni are given.

159. Bradburn, E. H., Huber, R. A., and Turner, P. W., "Mulitpass Electron Beam Welding for Controlled Penetration," Weld. J. (New York), 50 (1971), 190s-93s.

U-0.75w/oTi alloy plates, 360 mils thick, were welded using multipass electron beam methods. Partial penetration electron beam welds having a minimum penetration of 75-85% of the plate thickness were obtained without experiencing meltthrough ("spiking") or damage at the backside of the joint. Single pass methods were unsuccessful.

160. Brundige, E. L., Doll, D. T., Hanks, G. S., and Taub, J. M., "Fusion Welding of Uranium." Nuclear Metallurgy, Vol. 4. A Symposium on Uranium and Uranium Dioxide. IMD Special Report Series No. 4. New York: The Metallurgical Society of AIME (1957), 107-15.

Techniques for producing sound welds with U sheet, plate, and shapes using inert-gas W-arc method is described. Microstructure and mechanical properties of the welds and other welding techniques are also included.

161. Brundige. E. L., Taub, J. M., Hanks, G. S., and Doll, D. T., "Welding Thin-Walled Uranium Cylinders." U.S. Atomic Energy Commission, Office of Technical Information, Washington, D. C. Research Report No. TID-8019, 1958.

U welds free from porosity, cracks, and oxide inclusions were produced by an inert gas-shielded arc method. Tensile and yield strengths exceeded the strength of cast metal. Surface condition and purity of the inert gas used affected weld soundness. Straight polarity direct current was used to achieve maximum penetration and to provide arc stability.

162. Fuller, J. E. and Lynch, J. K., "Machining Study of a Uranium-4 Weight Percent Niobium Alloy." Dow Chemical Corporation, Rocky Flats Division, Golden, Colorado. U.S. Atomic Energy Commission Contract Report No. RFP-1743, November 1971.

A machining study in which tool force and surface finish were determined as functions of six machining and tool-geometry variables was made of a U-4.3w/oNb alloy. Nose radius, top rake angle, front clearance angle, feed rate, surface speed, and depth of cut were parameters investigated. Empirical equations for tool force and surface finish were derived as a function of the independent variables. Tool-force mimima were observed in surface speed and feed rate and were used advantageously when optimizing parameters.

163. Gough, J. R. C. and Roberts, D., "Welding of Uranium," Brit. Weld. J., 4 (1957), 393-403.

Adaptability of Ar arc, metal arc, and resistance spot welding processes to joining of U were assessed. Chemical and physical properties of U and their effect on welding are described.

164. Hanks, G. S., Doll, D. T., Taub, J. M., and Brundige, E. L., "Soldering of Uranium." U.S. Atomic Energy Commission, Office of Technical Information, Washington, D. C. Research Report No. TID-8018, 1958.

Joining of U to U using a number of soft solders and fusible alloys is described. Ultrasonic soldering iron proved to be the best method for joining U to itself and to other metals such as stainless steel. Soldering characteristics of U may be best compared to those of Al.

165. Hurst, J. S. and Read, A. M., "Machining Depleted Uranium." Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee. U.S. Atomic Energy Commission Contract Report No. Y-SC-39, April 1972.

Summary of experience in machining and handling depleted U acquired at Oak Ridge Y-12 Plant is presented. Parameters for turning, boring and facing, cutting, drilling, gun drilling, reaming, threading, tapping, milling, and grinding are given. The use of carbide tooling is recommended. Health and safety hazards are also discussed.

166. McDougal, J. R. and Greene, L. A., "Electron Beam Welding Study on U-Nb-Zr Alloy." Mound Laboratory, Miamisburg, Ohio. U.S. Atomic Energy Commission Contract Report No. MLM-1778, December 1970.

An electron beam welding study to determine the effects of the variations of welding parameters on the weld characteristics in partial penetration welds on 0.08-0.25in stock sheets of U-7.5w/oNb-2.5w/oZr alloy is reported. In the thin sheets (0.08in) welding defects were in the form of porosity and in the thicker sheets (0.25in) in the form of weld spiking and cold sheets at the weld root. Frequencies of 200-400 cps in a circle generator drastically reduced the number of weld defects.

167. Sprague, T. P., Googin, J. M., and Phillips, L. R., "Chemical Coolants for Machining Uranium in the Presence of Trace Amounts of Chloride." Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee. U.S. Atomic Energy Commission Contract Report No. Y-1475, October 1964.

The addition of a dibasic $NaPO_3$ during machining operations of U increased the Cl tolerance $\sim$10x. In the phosphate coolant sodium caprylate is required to retard corrosion of cast iron in machine tools and benzotriazole is required to eliminate corrosion of the Cu alloys in the coolant circulation system and bearings.

PHYSICAL AND MECHANICAL BEHAVIOR

Physical Properties

168. Bates, L. F. and Loasby, R. G., "Magnetic Susceptibility and Electrical Resistance Properties of Some Uranium Alloys," Proc. Phys. Soc., London, 72 (1958), 757-64.

Quenched U-alloys containing Zr, Cb, and Mo, metals which have 4, 5, and 6 outer electrons respectively, were measured from 90° to 300°K. General features of the three systems are the same, with anomalies at ~ 0.5 and 2.0a/o of the solute.

169. Chandrasekhar, B. S. and Hulm, J. K., "Electrical Resistivity and Superconductivity of Some Uranium Alloys and Compounds," Phys. Chem. Solids, 7 (1958), 259-67.

The electrical resistivity and superconductivity of a series of α (orthorhombic) and quenched γ bcc binary U-alloys containing up to 15a/oNb and Mo where investigated at temperatures down to 1°. Anomalous resistivity behavior occurred in both types of structures. The γ-alloys possessed a negative temperature coefficient from room temperature to the superconducting transition point, ~ 2°, and for the α-alloys ~ 1°K. A hypothetical band structure for U was determined. Work was also conducted on some intermetallic U compounds.

170. Gover, J. E. and Posey, L. D., "Dynamic Measurements of the Grüneisen Coefficients of Tantalum, Uranium, and Uranium-Molybdenum Alloys." University of New Mexico and Sandia Laboratories, Albuquerque, New Mexico. U.S. Atomic Energy Commission Contract Report No. SC-DC-72-2299, 1972.

Technique for making dynamic measurements of the Grüneisen coefficients of high atomic number materials and measuring the Grüneisen coefficients of U, U-1.5w/oMo, and heat treated as well as as-cast U-10w/oMo alloys is described. Ta was used as the reference material. Results showed γ-phase had slightly lower coefficients than the α-phase and that the U-10w/oMo alloy specimens, despite differences in grain size, had similar coefficients.

171. Kollie, T. G., et al., "Thermophysical Properties of Uranium-Based Mo, Nb, Zr, Ti Alloys from 77 to 1500K." Oak Ridge National Laboratory, Tennessee. U.S. Atomic Energy Commission Contract Report No. ORNL-TM-4253, June 1973.

Thermal expansion, specific heat, electrical resistivity, thermal conductivity, Seebeck coefficient, Poisson's ratio, and the shear Young's and bulk moduli were measured as a function of temperature for two polynary U alloys, U-3/4Nb-3/4Zr-3/4Mo-1/2Ti and U-1Nb-1Zr-1Mo-1/2Ti.

172. Konobeevsky, S. T., et al., "Some Physical Properties of Uranium, Plutonium and Their Alloys." Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy; Vol. 6, Basic Metallurgy and Fabrication of Fuels. Geneva: United Nations (1958), 194-203.

Physical properties including elastic and anelastic moduli, phase transformation temperatures, expansion coefficients, magnetic and paramagnetic susceptibilities, conductivities, and crystallographic orientation of U and Pu alloys are described. Phase diagrams for U-Mo alloys are presented.

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173. Loasby, R. G., "The Gamma Phase in Uranium Alloys," Proc. Phys. Soc., London, 72 (1958), 425-28.

Electrical resistivity and magnetic susceptbility of U-70a/oZr and U-25a/oMo alloys are described and interpreted in terms of a theoretical structure derived by x-ray work of P.C.L. Pfeil. Results showed fair agreement with the proposed structure based on a contribution of four electrons per atom by U in the γ and γ' modifications.

174. Mima, G. and Hasegawa, M., "Low-Temperature Internal Friction of Uranium-0.4w/oMo Alloys," Osaka Univ. Tech. Rep., 14 (1964), 721-43.

Low-temperature internal friction of U-0.4w/oMo alloy subjected to various heat treatments was measured to explain the behavior of Mo atoms in the alloy and the swelling of U-alloy fuels. On the internal friction temperature curves three maxima were discovered from 77°-360°K: (1) at 120°K, in alloys β-quenched or tempered at < 350°C, (2) at 150°K, in alloys in the annealed or fully tempered condition, (3) at 23°K obtained by β-quenching and disappeared after tempering at 100°C for 1 hr. Young's modulus was decreased abruptly by β-quenching and recovered during the room temperature aging, the rate formula of recovery agreed with the martensitic and nucleation theories.

175. Royce, E. B., "GRAY, A Three-Phase Equation of State for Metals." University of California, Lawrence Livermore Laboratory, Livermore. U.S. Atomic Energy Commission Contract Report No. UCRL-51121, September 1971.

A three-phase equation of state for metals was developed, based on the assumptions: (1) entropy of melting is independent of pressure, (2) temperature dependence of the specific heat in the liquid is a universal curve, scaled on the melting temperature, (3) pressure dependence of the melting temperature is given by a modified Lindemann law, (4) liquid-vapor region may be described by a hard-sphere model perturbed by van der Walls attraction. The equation of state is laid out in a P(V,E) form for use in numerical hydrodynamics calculations. Parameters for Be, Mg, Al, Ti, stainless steel, Ni, Monel, Cu, Nb, Ta, W, Au Pb, Th, Mulberry, and U are given. Experimental evidence for the validity of the equation of state is presented.

176. Schnizlein, J. G., Baker, L., Jr., and Bingle, J. D., "The Ignition of Binary Alloys of Uranium," J. Nucl. Mater., 20 (1966), 39-47.

The effect of alloying additions on the ignition of U was studied and differences in the temperature-time curves for U alloys containing 0.5, 1.0, and 2.0% of 24 different elements were noted. Results were interpreted in terms of the effect of the alloying addition on the previously demonstrated transition of the oxide at 400°-500° from an autocatalytic to a protective form. Additions of Al, particularly, and certain other alloys containing, for example Mo, Nb, Ti and V, inhibited the oxide transition and thereby lowered the ignition temperature. Additions of Cu, in particular, increased the protectiveness of the oxide formed at > 500°C. Complex but reproducible temperature-time curves were obtained when both effects occurred within the same alloy.

177. Schnizlein, J. G., et al., "Ignition Behavior and Kinetics of Oxidation of the Reactor Metals, Uranium, Zirconium, Plutonium, and Thorium, and Binary Alloys of Each, A Status Report." Argonne National Laboratory, Illinois. U.S. Atomic Energy Commission Contract Report No. ANL-5974, April 1959.

Methods of measurements of ignition characteristics of Zr and U were developed and used to determine the effects of variables as surface preparation, metallurgical history, specific area, additives to the metal, O content and presence of moisture in the oxidizing gas. Ignition temperature was determined for binary U-base alloys containing up to 2% of Al, Nb, Si, C, Mo, Ru, Be, Zr, H, Fe, or Cu.

178. Vamberskiy, Yu. V., Udovskiy, A. L. and Ivanov, O. S., "Experimental Determination and Calculation of Excess Thermodynamic Functions of Molybdenum Solid Solutions in Gamma-Uranium," J. Nucl. Mater., 46 (1973), 192-206.

Thermodynamic properties of the U-Mo system were investigated from 1048°-1173°K using the EMF method with a liquid electrolyte. Results indicated that the excess thermodynamic functions change their signs depending on the concentration. The concentration dependencies of the excess entropy, enthalpy, and free energy of mixing of the solid solution were calculated at 1100°K, based on new physical concepts advanced for the solid solution. An interpretation to explain the double change of sign of the excess entropy of mixing and the change of sign of enthalpy of mixing as a function of concentration is offered.

Mechanical Properties

179. Abey, A. E. and Joslyn, E. D., "The Elastic Constants of Uranium-7.5%Niobium-2.5%Zirconium as a Function of Pressure," J. Less Common Metals, 27 (1972), 9-15.

Elastic constants for U-7.5w/oNb-2.5w/oZr alloy (Mulberry) were measured in the pressure range, 1-18 kbar. Initial C_{11} and C_{12} values were found to be 1.34 and 0.92 mbar. For dC_{11}/dP and dC_{12}/dP values of 5.8 and 4.1 were obtained. Initial bulk modulus, K, was 1.06 mbar and dK/dP was determined to be 4.6.

180. Albright, C. E. and Stein, C., "The Low Strain Tensile Behavior of U-7.5WtPctNb-2.5WtPctZr," Met. Trans., 3 (1972), 2217-23.

The stress-strain response of polycrystalline, γ-quenched U-7.5w/oNb2.5w/oZr alloy was studied as a function of strain rate and compared to equilibrium stress-strain tests which were also performed on prestressed samples. Stress-induced transformation first occurred at stresses > 40,000 psi, was complete at stresses < 120,000 psi, and involved a transformation from a γs(bcc) structure to a γo(BCT) structure which is postulated to be a thermoelastic martensitic transformation. Tensile tests indicated strain rate sensitivity at strain rates > $3.0x10^{-2}min^{-1}$. A semiempirical equation describing the stress-strain behavior in terms of stress induced phase transformation was developed.

181. Bastelli, M. R., D'Amato, C., Renzoni, R., Saraceno, F. S., and Wilson, T. B., "Development of Ternary Uranium Alloys With a Low Alloying Content (U-Nb-Cr, U-Nb-Fe, U-Nb-Ni, U-Nb-Si, U-Nb-Zr)." Translated from the Italian for Oak Ridge National Laboratory, Tennessee. U.S. Atomic Energy Commission Contract Report No. ORNL-TR-2325, 1969.

Work on U-Nb-X ternary alloys included studies on β-quenched and tempered U-1%Nb-0.15-0.25%Cr alloys. Laboratory tests showed these alloys to have good structural stability at 550°, improved mechanical resistance both when cold and at high temperatures (550°), and improved thermal cycling resistance (0°-550°C). Creep resistance was higher when the Cr content was low (0.15%).

182. Boudouresques, B. and Englander, M., "Strength and Creep in Uranium Alloys." Progress in Nuclear Energy, Series 5. Metallurgy and Fuels, Vol. 2. Edited by H. M. Finniston and J. P. Howe. New York: Pergamon Press (1959), 621-31.

Mechanical properties - hardness, creep, brittleness, and tensile strength - of U-alloys containing < 10w/oMo, Zr, Ti, and Al in the temperature range where they are believed to be useful as nuclear fuel materials are presented in tabular form.

183. Bugrov, V. A., Grigorovich, V. K., and Ivanov, O. S., "Temperature Dependence of the Strength, Plasticity, and Elastic Properties of Alloys of Uranium with Zirconium, Niobium, and Molybdenum." Translated from the Russian for the University of California, Lawrence Radiation Laboratory, Livermore. U.S. Atomic Energy Commission Contract Report No. UCRL-Trans-10454, March 1970.

Temperature dependence of strength and elastic modulus was measured for a series of U alloys in the α region (< 500°) and in the γ region (700°-900°C). In the α region, U-20%Zr and U-70%Zr were stronger than U-20%Nb and U-20%Mo, but weaker than the ternary U-10%Zr-20%Nb. In the γ-phase the U-20%Nb and U-20%Mo alloys are strongest. Young's modulus of α-phase decreased with increasing temperature, then fell sharply when transformation to γ began.

184. Butcher, B. R. and Hatt, B. A., "The Mechanical Properties of Quenched Uranium-Molybdenum Alloys. Part II: A Preliminary Survey of the Deformation Mechanisms," J. Nucl. Mater., 11 (1964), 163-82.

The deformation of compressed specimens of martensitic α-phases and metastable γ-phases of quenched U-3-30a/oMo alloys was studied by metallographic and x-ray techniques. The various twinning phenomena in γ-phase deformation are discussed in terms of the order thought to exist in metastable phases.

185. Daniel, J. S., "The Deformation Modes of α-Uranium." Defense Research Establishment, Valcartier, Quebec. Report No. DREV-M-2060/71 (May 1971), 146-55. (AD 890 370)

Principal factors which influence the plasticity of α-U are summarized. Both the temperature dependence and strain-rate dependence of the flow of stresses in U appear to originate in the U crystal itself. Although α-U can have reasonable ductility at room temperature and normal strain rates it appears to be basically unsuitable for high strain rate applications.

186. Dupont, G., "A Survey of the Mechanical Properties of Uranium Alloys, U-5Mo-3Nbw/o and U-3Mo-3Nbw/o." Canadian Arament Research and Development Establishment, Valcartier, Quebec. Report No. CARDE-TN-1822/69, April 1969. (AD 857 784)

The influence of tempering heat treatments associated with extrusion on the ductility of γ extruded U-5w/oMo-3w/oNb and U-3w/oMo-3w/oNb alloys was studied. Mechanical properties of both alloys were measured in the extruded, extruded and annealed, and quenched and tempered conditions. Maximum elongation of 13.7% with a low amount of work hardening, was obtained for U-3Mo-3Nb alloy after annealing 1 1/2 hrs at 650° followed by a rapid cooling in H_2O at 21° and 17.3%, with a large amount of work hardening, for U-5Mo-3Nb alloy after vacuum annealing, normalizing, γ-phase solutionizing at 815°, and quenching in H_2O at 21°C.

187. Erickson, W. H., "A Study of the Mechanical Properties of Heat-Treated Uranium-Mo-Nb-Zr Alloy." Defence Research Establishment, Valcartier, Quebec. Report No. DREV-R-600/69, December 1969. (AD 871 854)

Mechanical properties of U-1Mo-.8Nb-.8Zr alloy were measured after oil-quenching from the γ-phase and aging in the temperature range 450°-1200°F. Isothermal interrupted quench treatments were evaluated as well, and resulting microstructures were observed and correlated with mechanical test results. Hardnesses from 32 to 56Rc were developed by aging and they correspond to tensile yield strengths from 92-256 kpsi, to bend strengths from 247-500 kpsi, and to compressive yield strengths from 160-320 kspi. At lower hardness levels, the alloy appeared to develop a tough structure, at high hardness levels, significant ductility was present after oil quench treatment (45% compressive deformation at 55 Rc); since the work-hardening rate is low, relatively low tensile elongations were obtained.

188. Erickson, W. H. and Irwin, G. J., "Some Mechanical Properties of Thermally Treated U-2Mo." Defence Research Establishment, Valcartier, Quebec. Report No. DREV-TN-1903/71, February 1971. (AD 883 354)

U-2w/oMo alloy was subjected to a series of aging heat treatments to select the microstructure that provided optimum mechanical properties for high-density projectile applications. Results showed that the lamellar structure (32Rc) obtained by aging at ~ 1000°F possessed the highest toughness and ductility. Aging in the α + γ region (1050°F) resulted in a basketweave structure which was accompanied by an increase in hardness and a decrease in toughness near the eutectoid line but at higher temperatures the properties were recovered.

189. Fackelmann, J. M., Bauer, A. A., and Moak, D. P., "Literature Survey on Dilute Uranium Alloys for Sandia Booster Concept to Sandia Corporation." Battelle Memorial Institute, Columbus, Ohio. Sandia Laboratories Subcontract Report for the U.S. Atomic Energy Commission. Research Report No. BMI-X-10264, July 1969.

Summary of data found on U-alloys containing < 10w/oMo, Nb, Zr, and Cr and U-7.5w/oNb-2.5w/oZr alloy in the unclassified literature from 1947 to 1969, interpreted and evaluated to present the most accurate property information available. Phase relationships, corrosion, dimensional stability, mechanical and physical property data are included for each alloy.

190. Federer, J. I., "Effect of Alloy Additions and Heat Treatments on the Mechanical Properties of U-0.5Ti Alloy." Oak Ridge National Laboratory, Tennessee. U.S. Atomic Energy Commission Contract Report NO. ORNL-TM-2482, 1969.

Effect of both heat treatments and the small addition of a third element on the mechanical properties of U-0.5Ti alloys was studied. Aging for 1 hr at 400° increased tensile strength from 144,600 to 173,000 psi and reduced elongation from 22.8% to 18.8%. Aging at 200° for 1 hr did not significantly change properties but aging at 600° for 1 hr overaged the alloy thereby decreasing strength and ductility. β quenching was detrimental to both strength and elongation.

191. Friske, W. H., "Some Properties of Uranium-Molybdenum Alloy Fuels for Organic Moderated Reactors." Atomics International, Canoga Park, California. U.S. Atomic Energy Commission Contract Report No. NAA-SR-4646, April 1960.

Mechanical and metallurgical properties of several U-alloys were investigated. U-3.5w/oMo exhibited increased thermal stability and creep strength at 900°F. These properties were further increased in U-3.5w/oMo-0.1w/oAl alloy. U-2.0w/oZr-0.1w/oAl alloy exhibited poor dimensional and geometric stability.

192. Friske, W. H., Kline, H. E., and Binstock, M. H., "Effect of Low Alloy Additions on the Properties of Uranium," Trans. ASM, 53 (1961), 29-41.

Evaluation of the effects of various alloying element additions on the dimensional stability - creep, hardness, tensile properties, and microstructure - were studied. U-3.5Mo, U-3.5Mo-0.5Si, U-3.5Mo-0.1Si, U-3.5Mo-0.5Al, U-3.5Mo-0.1Al and U-2Zr-0.1Al were the alloys studied and unalloyed U was used for reference.

193. Green, E. A., "The Yield Surface of Uranium +.75 Percent Titanium." University of California, Lawrence Radiation Laboratory, Livermore. U.S. Atomic Energy Commission Contract Report No. UCID-15362, July 1968.

The first and fourth quadrant yield surfaces of a U-0.75%Ti alloy were determined. The specimens were solution treated at 800°C for 20min, followed by a H_2O quench, and then electron beam welded. The electron beam welding process was used to weld two identical halves together to make one complete specimen and the effects of the process were tested. Results indicated that the weld metal is stronger than that of off-weld metal and fracture did not start or propagate through the weld. The tentative biaxial yield surface is described by the maximum strain criterion.

194. Greenspan, J. and Rizzitano, F. J., "Development of a Structural Uranium Alloy." Army Materials Research Agency, Watertown, Massachusetts. Report No. AMRA-TR-64-28, September 1964.

A polynary uranium alloy system containing equal amounts of Nb, Zr, and Mo up to 2w/o and 0.5w/oTi is described. Mechanical properties in both extruded and solutionized and aged conditions indicated UTS ~ 300 ksi, 0.1%YS > 200 ksi are possible.

195. Grigorovich, V. K. and Dedyurin, A. I., "Mechanical Properties of Deformed Binary Alloys of Uranium with Zirconium, Niobium, and Molybdenum." Translated from the Russian for Westinghouse Electric Corporation, Bettis Atomic Power Laboratory, West Mifflin, Pennsylvania. Report No. WAPD-TRANS-3, 1963.

Mechanical properties were correlated with constitution diagrams and structure of forged binary U-alloys containing 1-15a/oZr, Nb, and Mo and U-60-99a/oZr alloys. Results indicated: (1) effect of alloying elements on heat and creep resistance were irregular, (2) Zr lowered the creep rate more effectively than Nb or Mo, (3) Mo increased heat resistance at 550°-580°C more than Zr or Nb.

196. Hays, D. D., "Yield Surface of a Uranium-7.5wt Percent Nb-2.5wt Percent Zr Alloy (Mulberry)." Battelle Memorial Institute, Northwest Research Laboratory, Richland, Washington. U.S. Atomic Energy Commission Contract Report No. BNWL-1112, August 1969.

The yield surface of γ stabilized U-7.5w/oNb-2.5w/oZr alloy under biaxial stress conditions was determined and is best described by Von Mises theory of yielding.

197. Hemperly, V. C., "Compilation of the Mechanical Properties of Dilute (5 Percent Maximum) Alloys of Uranium." Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee. U.S. Atomic Energy Commission Contract Report No. Y-DA-3616, September 1970.

Compilation of mechanical property data on binary and ternary U-base alloys containing a maximum of 5%Hf, Ir, Mo, Nb, W, Ta, Th, Ti, V, and/or Zr prepared and tested at Oak Ridge, Y-12 Plant and compiled in their technical reports issued though October 1969 as well as unpublished data (designated as ABT) is presented. Where applicable the report number follows the data presented.

198. Hills, R. F., Butcher, B. R., and Howlett, B. W., "The Mechanical Properties of Quenched Uranium-Molybdenum Alloys. Part I: Tensile Tests on Polycrystalline Specimens," J. Nucl. Mater., 11 (1964), 149-62.

Tensile tests were performed on oil-quenched and Hg-quenched U-1.5-30a/oMo alloy specimens. Relationships of tensile results vs nominal composition and hardness vs composition were plotted. Circumferential cracking due to SCC by air occurred in alloys containing < 20a/oMo while intergranular cracking occurred with > 20a/oMo. Mechanical properties and the results of metallographic and x-ray analyses are presented in tabular form.

199. Hoge, K. G., "Mechanical Properties of Gamma-Phase Uranium-7.5w/oNiobium-2.5w/oZirconium Alloy Under Dynamic Loading." University of California, Lawrence Radiation Laboratory, Livermore. U.S. Atomic Energy Commission Contract Report No. UCRL-14805, April 1966.

Effects of dynamic tension loading on the mechanical properties of γ-phase U-7.5w/oNb-2.5w/oZr alloy are presented. Test data were taken at 23°, 200°, 300°, 400°, and 500° at strain rates varying from 10^{-3} to 160in/in/sec. Dynamic loading caused only a slight decrease in ductility and tensile strength increased moderately with increasing strain rates. TTT curves indicated that the γ-phase begins to transform to a cellular structure in a few minutes at temperatures slightly > 300° and to a pearlitic structure (α + γ 2) at temperatures > 500°C.

200. Hoge, K. G., "Some Mechanical Properties of Uranium-10 Weight Percent Molybdenum Alloys Under Dynamic Tension Loads," Trans. ASME, Series D- J. Basic Eng., 88 (1966), 509-17.

As-cast and wrought U-10w/oMo alloys with varying C content (71-880ppm) and having varied heat treatments were tensile tested on a universal machine at strain rates of 4.8×10^{-8} and 0.057in/in/sec and on a modified Dynapak at strain rates up to 100in/in/sec at 75°-600°F. Relatively low strain rates were used to determine the susceptibility to SCC and higher strain rates to determine the sensitivity of the mechanical properties to strain rate effects.

201. Horak, J. A., Yao, E., Rorke, G. L., Sasmor, D. J., and Gonzalez, F., "Mechanical Properties of a Potential Pulsed Reactor Fuel, U-6Wt%Mo." Sandia Laboratories, Albuquerque, New Mexico. U.S. Atomic Energy Commission Contract Report No. SLA-73-5154, 1973.

Thermomechanical properties of U-6-10w/oMo alloys, in which the γ-phase can be retained to room temperature and below, were determined. The temperature dependence of the mechanical properties of U-6w/oMo alloy from 77°-800°K indicated large dependence at < 300°K and small dependence above that temperature. Fractography studies revealed only ductile-type fracture at > 150°K. Plastic deformation and shear dimple size increased as the temperature increased. The percent elongation and toughness decreased just above 400°K.

202. Iannelli, A. A. and Rizzitano, F. J., "Notched Properties of High-Strength Alloys at Various Load Rates and Temperatures." Army Materials Research Agency, Watertown, Massachusetts. Report No. AMRA-TR-66-13, July 1966. (AD 647 884)

Notched and unnotched strengths for several alloys including U-8Mo-0.5Ti were determined at load duration of 10 msec-5 min at -320° to 500°F. With $K_t=9.5$, the notch strength of all the alloys was less than the unnotched strength at low temperature under both dynamic and static conditions but exceeded the unnotched strength in the higher temperature range.

203. Irwin, G. J. and Erickson, W. H., "The Effect of Heat-Treatment on the Mechanical Properties of U-2Mo and U-1Mo-.7Nb-.7Zr." Defence Research Establishment, Valcartier, Quebec. Report No. DREV-R-622/70, September 1970. (AD 880 242)

The mechanical properties of U-2Mo and U-1Mo-.7Nb-.7Zr alloys heat treated in various ways were studied and compared. Embrittlement occured in both alloys at 371° and just above the eutectoid line (565°C). The quaternary alloy generally had superior mechanical properties - hardness, flow stress, toughness, and ductility - but further tensile tests are required.

204. Jackson, R. J. and Boland, J. F., "Mechanical Properties of Uranium-Base Niobium Alloys." Dow Chemical Company, Rocky Flats Division, Golden, Colorado. U.S. Atomic Energy Commission Contract Report No. RFP-1703, June 1971.

Tensile, compressive, and impact properties of γ-quenched and aged U-4,5,6,8w/oNb alloys and U-7.5w/oNb-2.5w/oZr alloys are provided in graphic form. Tensile property data were obtained from 527 tests using 264 different combinations of composition, time, and temperature and impact property data from 100 tests using 36 combinations of composition, time and temperature.

205. Jackson, R. J. and Boland, J. F., "Transformation Kinetics and Mechanical Properties of the Uranium-7.5Niobium-2.5Zirconium Ternary Alloy." Dow Chemical Company, Rocky Flats Division, Golden, Colorado. U.S. Atomic Energy Commission Contract Report No. RFP-1652, December 1971.

Tensile and impact test data correlated with metallographic and x-ray studied for U-7.5w/oNb-2.5w/oZr alloy are presented. Strength is increased with no loss in supersaturation by aging at < 800°C for up to 80 hrs. Data are interpreted in terms of plastic deformation occurring by the motion of twin interfaces and in the pinning of twin interfaces by ordering on aging.

206. Jackson, R. J. Brugger, R. P. and Miley, D. V., "Tensile Properties of Gamma Quenched and Aged Uranium-Rich Niobium Alloys." Dow Chemical Company, Rocky Flats Division Golden, Colorado. U.S. Atomic Energy Commission Contract Report No. RFP-933, June 1967.

Tensile test data for U-11,15,17 and 19a/oNb alloys in both the solution-quenched and aged conditions are presented and correlated with concurrent metallographic and x-ray studies. Results show a wide range of mechanical properties are available from these heat-treatable, corrosion-resistant high-density alloys.

207. Jaynes, G. E., "Addition of Rare Earths to Uranium and Uranium Alloys." Los Alamos Scientific Laboratory, New Mexico. U.S. Atomic Energy Commission Contract Report No. LA-3911, April 1968.

The rare earths Tm, Lu, and Y (0.1-0.3w/o) were added to U and U-alloys with Ni, Co, and Rh being the noncarbide carrier metals and their mechanical and physical properties were determined. Material containing Rh and Y additions exhibited the greatest increase in tensile strength.

208. Linard, M., "Study of Uranium-Titanium Alloys with a Low Titanium Content (0-1.5 Percent) by Weight." Translated from the French for Oak Ridge National Laboratory Tennessee. U.S. Atomic Energy Commission Contract Report No. ORNL-TR-2579, 1971.

Additions of up to 1.5%Ti improved the mechanical properties of U especially when cooled rapidly from the γ-phase. Rupture and yield strength increased uniformly with the Ti content and maximum elongation occurred with 0.4-0.6Ti content. U-.55Ti alloy was studied extensively and results showed it to be relatively insensitive to quenching conditions.

209. Livesey, D. J., "The Variation With Temperature of Young's Modulus for Some Uranium Alloys and for Thorium, Vanadium, and Niobium," J. Inst. Metals, 88 (1959), 144.

The temperature dependence for Young's Modulus for U-1/2a/oMo and U-1/2a/oCr were measured dynamically up to 500°C. E decreased from ~ $19x10^{11}$ dynes/cm^2 at 20° to ~ $1.2x10^9$ dynes/cm^2 at 500°C. Alloying elements did not significantly alter the behavior.

210. Lord, D. E., "Model Relating Stress, Strain, Strain Rate, and Temperature With an Experimental Data Fit for a Uranium-7.5%Niobium-2.5%Zirconium Alloy." University of California, Lawrence Livermore Laboratory, Livermore. U.S. Atomic Energy Commission Contract Report No. UCID-16254, April 1973.

Theoretical results obtained from a model developed as a result of a strain energy-to-failure investigation of properties of U-7.5w/oNb-2.5w/oZr alloy agreed well with experimental results of a previous investigation. A relationship was established between strain rate and temperature over wide ranges, including a phase change for the alloy. A softening-point correlation was also established.

211. McIntosh, A. B. and Heal, T. J., "High-Temperature Properties of Uranium and Its Alloys." Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy; Vol. 6, Basic Metallurgy and Fabrication of Fuels. Geneva: United Nations (1958), 413-25.

Data are presented on creep strength at 400°-550°, the effect of thermal cycling, tensile properties between 600°-700°C, thermal expansion, and thermal conductivity for a large range of U-alloys.

212. Murphy, D. J., "Some Properties of Uranium-Low Titanium Alloys," Trans. ASM, 50 (1958), 884-904.

Addition of 0.1-1.5w/oTi to U improved its mechanical properties and corrosion resistance. Mechanical properties of the U-Ti alloy were very dependent upon the rate of cooling applied after heat treatment in the γ-temperature region. Increasing the amount of Ti increased strength, hardness, and corrosion resistance but decreased ductility and impact strength.

213. Myers, M. and Edelman, R. E., "Heat Treatment and Mechanical Properties of a Uranium-2 Percent Mo-2 Percent Nb-0.5 Percent Ti Alloy." Frankford Arsenal, Philadelphia, Pennsylvania. Research Report No. FA-M67-1-1, July 1966. (AD 637 777)

Study of the U-2%Mo-2%Zr-2%Nb-0.5%Ti alloy indicated that in as-forged and as-rolled conditions it possessed little or no ductility, but in the solution-treated and aged conditions possessed a measurable amount of ductility (1-3% elongation).

214. Nolan, M. F., "The Mechanical Properties of Dilute Uranium Alloys at Elevated Temperatures." Mallinckrodt Chemical Works, Uranium Division, Weldon Spring, Missouri. U.S. Atomic Energy Commission Contract Report No. MCW-1505, August 1966.

High temperature tensile tests (up to 600°) and prolonged hot hardness tests (400°C) of U alloys were conducted for correlation of results with in-reactor behavior. The mechanism of flow and fracture is discussed in terms of temperature, structure, strain, and strain rate. Activation energy values for plastic flow are given. Resistance to identification appeared to be a function of solid solution strengthening and not of total alloy content.

215. Oakes, R. E., Jr., "The Anomalous Mechanical Properties of Uranium-7.5 Weight Percent Niobium-2.5 Weight Percent Zirconium Alloy." Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee. U.S. Atomic Energy Commission Contract Report No. Y-1732, September 1970.

Abnormal mechanical properties - nonlinear "elasticity", rubberlike amounts of "elastic" spring back, and large amounts of mechanical hysteresis - of U-7.5w/oNb-2.5w/oZr alloy were examined in uniaxial tension and compression with respect to stress, strain, and aging. Results indicated a stress-induced phase transformation in both the as-quenched and aged alloy. This is substantiated by volumetric, resistance, and microstructural changes in the alloy under stress.

216. Peterson, C. A. W. and Elkington, W. E., "Physical and Mechanical Properties of U-7.5w/oNb-2.5w/oZr Alloy." University of California, Lawrence Radiation Laboratory, Livermore. U.S. Atomic Energy Commission Contract Report No. UCRL-14724, February 1966.

The physical and mechanical properties of U-7.5w/oNb-2.5w/oZr alloy in the temperature range 150°-350°C are described. Results indicated mechanical strength increases with aging temprature and time within this range. Tensile yield strength after heat treatment for 1 hr at 150° was 92,000 psi, and after 4 hrs at 350°, 215,000 psi, with elongation for these strength levels 20% and 3.5% respectively. Electron diffraction data showed that an ordered structure is developed during aging at 150°C for 10^4 min and it is believed this ordering is partly the cause for the increase in strength.

217. Peterson, C. A. W. and Vandervoort, R. R., "Mechanical Properties of Some Uranium Alloys." University of California, Lawrence Radiation Laboratory, Livermore. U.S. Atomic Energy Commission Contract Report No. UCRL-7771, March 1964.

Summary of the mechanical properties of high-strength, γ-phase U-base alloys containing Mo, Nb and/or Zr. Data for room temperature and elevated temperature tensile properties, DPN hardness, Charpy impact strength, and tensile properties of TIG welds are included.

218. Peterson, C. A. W. and Vandervoort, R. R., "The Properties of a Metastable Gamma-Phase Uranium-Base Alloy." University of California, Lawrence Radiation Laboratory, Livermore. U.S. Atomic Energy Commission Contract Report No. UCRL-7869, May 1964.

The U-7.5w/oNb-2.5w/oZr alloy was studied and the relationship of transformation characteristics to physical and mechanical properties was determined. Tensile yield strengths of 100,000-200,000 psi were obtained, with elongations of 12% to 4%, respectively, depending on heat treatment.

219. Plante, J. and Dube, A., "A Study of Means of Increasing the Ductility of High Strength Uranium Alloys." Defence Research Establishment, Valcartier, Quebec. Report No. DREV-M-2060/71 (May 1971), 190-215.

The influence of the γ grain size on the mechanical properties of quenched and tempered U-2Mo alloys is described. Experimental results indicate that refining the grain size from 500 to 600 μm when tempering at < 400°C slightly improved the alloy strength. Ductility was decreased at all aging temperatures and strength generally increased. Reducing the C content from 200 to 85ppm led to a systematic increase of the reduction of area and a 15% increase of bend strength.

220. Sandstrom, D. J., "Some Mechanical and Physical Properties of Heat-Treated Alloys of Uranium with Small Additions of Ti or Mo." Los Alamos Scientific Laboratory, New Mexico. U.S. Atomic Energy Commission Contract Report No. LA-4781, December 1971.

Wrought U-<1.5Ti alloys prepared from castings by hot rolling or hot extrusion were heat treated by quenching in H_2O from the γ-region. The as-quenched material was ductile and strong. Aging at 400°C for 2 hrs produced a 30-50% increase in yield strength and increased ductility. The alloys did not appear to be susceptible to SCC in 100% relative humidity environments and appeared to have superior corrosion resistance to that of unalloyed U.

221. Spence, N. S. and Skelly, H. M., "Properties and Heat Treatment of Cast Uranium Molybdenum Alloys." Defence Research Establishment, Valcartier, Quebec. Report No. DREV-M-2060/71 (May 1971), 232-52. (AD 890 370)

Procedure for melting, alloying, and casting of U-Mo, U-Mo-Nb, U-Mo-V, U-Mo-Zr, and U-Mo-Ti alloys on a laboratory scale was established. Maximum heat treatment hardness (463-639VHN) was obtained by heating to 800° for 1/2 hr, H_2O quenching, and aging from 1/2 min to 2 hrs at 400°-500°C for the U-1Mo and U-1Mo-2Ti alloys. Maximum as-cast tensile strength was 176 kpsi for the U-1Mo-2Nb and heat-treated tensile strength was 219 kspi for U-1Mo-0.5Ti. Densities ranged from 17.7g/cc (U-1Mo-2Ti) to 18.9g/cc (U-1Mo).

222. Tardif, H. P., "The Heat-Treatability and Properties of Uranium Alloys," Can. Mining Metal. Bull., 58 (1965), 1167-71.

General characteristics of U and some possible nonnuclear applications of U-alloys are surveyed. Metallurgy, general principles of alloying, and heat treatment of U are described. Response to heat treatment of various U-Mo, Nb, Fe, Cr, Si, Ti, Zr, V, Ni, Mn, Co, W, Ta alloys was determined by hardness measurements. Compression, tensile, bend, and impact properties as well as corrosion properties of the more promising alloys were determined. Results indicated that high-density, high-strength U-alloys can be developed successfully.

223. Tardif, H. P., "The Properties of Uranium Alloys Containing Tungsten and Tantalum." *Canadian Armament Research and Development Establishment, Valcartier, Quebec.* Report No. CARDE-TR-593/68, August 1968. (AD 843 212)

The effects of adding, together or separately, 1%W and 1%Ta to U-Mo-Nb alloys were determined. Addition of W and Ta did not appear to affect strength and ductility of heat treated U-alloys but did seem to have an important effect on corrosion, especially in the presence of Nb. Alloys containing small amounts of Cr and Ni were tested and results confirmed an increase in corrosion resistance.

224. Tardif, H. P., "A Study of Polynary Uranium Mo-Zr-Nb-V Alloys," Can. Mining Metal Bull., 61 (1968), 1289-1304.

Ternary, quaternary, or more complex U-base-Mo, Zr, Nb, V alloys formulated by varying the amount of and by removing one or two of the alloying elements in turn from the base alloy were studied. Each alloy was studied under three different heat treatments and the mechanical and corrosion properties of each were determined. Most exhibited the desired hardness and strength but were extremely brittle and notch-sensitive under tensile stresses.

225. Tardif, H. P., "A Study of Soft Uranium Alloys." Canadian Armament Research and Development Establishment, Valcartier, Quebec. Report No. CARDE-TR-592/68, October 1968. (AD 858 215)

The conditions under which soft U-Nb-Mo alloys with varying amounts of alloy addition can be obtained and also retained in the soft and ductile state and in the soft α- and γ-phases at room temperature are described. Mechanical properties were determined and the changes in properties of the alloy phases after decomposition or transformation by heat treatment or cold work were measured during and after treatment. Results indicated that the α-phase alloys are unstable and transform rapidly during deformation but γ-phase alloys do not decompose as readily but can be deformed more extensively.

226. Tardif, H. P. and Perron, P., "Uranium and Uranium Alloys." Canadian Armament Research and Development Establishment, Valcartier, Quebec. Report No. CARDE-TR-497/64, August 1964.

The principal physical, chemical, and mechanical properties of both natural and depleted U are presented in a brief summary. The various techniques for processing U are described. Heat-treatable U-alloys with high mechanical properties are considered.

227. Waldron, M. B., Burnett, R. C., and Pugh, S. F., "Mechanical Properties of Uranium-Molybdenum Alloys." Atomic Energy Research Establishment, Harwell, England. Report No. AERE-M/R-2554, 1958.

Tensile properties and hardness of U-0-14%Mo alloys were studied at room temperature and elevated temperature. With Mo additions < 5.5% the breakdown of the γ solid solution to unstable microstructure led to pronounced aging effects but with > 5.5% additions the γ-solid solution was retained to room temperature and showed enhanced properties up to 800°C.

228. Waldron, M. B., Burnett, R. C., and Pugh, S. F., "Mechanical Properties of Uranium-Molybdenum Alloys," Nucl. Power, 3 (1958), 599-600.

U-Mo alloys are susceptible to a wide variety of heat treatments. Three groups of alloys exist in which hardening is due to: (1) solid solution of Mo in α-U, (2) formation of α + γ dispersions, (3) solid solutions of Mo in γ-U. Effects of irradiation are not clear.

229. Weiss, H. D., "Properties of Mulberry." University of California, Lawrence Radiation Laboratory, Livermore. U.S. Atomic Energy Commission Contract Report No. UCID-15170, July 1967.

Mechanical and physical properties of Mulberry, a γ-phase metastable U-7.5w/oNb-2.5w/oZr alloy, are described in detail. Tabular data figures are provided.

230. Willows, R. and Whitlow, G. A., "High Strength Uranium Alloys. Mechanical Properties." Atomic Weapons Resarch Establishment, Aldermaston, England. Report No. AWRE-O-34/70, May 1970.

Mechanical properties, tensile properties, and fabrication of binary and ternary U-alloys were studied. Effects of quenching and aging on hardness of U-Mo alloys were investigated. Additions of 1-5%Al, Mo, Nb, Si, or Sn had little effect on the hardness. Effects of time and temperature on the tensile properties of solution treated and aged U-Mo alloys were also determined. Hot working properties of the U-Mo alloys previously reported are summarized.

231. Wolf, S. M., "Metallurgical Investigation of Several Structural Uranium Base Cb-Mo-Zr-Ti Alloys." Army Materials and Mechanics Research Center, Watertown, Massachusetts. Report No. AMMRC-TR-67-04, September 1967. (AD 661 054)

Small additions of Mn, Ni, Ta, W, V, Hf or Cr to the polynary U-1-1/2Nb-1-1/2Zr-1-1/2Mo-1/2Ti alloy were found to have little influence on mechanical properties. Corrosion in boiling water is reported. Three alloys with higher Nb content (up to 7.4w/o) exhibited adequate ductility, impact energy, and corrosion resistance at the 200 ksi yield strength level.

232. Wolf, S. M. and Rizzitano, F. J., "Properties of Several Structural U-Mo-Cb-V-Ti Alloys." Army Materials Research Agency, Watertown, Massachusetts. Report No. AMRA-TR-67-18, June 1967. (AD 658 679)

Metallurgical properties and structures of 12 U-base alloys containing 0.13-4.5w/oMo, Cb, V, and Ti were determined for various heat treatments. In general, tensile ductility and impact energy were increased at constant tensile strength levels for extruded, solutionized, quenched and aged material compared to as-extruded material. Grain size was enlarged and chemical homogeneity improved by the heat treatment. Replacing Zr with V in the U-2Mo-2Cb-2Zr-0.5Ti alloy improved corrosion resistance in boiling H_2O at atmospheric pressure.

233. Yao, E., "The Mechanical Behavior of a Fast Burst Reactor Fuel Candidate." Unpublished Ph.D. Dissertation University of New Mexico, 1972.

The mechanical properties, deformation characteristics, and fracture behavior of γ-phase U-6w/oMo alloy were studied. Environment controlled elevated temperature tensile testing system and a cryogenic temperature tensile testing apparatus were used to determine the mechanical properties from 77°-798°K. Activation enthalpy and volume, and other strain rate parameters were calculated from the data obtained by strain rate cycling and stress relaxation measurements for the analysis of the deformation mechanisms. Metallographic and fractographic methods were used to characterize plastic deformation and fracture behavior. It was established that fracture mechanism is a function of testing temperature.

234. Zehr, S. W., "Mechanical Properties of U-2.3w/oNb Heat Treated to Produce Various Two-Phase Structures." Sandia Laboratories, Livermore, California. U.S. Atomic Energy Commission Contract Report No. SCL-TM-72-0226, March 1972.

Preliminary experiments with two-phase heat treatments of a U-2.3w/oNb alloy indicated that improved mechanical properties can be achieved by age hardening and/or strain hardening. Young's modulus 20x10^6 psi, yield strength (0.2% offset) 120,000 psi and elongation 5% can be obtained.

235. Zukas, E. G., "Properties of As-Cast and Heat-Treated 2% Molybdenum-Uranium," Trans. ASM, 51 (1959), 752-57.

Mechanical properties obtained by five different heat treatments of U-2%Mo alloy for use at temperatures from -198° to 100° are reported. Tensile strengths reached a maximum of > 200,000 psi at -30° but failed in a brittle manner. Impact strengths were generally low and decreased at temperatures < -30°C. Homogenization followed by furnace cooling increased ductility but decreased tensile and yield strengths.

236. Zukas, E. G and Green, W. V., "High-Density, High-Strength Alloys Having Some Ductility at Ambient Temperature. A State of the Art Survey." Los Alamos Scientific Laboratory, New Mexico. U.S. Atomic Energy Commission Contract Report No. LA-4670, May 1971.

The U-8w/oMo alloy was one of many materials considered in a program to develop a high strength, high density, low-temperature ductility alloy. Recommended areas for further study include fiber reinforcing the U-Mo alloy with W or W-alloy wire and alloying additions to the U-8w/oMo alloy.

237. U.S. Patent No. 3,170,788. February 23, 1965. Uranium Base Alloys. Martin H. Binstock and Harold E. Kline to the U.S. Atomic Energy Commission

A U-base alloy containing 1.5-6.0w/oMo-0.1-1.0w/oAl-0.2-1.0w/oAl and Si in which either Al or Si is at least 0.1w/o with improved high temperature deformation was developed.

238. U.S. Patent No. 3,266,890. August 16, 1966. Structural High Strength Uranium Alloys. Jacob Greenspan and Fortunato J. Rizzitano to the United States of America.

Method of producing high strength U alloys containing 93.5-96.5w/oU, 0.75-2.0w/o each of Mo, Zr, and Nb, and 0.25-0.50w/oTi. In the "as solutionized" condition these alloys exhibit maximum ductility and impact resistance whereas maximum strength and hardness are obtained in the "as extruded" condition.

PHYSICAL METALLURGY

Microstructure

239. Bar-Or, A. and Wynblatt, P., "The Appearance of Columnar Grains in Uranium-Chromium Alloy," J. Inst. Metals, 92 (1964), 183-184.

The influence of isothermal heat treatment at temperatures between 600°C and the eutectoid transformation temperature on grain size was investigated. Formation of columnar grains in U-45a/oCr alloy after quenching at 720° and transforming isothermally between 635° and 600°C was due to the difference between the surface and bulk nucleation rates.

240. Bauer, A. A. Thompson, C. R., and Farkas, M. S., "Microstructural Studies of Cast Uranium," in Technical Papers of the Eighteenth Metallographic Group Meeting held at Atomics International, Canoga Park, California, 22-24 June 1964. U. S. Atomic Energy Commission Contract Report No. NMI-5025, Pt. 1, (August 1965), 127-51.

Results of a brief program using metallographic and electron microscopic techniques in detecting microstructural differences in cast U of varied chemistry and casting history are described and evaluated. Evidence of differences in substructure and in fine-particle distribution and form between the various materials are reported. Micrographs illustrating the effectiveness of the techniques are included.

241. Boyle, R. F. and Halteman, E. K., "Calorimetric Determination of Ordering in the U-Mo System," in Bettis Technical Review. Reactor Metallurgy. Westinghouse Electric Corporation, Bettis Plant, Pittsburgh, Pennsylvania. U. S. Atomic Energy Commission Contract Report No. WAPD-BT-10, October 1958.

Calorimetric and x-ray spectrometer measurements were used to verify the presence of an order-disorder reaction in the U-Mo system. Results were in good agreement with order-disorder theory but a slight adjustment of previously accepted phase boundaries was necessary.

242. Colombie, M. and Decours, J., "Influence of Carbon on the Primary Crystallization of Low-Concentration U-Mo Alloys." Translated from the French for Oak Ridge National Laboratory, Tennessee. U. S. Atomic Energy Commission Contract Report No. ORNL-tr-1668, 1966.

Experimental results showed that the addition of small amounts of C can lead to considerable refinement of the γ-grain size of U-1.1%Mo alloys. The mechanism for the C effect is discussed and methods of introducing C to the U-Mo alloy are proposed.

243. Colombie, M., Decours, J., Foure, M., and Magnier, P., "Influence of Small Additions of Alloying Elements." Translated from the French for Los Alamos Scientific Laboratory, New Mexico. U. S. Atomic Energy Commission Contract Report No. LA-tr-69-25, 1969. (N70-26671)

Grain refinement of the γ-phase of U and U alloys be addition of small amounts of low atomic number elements is described. γ-grain refinement by C was maximum at 500-800 ppm C for fast cooling rates; however, the maximum disappeared at slow cooling rates. Mechanism for grain refinement is discussed.

244. Craik, R. L., Birch, D., Fizzotti, C., and Saraceno, F., "Phase Equilibria in Uranium-Rich Binary Alloys Containing Molybdenum and Zirconium and the Effect of Ternary Additions of Carbon," J. Nucl. Mater., 6 (1962), 13-25.

The metallographic characteristics of microstructures of U-0.2-2.0w/oMo, U-1.0-8.0w/oZr and up to 2w/oC additons to these alloys which were slowly cooled to room temperature with intervening stop-annealing treatments at <950°C are described. Distinction between the constituent phases in these alloys was made by replica techniques. Possible effects of the microstructural condition of the alloys during irradiation are discussed.

245. Fizzotti, C. and Masperoni, A., "Study of Ternary Alloys of Uranium-Molybdenum-Niobium and Uranium-Molybdenum-Zirconium With a Low Alloying Content." Translated from the Italian for Oak Ridge National Laboratory, Tennessee. U. S. Atomic Energy Commission Contract Report No. ORNL-tr-2252, 1968.

U-0.2-0.5Mo-0.5-0.7Nb and U-0.2-0.4Mo-1.0-2.0Zr alloys were investigated in order to improve the irradiation resistance of metallic U. Microstructures were characterized according to heat treatment, with optimum grain size obtained by continuous cooling. TTT diagrams, aging response, and isothermal sections of the U-Mo-Nb system are reported.

246. Gittus, J. H., "Analysis of Effects of Dilute Alloying Additions on the Grain-Size of Uranium," Nature (London), 201 (1964), 916.

Jominy end-quench data for binary, ternary, and quaternary U-alloys with Mo, Cr, and Nb indicated grain size of the alloy specimens was comparable to predictions of equations based on additive and multiplicative models. Better correlations for the additive models were obtained.

247. Hayes, E. E., "Grain Refinement of Uranium by Heat-Treatment and Alloying." Fuel Elements Conference, Paris, 18-23 November 1957. U. S. Atomic Energy Commission, Washington, D. C. Report No. TID-7546, Book 1 (March 1958), 75-101.

Dilute U-alloys (up to 5a/oCr, Si, and Zr) can be used to reduce as-cast, fabricated, and β-treated grain size (<60μm). The neutron absorption cross section and concentration required for each of alloying elements are sufficiently low to permit the use of natural U in thermal neutron reactors.

248. Howe, L. M., "Effect of Carbon on the Grain Refinement of Uranium." Atomic Energy of Canada Limited, Chalk River, Ontario. Research Report No. CRMet-751, April 1958.

Study of microstructures in samples β-phase quenched and annealed at high α-phase temperatures supported a recrystallization mechanism for grain refinement. The effect of C content on the magnitude of grain refinement was small in the surface layers but large on the interior. Within the range 10-1000 ppm, grain refinement increased with increasing C content.

249. Minty, D. C. and Butcher, B. R., "Grain Refinement of Uranium-Chromium Alloys by Continuous Cooling." Atomic Energy Research Establishment, Harwell, England. Report No. AERE-R-3896, 1962.

Transformation temperatures and grain sizes of dilute U-Cr alloys were studied as a function of cooling rate. Results indicated that an alloy which would transform from the β-phase to fine equiaxed α-grains could be developed by a non-orientation dependent mechanism, when cooled to rates comparable to those observed on air-cooling large bars.

250. Nicholson, S., Harris, D. G., and Stobo, J. J., "The Effect of Ternary Additions on the Microstructures of Dilute U-Mo Alloys," J. Nucl. Mater., 12 (1964), 173-83.

An attempt to develop ternary alloys, with an element added to the U-3.6a/oMo alloy, having the same reactivity loss as the binary alloy and containing a high γ/α ratio when heat treated to give lamellar or "divorced" (α+γ) microstructures is reported. The U-Mo-Nb, U-Mo-Fe, U-Mo-Al, U-Mo-Ru, and U-Mo-Cr systems were investigated and the summary of the compositions, heat treatments, and phases detected are presented in tabular form. The U-3.6a/oMo-6.9a/oNb alloy was partially successful but the higher γ/α ratio did not persist at 550°C.

251. Strelova, S. V., Umansky, Ya. S., and Ivanov, O. S., "Short-Range Order in Uranium-Niobium Solid Solution," J. Nucl. Mater., 34 (1970), 160-64.

Short-range order in U-Nb solid solutions of equiatomic composition was studied by an x-ray diffuse scattering method. Short-range order parameters for three shells were measured and the static distortion parameters of the crystal lattice due to differences in the atomic volumes of the components were determined.

252. Wynblatt, P. and Bar-Or, A., "Grain Refinement of Dilute Uranium Chromium Alloys," J. Nucl. Mater., 12 (1964), 237-42.

Optimum composition and heat treatment of U-0.3, 0.45, 0.6a/oCr alloys to yield maximum grain refinement were investigated. Optimum isothermal transformation temperature in the 0.45Cr alloy was 525° and for the 0.6Cr alloy, 500°C. Increasing the Cr content from 0.3 to 0.6 decreased the temperature at which maximum grain refinement was achieved. Prior thermal history had no effect on grain size obtained by isothermal transformation.

253. British Patent No. 983,803. February 17, 1965. Improvements In or Relating to to Uranium Alloys. David J. Marsh to the United Kingdom Atomic Energy Authority.

Method of producing U-Mo-Nb alloy with grain structure refined to 50-100μm from 175-225μm by heat treating cast alloys (0.8-1.2a/o each of Mo and Nb) to 700°-900° and continuously cooling the alloy from this temperature at a rate of 100°-250°C/min.

254. British Patent No. 1,097,904. January 3, 1968. Uranium Alloys. Comitato Nazionale per l'Energia Nucleare.

Method of producing ternary U-alloys-U-0.1-0.3w/oMo-0.6-0.8w/oNb and U-0.2-0.4w/oMo-1.5-2.2w/oZr. The γ-phase of the alloy is heat treated at 900°and then continuously cooled at a rate of 5°-60°C/min. The grain size after heat treatment is 20-100μm, depending on the cooling rate.

Phase Transformations

255. Althaus, W. A. and Cook, M. M., "A contribution to the Study of Uranium-Base Dilute Aluminum Alloys," in Advances in Metallography. Technical Papers of the Twentieth Metallographic Conference, 18-20 May 1966, Denver, Colorado. Edited by R. J. Jackson and A. E. Calabra. Dow Chemical Company, Rocky Flats Division, Golden, Colorado. U. S. Atomic Energy Commission Contract Report No. RFP-658 (October 1966), 26-37.

Isothermal annealing characteristics of the eutectoidal decomposition of β-U-base dilute Al alloys were studied by optical and electron microscopy. The effects of Fe and C on the decomposition are described.

256. Anagnostidis, M., Baschwitz, R., and Colombie, M., "Metastable Phases in Uranium-Titanium Alloys." Translated from the French for Oak Ridge National Laboratory, Tennessee. U. S. Atomic Energy Commission Contract Report No. ORNL-tr-2459, 1966.

U-Ti alloy system differs from U-Nb and U-Mo alloys with regard to the nature and processes of formation of metastable phases in the following points: (1) the existence of a biphase region $\alpha''_b = \gamma^\circ$, (2) the variation of the parameter does not follow Vegard's law, (3) the boundaries of the different phases do not correspond to the same contractions of the parameter, b. These differences could be due to the relative positions of Ti, Mo, and Nb [illegible] the periodic table or to different bonds between the U and Ti.

257. Bar-Or, A., "Pearlite Reaction in Some Uranium-Chromium Alloys," J. Inst. Metals, 94 (1966), 214-17.

Characteristic needles of Cr were found following the $\beta \rightarrow \alpha$ transformation in U-Cr alloys made from electrolytic pure U (EPU) but not in alloys made from nuclear pure U (NPU). Growth rate (G) and its dependence on undercooling and Cr content of the eutectoid decompostion product in EPU alloys varied from those established for the NPU alloys and was attributed to the difference in the mode of nucleation of Cr. It is suggested that the growth of α or another process not dependent on the interspacing between the needles is the growth governing factor.

258. Bar-Or, A. and Kimmel, G., "Nucleation and Growth of Martensite in Some Uranium-Chromium Alloys," Trans. Met. Soc. AIME, 239 (1967), 1615-19.

The rates of nucleation and both lateral and longitudinal growth of martensite plates (needles) in $\beta \to \alpha$ transformation in U-0.1, 0.16, and 0.21w/oCr alloys were determined as a function of temperature and activation energies were calculated. The lateral and longitudinal growth rates had identical values suggesting they are both controlled by the same process, the rate of single-atom movement.

259. Bar-Or, A. and Kimmel, G., "Phase Transformations in Uranium-Chromium Alloys." The Mechanism of Phase Transformations in Crystalline Solids: Monograph and Report Series No. 33. London: The Institute of Metals (1969), 248-53.

Growth rates of pearlite, bainite, and martensite in U-Cr alloys were determined. For bainite, experimental results showed good agreement with the predictions of a model based on growth control by interface atom jumps. The bainite measurements, extrapolated into the pearlite range, showed good agreement with measured pearlite growth rates, and hence a similar growth mechanism was indicated. The growth-rate measurements in martensite were consistent with interface movement which is controlled by individual atom jumps. Martensite growth is believed to occur in two steps: a rate controlling step and a step in which some atoms cross the interface by a cooperative process.

260. Bar-Or, A., Wynblatt, P., and Hirsch, G., "The Rates of Nucleation and Growth of Alpha Uranium Transformed from the Beta in Dilute Uranium-Chromium Alloys," Trans. Met. Soc. AIME, 233 (1965), 1100-04.

Rates of nucleation and growth rates of α-phase U-0.45, 1.1, and 1.35a/oCr alloys were determined at various temperatures and proof that the $\beta \to \alpha$ transformation is controlled by nucleation and diffusional growth was obtained. The experimental results were in agreement with the classical theories that nucleation is controlled by the law of nuclei formation and the growth is controlled by bidimensional nuclei formation. Cr retarded both the rates of nucleation and growth.

261. Bar-Or, A., Hirsch, G., Goldstein, I., and Wynblatt, P., "Uranium Alloys." Third United Nations International Conference on the Peaceful Uses of Atomic Energy; Vol. 11, Nuclear Fuels II. Types and Economics. New York: United Nations (1965), 177-82.

Nucleation and growth rates, measured for several U-Cr alloys undergoing transformation, were found to be in agreement with the Volmer-Turnbull theories for nucleation and growth. Kinetics of γ decomposition in a U-10.8w/oMo alloy were determined by x-ray measurements. Two C curves were detected; at 550° $\gamma \to \alpha + \gamma'$ proceeded directly, while at 500°C and below $\alpha + \gamma'$ is preceded by the appearance of $\alpha + \gamma$.

262. Baschwitz, R., Colombie, M., and Foure, M., "Annealing of Metastable Orthorhombic Phases of Uranium-Titanium Alloys Containing 4.8 and 9.5 Percent Titanium." Translated from the French for Oak Ridge National Laboratory, Tennessee. U. S. Atomic Energy Commission Contract Report No. ORNL-tr-2440, February 1971.

Metastable phases of U-4.8 and 9.5a/oTi alloys were studied by micrography, x-ray diffraction, and both hardness and microhardness measurements and compared with the behavior of U-Mo and U-Nb alloys. The metastable phases in the U-Ti alloy appeared to behave quite differently from those in U-Mo and U-Nb alloys. This may be due to the presence of the intermetallic U_2Ti.

263. Brook, G. B., "Transformation Characteristics of Quaternary Uranium Alloy Containing Molybdenum, Niobium and Zirconium." Defence Research Establishment, Valcartier, Quebec. Report No. DREV-M-2060/71 (May 1971), 369-88. (AD 890 370)

Transformation characteristics of U-1w/oMo-1w/oNb-1w/oZr and U-2w/oMo-2w/oNb-2w/oZr alloys were determined by dilametry and thermal analysis. The alloy richer in U decomposed rapidly during cooling: the eutectoid temperature was 661° and the M_s temperature 495°. The more highly alloyed material had a eutectoid temperature of 642°, displayed a shear transformation, $\gamma\to\gamma^\circ$, at ∿420°, and the M_s for $^\circ\gamma\to\alpha_b''$ was 315°C. Possibilities of thermo-mechanical treatment for improved toughness and strength of these alloys are discussed.

264. Browne, J. D. and Williamson, G. K., "The Stability of the Tetragonal Phase Gamma Prime Uranium-Niobium Alloys," J. Inst. Metals, 89 (1961), 246-47.

High temperature x-ray diffraction of U-10-20a/oNb alloys showed a cubic γ-phase was present with no evidence pointing to a stable γ'-tetragonal phase.

265. Burke, J., "Martensite and Bainite Transformations in Uranium." Physical Properties of Martensite and Bainite. Special Report 93. London: The Iron and Steel Institute (1965), 83-89.

Martensite and bainite transformations in U and U-base alloys are reviewed and results of recent kinetic and metallographic studies presented. In U-alloys the martensite change occurred isothermally by slow growth and had C-curve kinetics. Addition of 1.0w/oCr to U decreased M_s from 600° to ∿200°C. Driving force above M_s was found to be ∿50cal/mole and the reaction above M_s was similar to the bainite reaction in steels and is thought to involve both lattice shear and diffusion of Cr in the β-phase.

266. Burke, J. and Evans, M. A., "Time/Temperature/Transformation Characteristics of Uranium-Chromium Alloys," J. Inst. Metals, 99 (1971), 315-18.

Isothermal $\beta\to\alpha$ phase transformation of U-1%Cr alloy after quenching from 700°-740°C were studied by resistivity measurements, and by metallographic and SEM observations. Results confirmed earlier conclusions that the TTT diagram comprises three C-curves and the activation energies are ∿70, 45, and 22 kcal/mole respectively. α-U with a dispersion of Cr particles was produced by reaction in C_1 and heavily dislocated α-U in C_2.

267. Butcher, B. R. and Holden, A. N., "The Kinetics and Crystallography of the Transformations Between the Primary Phases of Uranium and Its Dilute Alloys." Progress in Nuclear Energy, Series 5. Metallurgy and Fuels, Vol. 2. Edited by H. M. Finniston and J. P. Howe. New York: Pergamon Press (1959), 419-29.

The experimental work on the $\beta\to\alpha$ and $\gamma\to\alpha$ phase changes in U and dilute U-alloys is reviewed. The $\beta\to\alpha$ phase change may take place by normal diffusion controlled nucleation and growth rate or by a low temperature mode in which the growth of α -phase takes place slowly and isothermally. The $\gamma\to\alpha$ phase change may take place by a diffusion-controlled nucleation and growth mechanism, and there appears to be at least three other modes. In dilute Mo alloys an acicular product forms but with increasing Mo content and other alloys a banded structure occurs. Another product in some ways similar to both a Widmanstätten pattern and a banded structure occurs and some work suggests a phase change in the β temperature range.

268. Castaldelli, L., Fizzotti, C., and Gandini, A. G., "Transformation Processes in Some Uranium Alloys Low in Molybdenum and Niobium." Translated from the Italian for Sandia Laboratories, Albuquerque, New Mexico. U. S. Atomic Energy Commission Contract Report No. SC-T-72-2457, February 1972.

TTT curves for U-1.0%Mo, U-1.0%Nb, U-0.5%Mo-0.5%Nb, and U-0.2%Mo-0.7%Nb alloys are presented and discussed. Transformations that occurred at various temperatures are summarized and the morphology of the precipitated phases are discussed.

269. Castaldelli, L., Fizzotti, C., and Gandini, A. G., "Transformation Processes in Uranium Alloys with 2 Percent Contents of Molybdenum." Translated from the Italian for Sandia Laboratories, Albuquerque, New Mexico. U. S. Atomic Energy Commission Contract Report No. SC-T-72-2458, February 1972.

TTT curves for U-2w/oMo and U-2w/oNb alloys are presented and discussed together with different transformations which occur at various temperatures.

270. Chaudhuri, D. K. and Tangri, K., "Some Observations on the Metastable Phases in Uranium Base Ruthenium Alloys," Trans. Indian Inst. Metals, 15 (1962), 214-19.

Results of the metallographic and x-ray diffraction studies on metastable phases produced in γ-quenched U alloys containing up to 10a/oRu are reported. The effect of alloy content on the distortion of the orthorhombic structure, microstructure, and hardness was investigated.

271. Crocker, A. G. and Ross, N. D. H., "The Crystallography of Martensitic Transformations in Uranium and Its Alloys." The Mechanism of Phase Transformations in Crystalline Solids. Monograph and Report Series No. 33. London: The Institute of Metals (1969), 176-80.

Theories of martensite crystallography are analyzed using the $\beta\to\alpha$ and $\gamma\to\alpha$ transformations in U and U-5a/oMo. Insufficient experimental data exist for any conclusions to be drawn about $\beta\to\alpha$ transformations. For some observed cases of the $\gamma\to\alpha$ transformations, no real solutions of the theories are possible, demonstrating inadequacies of the theories. Preliminary account of a new theory of transformation shears is given.

272. Dean, C. W., "A Study of the Time-Temperature Transformation Behavior of a Uranium-7.5 Weight Percent Niobium-2.5 Weight Percent Zirconium Alloy." Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee. U. S. Atomic Energy Commission Contract Report No. Y-1694, October 1969.

TTT behavior of γ-U-7.5w/oNb-2.5w/oZr alloy was determined for the temperature range 200° - 800° and a TTT diagram consisting of two overlapping C-curves was determined by metallography, microhardness, and x-ray diffraction techniques. The critical temperature was determined to be 650°C, above which the bcc γ-phase was stable. Upon H_2O quenching to room temperature, a transition γ^s-phase was formed in which the body-centered atoms were slightly shifted. Aging transformed this phase to γ° (tetragonal) and further aging produced α'' which is a monoclinic crystal structure with hardness of 250 to >600DPH.

273. Dixon, P. H. and Burke, J., "A Resistometric Study of the Beta→Alpha Phase Change in a Uranium - 1/2% Chromium Alloy." Uranium and Graphite. Monograph No. 27. London: The Institute of Metals (1962), 9-16.

Resistivity, metallographic, and microhardness techniques were used to study the $\beta \rightarrow \alpha$ transformation of U-0.5a/oCr alloy at sub-critical temperature. Results indicated that the TTT diagram consists of three C-curves: (1) highest-temperatures (650°-530°) associated with diffusion-controlled transformation, (2) intermediate temperature (530°-400°C) involving simultaneous lattice shear and short-range diffusion, (3) low-temperature as applied to martensitic transformation by a shear mode.

274. Djuric, B., "Decomposition of Gamma Phase in a Uranium-9.5 Wt. Percent Niobium Alloy," J. Nucl. Mater., 44 (1972), 207-14.

X-ray diffraction and metallography were used to study the isothermal decomposition of the γ solid solution of U-9.5w/oNb alloy at 450°-600°C. The decomposition proceeded in two steps: (1) a discontinuous precipitation of a lamellar two-phase aggregate compound of α solid solution and a metastable γ-phase, having a constant composition at given temperature, (2) an equilibrium $(\alpha+\gamma_2)$ phase mixture after longer annealing. A modification of the original lamellar microstructure took place during the process.

275. Douglass, D. L., "The Structure and Mechanical Properties of Uranium-Titanium Martensites," Trans. ASM, 53 (1961), 307-19.

Up to $\sim$2a/oTi additions were very effective in increasing the strength of martensitic U. Lattice parameter changes with composition were continuous with a_o and c_o increasing the b_o decreasing with increasing solute. X-ray diffraction line broadening indicated non-uniform microstresses were present. Volume strain during $\gamma \rightarrow \alpha'$ transformation at M_s decreased at $\sim$2a/oTi; it is suggested hydrostatic pressure during transformation decreased to below the yield stress at this composition. Both tangential stress and hydrostatic stress were sufficient to plastically deform the specimens.

276. Gomozov, L. I., Makhova, V. A., Gomov, V. V., and Ivanov, O. S., "Kinetics of the Gamma-Phase Transformation in U-Zr-Nb and U-Nb-Mo Alloys." Translated from the Russian for Sandia Laboratories, Albuquerque, New Mexico. U. S. Atomic Energy Commission Contract Report No. SC-T-72-2548, 1972.

Results of γ-phase isothermal transformation of U-Zr-Nb and U-Nb-Mo alloys (containing <15a/o components other than U) at temperatures >500°C indicated that in the upper range of the S-curves transformation was governed in the early stages by supercooling, and in the later stages by the difference in composition between the parent and forming phases. In the U-Zr-Nb alloy disintegration proceeded homogeneously, but in the U-Nb-Mo alloy, heterogeneously. Attainment of the equilibrium composition of the forming γ and δ-phases does not generally mean the cessation of volume changes (to within $5\text{-}10^{-3}$%/hr).

277. Haberlin, M. M. and Slattery, G. F., "Transformations Kinetics of the β→α Phase Change in a Uranium-Chromium-Molybdenum Alloy." The Mechanism of Phase Transformations in Crystalline Solids. Monograph and Report Series 33. London: The Institute of Metals (1969), 254-59.

Dilatometry, metallography, hardness, and x-ray diffraction were used to study the β→α transformation in U-0.25a/oCr-0.5a/oMo alloy. A TTT diagram consisting of two C-curves was developed. The upper curve was predominantly associated with a diffusion-controlled transformation but testing results suggest a subdivision of this upper region at 480°-510°. The intermediate mechanism of transformation was of a bainitic type and extended down to ~425°C. The low-temperature C-curve appeared to involve a shear-type transformation.

278. Harding, A. G. and Waldron, M. B., "Transformation in Uranium Alloys With High Solute Solubility in the B.C.C. Gamma Phase. Part I. Preliminary Observations on the 'Banded Structures' Produced by Non Equilibrium Transformations in Uranium Alloys." Atomic Energy Research Establishment, Harwell, England. Report No. AERE-M/R-2673, September 1958.

The γ-phase of U-10%Ti, Nb, Zr or Mo alloys is metastable under critical cooling conditions and may transform by a shear mechanism to form a characteristic banded structure or by a nucleation and growth process to equiaxed grains. Metallographic appearance of these structures differ, but x-ray patterns are similar, termed "distorted" because of a contraction of the b parameter. Formation of the metastable structures depends on composition, cooling rate, the effect of the solute on the incubation period, and decomposition rate of the γ-phase.

279. Harding, A. G., Waldron, M. B., and Knight, C., "Transformations in Uranium Alloys With High Solute Solubility in the Gamma Phase, Part II: Transformation in Uranium Alloys of 5, 10, 15, and 20 at % Titanium on Quenching from the Gamma Phase." Atomic Energy Research Establishment, Harwell, England. Report No. AERE-M/R-2673A, 1958.

Three metastable phases are encountered when quenching U-Ti from the γ-phase: (1) α_3 is formed by shear transformation at 10a/oTi, (2) γ_1° exhibiting some degree of anisotropy at 15a/oTi, (3) α'_n, a distorted α structure formed by nucleation and growth on slower cooling. γ-phase can be retained in 20%Ti alloy. Hardness changes along end quenched rods are attributed to precipitation of U_2Ti from the supersaturated metastable phases.

280. Hatt, B. A., "The Orientation Relationship Between the Gamma and Alpha Structures in Uranium-Zirconium Alloys," J. Nucl Mater., 19 (1966), 133-41.

The orientation relationship between the γ-phase of U and α-like phase resulting from its direct transformation was determined for U-50a/oZr alloys. Results showed it to be similar to that reported for the transformation of the bcc structure to the hexagonal close-packed structure in Zr. Relationships of the metastable α' structure to α-U is discussed. It is shown how a banded microstructure can develop by the transformation of γ along all crystallographically equivalent paths so that each band is twin-related to adjacent bands.

281. Hills, R. F., Howlett, B. W., and Butcher, B. R., "Further Studies on the Decomposition of the γPhase in Uranium-Low Molybdenum Alloys," J. Less-Common Metals, 5 (1963), 369-73.

U-alloys containing 0.9-4.17a/oMo were cooled at various rates from the γ-phase field and studied by an end-quenching technique. The alloy structure was examined by metallography, x-ray diffraction, and hardness measurements. Structure was found to be dependent on the cooling rate and the original γ-grain size.

282. Hills, R. F., Butcher, B. R., Howlett, B. W., and Stewart, D., "The Effect of Cooling Rate on the Decomposition of the γ-Phase in Uranium-Zirconium Alloys," J. Nucl. Mater., 16 (1965), 25-38.

Rods of U-2.5-50a/oZr alloys were end-quenched and the phases formed, their distribution and hardness were studied as a function of composition and cooling rate. It was found that in alloys containing 10-50a/oZr, the α-phase played a large part in the decomposition but in those alloys containing 10-30a/oZr the α-phase was unstable at room temperture, and in the more dilute alloys there was no evidence of its appearance.

283. Hills, R. F., Harries, D. R., Hodkin, D. J., and Waldron, M. B., "Transformation of Metastable Phases in the Uranium-Molybdenum Alloy System." Atomic Energy Research Establishment, Harwell, England. Report No. AERE-M/R-2840, March 1959.

Metallographic, x-ray, and hardness measurements were used to study transformation of U-Mo (up to 25a/oMo) alloys at 450°-550°. In 5, 10 and 15a/o Mo alloys, transformation to equilibrium α+γ' increased hardness whereas transformation of the 25 and 30a/oMo alloys produced only minor hardness changes. Two metallographic forms of γ' were observed in U-25a/oMo, a banded appearance at 450° and an acicular form at 550°C.

284. Hills, R. F., Howlett, B. W., Butcher, B. R., and Stewart, D., "The Effect of Cooling Rate and Composition on the Transformation of the Gamma-Phase in Uranium Ruthenium Alloys (With an Appendix on Ruthenium as a Grain-Refining Element)," J. Nucl. Mater., 16 (1965), 109-28.

U-1.0-10a/oRu alloys were cooled from the γ-phase and the transformations studied by an end-quenching technique. At the quenched ends a monoclinic α-type structure, α''_b, was found and beyond the quenched ends the decomposition is dominated by the rapid diffusion of Ru→U_2Ru. Apendix on the grain refinement of the α-phase produced from isothermal transformation of β-U.0.25-1.0a/oRu alloys is included.

285. Howlett, B. W., "A Study of the Shear Transformations from the Gamma-Phase in Uranium-Molybdenum Alloys Containing 6.0-12.5 at % Molybdenum," J. Nucl. Mater., 35 (1970), 278-92.

Study of the shear transformations in the γ-phase U-6.0-12.5a/oMo alloys showed two shear transformations occurred successfully over most of the composition range; enthalpies were measured as a function of composition and cooling rate. The dominant factor appeared to be the changes in the degree of order produced by the change in cooling rates.

286. Howlett, B. W., Eycott, A. J., Kang, I. K., and West, D. R. F., "The Kinetics of the Isothermal Decomposition of a Gamma-Phase Uranium-6 Atomic % Molybdenum Alloy," J. Nucl. Mater., 9 (1963), 143-54.

The kinetics of the isothermal decomposition of γ-U-2.5w/oMo alloy at 390°-670°C was investigated using dilatometry, metallography, hardness measurements, and x-ray diffraction.

287. Ivanov, O. S. and Virgiliev, Yu. S., "The Decomposition of the γ-Uranium Base Solid-Solutions as Revealed by X-ray Investigations," J Nucl. Mater., 6 (1962), 199-202.

X-ray patterns were analyzed and results suggest that the decomposition of the γ solid solution of U-Mo alloys takes place by the formation of U_2Mo regions, ordered to a considerable degree and coherently bound to the initial γ solid solution on the (001) planes. In the U-Nb and U-Zr-Nb alloys the γ solid solution decomposes homogeneously at low temperature and low Nb concentrations due to the formation of highly dispersed precipitates of α-U, and heterogeneously at high temperatures and high Nb concentrations due to the limited number of centers and proceeds as diffusion continues.

288. Jackson, R. J., "Isothermal Transformations of Uranium-13 Atomic Percent Niobium." Dow Chemical Corporation, Rocky Flats Division, Golden, Colorado. U. S. Atomic Energy Commission Contract Report No. RFP-1609, April 1971.

The isothermal transformation behavior of γ-U-13a/oNb alloy was determined for the temperature range 23°-640°C. A TTT diagram was constructed from hardness, x-ray diffraction, and both optical and electron micrographic data. Two overlapping C-curves were disclosed in the diagram, the upper one corresponding to α-plus a Nb-deficient γ-phase which gradually enriches in Nb to form the equilibrium γ_2 structure and the lower one being a general precipitation of α-phase on dislocations.

289. Jackson, R. J., "Reversible Martensitic Transformations Between Transition Phases of Uranium-Base Niobium Alloys." Dow Chemical Company, Rocky Flats Division, Golden, Colorado. U. S. Atomic Energy Commission Contract Report No. RFP-1535, December 1970.

The occurrence and generation of transition phases in U-Nb alloys are discussed and the transition phases and unit cell parameters as a function of composition and temperature are presented. Three distinct phases, α'_t(orthorhombic), α''_t(monoclinic) and γ°_t(tetragonal), occurred as an intermediate in the direct γ→α transformation. An approximated transition phase diagram and a model for the consecutiveness of the transformation are also presented.

290. Jackson, R. J., "Structures and Transformation Kinetics of Phases in the Uranium-Rhenium Alloy System." Unpublished Ph.D. dissertation Iowa State University, 1964.

Time-temperature-composition dependence of crystal structure and microstructure under nonequilibrium cooling conditions for U-rich U-Re alloys was studied. Sluggish reactions of the stable phases led to nonequilibrium quantities of the equilibrium α, β, γ, and δ phases. The γ→α transformation was found to proceed by an isothermal martensitic reaction or by sluggish nucleation and growth. Under certain conditions, β→α transformation was direct, passing through the intermediate β structure, but was accompanied by a number of metastable transition states. Compositional limits within which stable and metastable phases form and the effect of cooling rate and temperature on producing alternative structures were determined.

291. Jackson, R. J. and Johns, W. L., "Temperature-Induced Shape Memory in Polycrystalline Uranium-Base Niobium Alloys: Characterization." Dow Chemical Company, Rocky Flats Division, Golden, Colorado. U. S. Atomic Energy Commission Contract Report No. RFP-996, September 1970.

An unusual, internal, athermal, and reversible strain behavior was observed in U-6-21a/oNb alloys (maximum at 15a/oNb) in the temperature range - 200° to +400°. Dimensional change per temperature increment varies as a function of temperature, composition, and cooling rate from the γ-region. Conditions necessary for subsequent temperature-induced shape change are: (1) sample must be cooled rapidly from the γ-region, (2) as-quenched shape must be subjected to a plastic deformation at <425°C.

2. Kawasaki, M., Nagasaki, R., Itagaki, M., and Takemura, T., "Some Studies on the Uranium-Molybdenum Alloy." Translated from the Japanese for the U. S. Atomic Energy Commission, Office of Technical Information, Washington, D. C. Report No. AEC-tr-4468, 1960.

General properties and characteristic behavior of heat treated U-Mo alloys were investigated. Specimens were made by vacuum induction melting and rolled at 600° and 900°. Phase changes by quenching from various high temperature phases and the effect of quenching rate from the γ-phase were studied. M_s was determined for U-1.3a/oMo. Thermal cycling tests on U-0.5-9.0%Mo rolled rods indicated that greater improvement was obtained by γ-quenching followed by α-annealing. Oxidation in air at 300°, 400°, and 500°C showed the rate constant decreased with increasing Mo content in the lower Mo range but increased as Mo content became higher.

293. Kishinevskii, V. B., Tret'yakov, A. A., Gomozov, L. I., and Ivanov, O. S., "Kinetics of the Isothermal Transformation of Gamma Solid Solutions of Some Uranium Alloys." Translated from the Russian for the University of California, Lawrence Radiation Laboratory, Livermore. U. S. Atomic Energy Commission Contract Report No. UCRL-Trans-10452, March 1970.

Kinetics of the decomposition of γ-solid solution in ternary U-Zr-Nb alloys and in binary U-20a/oNb alloys were studied by dilatometry, and TTT diagrams were constructed. Resulting C-shaped curves consisting of two branches indicated that the transformation occurred by different mechanisms at high and low temperatures.

294. Kitchingman, W. J., Pickwick, K. M., Brown, I. G., and Edwards, R. J., "The Mechanism and Transformation Kinetics of the β→α Phase Change in the Uranium/1 AT % Platinum Alloy," J. Nucl. Mater., 18 (1966), 219-25.

β→α transformation in U-1a/oPt alloy, at 0°-600°, measured by electrical resistivity suggested three modes of transformation: (1) at high temperatures nucleation-and-growth process occurs and is consistent with a diffusion-controlled process, (2) at intermediate temperatures the reaction is consistent with a bainite process, (3) at low temperatures, <100°C, the reaction is characterized by a shear mechanism. Measurements were unable to separate the high temperature β→α transformation in dilute U-Pt alloys.

295. Kramer, D. and Rhodes, C. G., "The Gamma to Gamma Prime Transformation in the Uranium-Molybdenum System." Atomics International, Canoga Park, California. U. S. Atomic Energy Commission Contract Report No. NAA-SR-6617, December 1961.

Kinetics of the γ→γ' transformation in U-16w/oMo alloys were studied by metallography and electrical resistance measurements. A nonequilibrium α-phase appeared in the transformation anneal, reached a maximum volume fraction when γ' emerged, and in time disappeared. At 550° transformation to γ' first appeared in 48-72 hrs, but at 500°C it took 120 hrs.

296. Kramer, D. and Rhodes, C. G., "The Precipitation of Metastable Alpha Phase During the Gamma to Gamma Prime Transformation in Uranium-16 wt pct Molybdenum," <u>Trans. Met. Soc. AIME</u>, <u>224</u> (1962), 1015-20.

The kinetics of formation and disappearance of the transient α-phase during the γ-to (ordered bct) γ' transformation in U-16w/oMo alloys at 400°-500°C were studied using quantitative metallography and electrical resistivity measurements. It was shown that the α-phase is not an equilibrium phase at any temperature but that it is easy to nucleate from the γ-phase and it contributes to a reduction in the free energy of the system. A final decrease in free energy occurs when γ' forms and occupies the whole sample.

297. Lehmann, J. and Hills, R. F., "Proposed Nomenclature for Phases in Uranium Alloys," <u>J. Nucl. Mater.</u>, <u>2</u> (1960), 261-68.

A nomenclature system devised for U-Mo alloys is described. It is believed to be sufficiently general to cover equilibrium and metastable phases existing in all U-systems showing a solubility in the bcc γ-phase. The proposed terminology is presented in tabular form and illustrated by micrographs.

298. Marsh, D. J., Slattery, G. F., and Gittus, J. H., "Use of the Jominy End-Quench Test to Explore the Transformation Characteristics of Some Uranium Alloys," <u>J. Inst. Metals</u>, <u>93</u> (1965), 260-67.

Binary, ternary, and quaternary alloys of U with Mo, Cr, Nb, Fe, and Al were end-quenched from 720°-800°C using a Jominy rig. The grain refinement produced depended on the arithmetic sum of the effect on grain size which the alloying elements separately produced. Binary U-Cr alloys transformed by a shear process but U-Nb and U-Nb-Cr alloys gave a fine grain size when air cooled.

299. Mihajlovic, A., "Activation Energy of Isothermal Martensitic β-α' Transformation," <u>J. Mater. Sci.</u>, <u>5</u> (1970), 955-59.

Kinetics of isothermal β-α' martensitic transformation in a U-0.5w/oMo alloy was investigated. Specimens were quenched from the β-region at 690° and held isothermally at temperatures from 120°-196°C. The percentage of the α-phase formed was determined and the half-thickness, "c", and radius "r", of plates were calculated by quantitative metallographic methods. It was found that the activation energy for nucleation depends linearly on temperature and that the nucleation rate is a parabolic function of temperature.

300. Mihajlovic, A., Kostic, M., and Tepavac, P., "Transformation in Uranium-0.45% Molybdenum Alloy in Relation to Cooling Rates and Overheating Temperature," J. Nucl. Mater., 31 (1969), 107-10.

The kinetics of transformation in U-0.45w/oMo alloy at different cooling rates, 2°C/sec-80°C/sec, from the β and $\beta+\gamma$ regions were studied. The changes in microstructure with the changes in temperature in the β and $\beta+\gamma$ regions and with cooling rate are presented. A change in the mechanism of transformation as a function of the cooling rate was observed in all specimens. Contrary to previous investigations, lowering the overheating temperatures did not accelerate transformation.

301. Mihajlovic, A., Mance, A., and Djuric, B., "Kinetics of Beta→Alpha Prime Transformation in Low Molybdenum-Uranium Alloy," Proceedings of Conference on Metastable Metallic Alloys, Brela, Yugoslavia, September 1970. Fizika, 2, Suppl. 2 (1971), No. 43.

The effect of the degree of superheating in the γ and β temperature regions on the kinetics of isothermal $\beta\rightarrow\alpha'$ transformation in U-0.45 and 0.6%Mo alloys was investigated. At room temperature the $\beta\rightarrow\alpha'$ transformation depended on time which indicated that thermal activation affects the kinetics of the process. A modified Avrami equation, $x=1-\exp[-k\tau^n]$, where "τ" is time and "k" and "n" are constants, was used to analyze the kinetics of transformation. The calculated value of parameter, n=2÷3, concurred with the mode of growth of the martensitic phase experimentally established. There are indications that the kinetics of $\beta\rightarrow\alpha'$ transformation changes at the transition from the upper to the lower β-solid solution region.

302. Ostberg, G. and Lehtinen, B., "The $\gamma\rightarrow\gamma'$ Ordering Reaction During Isothermal Transformation of γ in a U-1.6wt%Mo Alloy," J. Nucl. Mater., 13 (1964), 123-24.

A selected area electron diffraction technique was used to study the isothermal transformation of γ in U-1.6w/oMo alloy. Results showed this technique to be more sensitive to detection of γ'-phase, formed as discrete particles in the γ-matrix, than the x-ray method previously used.

303. Ostberg, G., Möller, M., and Schönning-Christiansson, B., "Metallographic Study of the Transformation of γ Phase Into ($\alpha+\gamma'$) Phases in a U-1.6wt%Mo Alloy," J. Nucl. Mater., 10 (1963), 329-38.

The isothermal transformation of γ in U-1.6w/oMo alloy at 500°-640°C was studied using ordinary light, electron microscopy, and x-ray diffraction. The TTT diagram for the transformation of γ conformed to normal C curves representing beginning and end of the formation of α and γ'.

304. Peterson, C. A. W. and Steele, W. J., "A Study of the Effect of Alloying on the Gamma-Phase Stability of Uranium Using Vacuum Differential Thermal Analysis." University of California, Lawrence Radiation Laboratory, Livermore. U. S. Atomic Energy Commission Contract Report No. UCRL-7595, November 1963.

A simple automatic, high-temperature high-vacuum thermal analysis apparatus based on the differential method is described. The phase transformations of a series of U-Mo, U-Nb and U-Zr alloys were determined using samples of a few grams heated and cooled over a range of 1000°C in a vacuum of 10^{-5} torr. The effects of the alloying additions on the γ-phase stability of the U under low rates of thermal changes were recorded, Mo>Nb>Zr.

305. Peterson, C. A. W., Steele, W. J., and DiGiallonardo, S. L., "Isothermal Transformation Study of Some Uranium-Base Alloys." University of California, Lawrence Radiation Laboratory, Livermore. U. S. Atomic Energy Commission Contract Report No. UCRL-7824, August 1964.

Isothermal TTT characteristics for γ-phase binary and ternary U-alloys containing Mo, Nb, and/or Zr are presented. Hardness and microstructural changes are described and correlated with time, as determined by resistivity measurements, to initiate transformation at a given temperature.

306. Provow, D. M. and Fisher, R. W., "The Electrical Resistivity of Solid and Molten Uranium-Chromium Eutectic," J. Less-Common Metals, 6 (1964), 313-21.

Electrical resistivity of U-4.9w/oCr eutectic was determined as a solid from room temperature to its melting point, 870°±3° and as a liquid from its melting point to 1000°C. Measurements were obtained in vacuum by use of a standard four-probe method with current reversal. Comparison of the eutectic with pure U showed a reduction in the temperature of the phase transformations of the alloys and in the magnitude of the drop in resistance.

307. Repas, P. E., Goodenow, R. H., and Hehemann, R. F., "An Investigation of Transformation Characteristics of Three Uranium Base Alloys." Case Institute of Technology, Cleveland, Ohio. Army Materials Research Agency, Watertown, Massachusetts. Contract Report No. AMRA-CR-63-02/1F, January 1963. (AD 403 776)

Part I-TTT diagrams using metallographic, dilatometric, hardness, and x-ray techniques are presented and transformation kinetics are described for U-10%-Mo, U-8%Mo, U-8%Mo-1/2%Ti, U-8%Mo-1%Ti, and U-2%Mo-2%Nb-2%Zr-1/2%Ti. Part II-Metallographic techniques suitable for the identification of phases, intermetallic compounds, and non metallic constituents in these alloys were developed. Techniques for U-base alloys were perfected for nearly all conditions of heat treatment. Certain low temperature transformation structures and the identification of nonmetallic inclusions were not completely resolved.

308. Repas, P. E., Goodenow, R. H., and Hehemann, R. F., "Transformation Characteristics of U-Mo and U-Mo-Ti Alloys," ASM Trans. Quart., 57 (1964), 150-63.

The high and low temperature characteristics of binary U-8Mo and U-10Mo and ternary U-8Mo-0.5Ti and U-8Mo-1Ti alloys are described. TTT diagrams based on metallographic, dilatometric, microhardness, and x-ray diffraction data are presented. Decomposition of the bcc γ-phase at high temperature was a result of either a cellular mechanism or a combination of cellular Widmanstatten mechanisms at low temperature by a different but unrevealed mechanism and was initiated by precipitation of γ" homogeneously throughout the γ-matrix.

309. Rhodes, C. G. and Kramer, D., "On the Gamma to Gamma Prime Transformation in Uranium-33 At % Molybdenum," J. Nucl. Mater., 9 (1963), 114-15.

Comments on the work reported of Ivanov and Virgileev (See-Entry No.287) on the x-ray diffraction measurements of the γ-transformation mechanism in U-Mo alloys. It is proposed that the transformation occurs by the formation of γ'-nuclei with some small degree of ordering. These grow as plates and continue to order simultaneously.

310. Ross, N. D. H. and Crocker, A. G., "Type II Twinning in Martensite Crystallography Theories," Scr. Met. , 3 (1969), 37-42.

Type II deformation twins having irrational twin planes, but rational twin directions predominant in metals. Crystallographic restrictions imposed by Type II twinning on the martensite theories are considered and extended to the case of U-5%Mo alloys to include the possibility of Type II twins arising from two-fold rotation axes of the parent γ structure.

311. Sivaramakrishnan, K. S. and Somasundaram, R., "Studies on the Transformation Behaviour of Low Ternary Alloys of Uranium," Trans. Indian Inst. Metals, 16 (1963), 247-51.

The properties of U-alloys containing <0.1w/oCr, Mo, and Nb were investigated to study structural refinements and to find a satisfactory combination of random structure, fine grain size, and high temperature properties which are essential for reactor fuel elements. TTT curves for U and the U-alloys are presented. Additions of Cr and Mo in the ternary alloys, isothermally treated at 500°C, refined the grain size and were thermally stable but the Nb additions were so small (0.04-0.07w/o) no changes were observed.

312. Storhok, V. W., Bauer, A. A., and Dickerson, R. F., "Survey of Ternary Metastable Gamma-Phase Uranium Alloys." Battelle Memorial Institute, Columbus, Ohio U. S. Atomic Energy Commission Contract Report No. BMI-1278, July 1958.

Effects of ternary and quaternary alloying on the stability and properties of U-Zr, U-Nb, and U-Mo γ-phase alloys are reviewed. The effects of ternary and quaternary additions of Cr, Mo, Cb, Ru, V, and Zr on transformation kinetics, transformation temperature, hot hardness, and corrosion resistance were also investigated.

313. Tangri, K. and Chaudhuri, D. K., "Metastable Phases in Uranium Alloys with High Solute Solubility in the BCC Gamma Phase. Part I-The System U-Nb," J. Nucl. Mater., 15 (1965), 278-87.

Mode of formation of metastable phases in the U-Nb system (1.0-18.15a/oNb), were studied. Composition limits of α', α", and γ° phases and changes in parameters a, b, c, and γ (ab) were determined. A study of the effect of cooling rate showed its effect on the mode of formation is similar to that observed in the U-Mo system. Reasonably accurate values of the α'/α" boundary composition for various binary U-alloys based on atomic size may be calculated.

314. Tangri, K. and Williams, G. I., "Metastable Phases in the Uranium-Molybdenum System and Their Origin," J. Nucl. Mater., 4 (1961), 226-33.

Composition limits of metastable α'- and α"-phases, changes in parameters a, b, c, angle γ(ab) of α-U lattice with increasing Mo additions (0.07-11.39%), and effect of cooling rates in producing alternative structures were determined. Increasing Mo additions stiffened the U lattice, making it more resistant to shear but increasing the cooling rate favored shear and carried the transformation toward completion.

315. Townsend, R. D. and Burke, J., "The Effects of Thermal History on the Kinetics of the $\beta \to \alpha$ Phase Change in Uranium and Uranium-Chromium Alloys," J. Nucl. Mater., 17 (1965), 215-26.

The effects of various heat treatments on the kinetics of the $\beta \to \alpha$ phase transformation in U and U-0.5-0.85w/oCr alloys were examined using an electrical resistivity technique. Transformation at temperatures near the equilibrium transition temperature was reduced by increasing the β-quenching temperature. This retardation was due to increased β grain size in the alloys, but in the pure U other factors are involved. At temperatures in the martensitic and bainitic region transformation was accelerated with increasing temperature because of the removal of the grain boundaries.

316. Vandermeer, R. A., "The Body-Centered Cubic (γ) to Tetragonal (γ_o) Phase Transformation in Uranium-Niobium-Zirconium Alloys." Proceedings of the Conference on Local Structural Order and Decomposition of Titanium, Uranium, and Zirconium-Base B.C.C. Solid Solutions. Cosponsored by the Office of Naval Research and the Cornell Materials Science Center, Ithaca, New York (15-16 May 1972), 12. (AD 748 035)

X-ray diffraction study of the decomposition of U-7.5w/oNb-2.5w/oZr indicated atom displacement ordering in as quenched tetragonal phase (γ_o). An intermediate stage in γ to γ_o transition was found; this γ_s state is reflective of the high temperature γ-phase and is spoken of as the short range atom displacement ordering counterpart to the γ_o phase.

317. Yakel, H. L., "Crystal Structures of Transition Phases Formed in U-16.6 at %Nb-5.64 at %Zr Alloys," J. Nucl Mater., 33 (1969), 286-95.

Two metastable transition phases were revealed when γ-quenched and aged U-7.5w/oNb-2.5w/oZr alloys were studied by single crystal x-ray diffraction. The first transition structure, γ^s, is cubic with space grouping of 143m and may be described as eight unit cells of the γ-structure in which the body-centered atoms have moved in correlated <100> directions. Aging at 150° or 350°C produced the second transition structure, γ°, which is tetragonal with space grouping of P4/nmm. No evidence was found to suggest significant chemical order in either transition structure.

318. Yakel, H. L., "The Decomposition of Uranium-Base B.C.C. Alloys." Proceedings of the Conference on Local Structural Order and Decomposition of Titanium, Uranium, and Zirconium-Base B.C.C. Solid Solutions. Cosponsored by the Office of Naval Research and the Cornell Materials Science Center, Ithaca, New York, (15-16 May 1972), 5-6. (AD 748 035)

Metastable phases occurring in the decomposition of bcc γ-phase in U-Mo, U-Nb and U-Nb-Zr systems to equilibrium phases are described. Degree of distortion decreased with increasing solute concentration in alloys quenched from the γ field. γ^s appearing in high solute as-quenched crystals, had atoms shifted by displacement waves over short distances only; for decreased solute or prolonged aging, monoclinic α'' was obtained. Finally, orthorhombic α' is described which is most closely related to equilibrium α.

319. Zukas, E. G., "Transformation Kinetics and Mechanical Properties of Uranium-0.5w/o Columbium-0.5w/o Molybdenum Alloy," Trans. ASM, 52 (1960), 797-811.

Isothermal transformation studies were made on the U-0.5w/oCb-0.5w/oMo alloy at 950°, the high temperature γ-phase field and at 675°C, the (β+γ) phase field to increase the amount of retained β-phase. Transformation boundaries were determined by hardness, density, metallography, and x-ray diffraction. Tensile and impact properties were determined from -198° to 100°C after four heat treatments which were chosen on the basis of isothermal kinetics studies. The isothermal transformation diagrams are presented.

320. U. S. Patent No. 3,567,523. March 2, 1971. Pseudo-Plastic Behavior of Uranium-Niobium Alloys. Ross J. Jackson, Joseph F. Boland, and Julius L. Frankeny to the Dow Chemical Company.

Process of achieving an unusual, thermally recoverable and reversible pseudo-plastic strain behavior in U-Nb alloys (5.0-25.0a/oNb) which comprises heating the alloy to ~850°, H_2O quenching from the γ-region at room temperature, and plastically deforming it at a temperature <450°C.

321. British Patent No. 1,315,652. May 2, 1973. Binary Alloys Reversibly Changing Shape With Temperature. Greville B. Brook and Roger F. Iles to Fulmer Research Institute, Ltd.

Alloy specimens as U-4-6%Mo, U-4-10%Nb, U-2-7%Re, and other alloys, useful as thermal sensors, change their shape reversibly when deformed or strained at low temperature and heated above a transition temperature to induce a metastable stressed high-temperature structure. A stress transformation to a martensitic structure occurred on cooling, causing the change in shape. Shape memory on cycling through the temperature -196° and +100°C is described using U-5%Mo as an example.

322. British Patent No. 1,315,653. May 2, 1973. Heat-Recoverable Alloys. Greville B. Brook and Roger F. Iles to Fulmer Research Institute, Ltd.

Binary U-alloys containing 2-7w/oMo, 3-10w/oNb, or 2-7w/oRe and other alloys were provided with good heat recoverable properties by preheating, cooling rapidly to prevent α-phase or eutectoid precipitation, and deforming at the M_s transformation temperature. Original shape was recovered by reheating above a critical temperature. Shape memory is described for U-5Mo deformed at room temperature, heated to 150°-200°C, and subsequently cooled to room temperature again.

Precipitation

323. Ammons, A. M., "Precipitation Hardening of Uranium-Titanium Alloys Containing Less Than 1.0 Weight Percent Titanium." Union Carbide Corporation, Y-12 Plant, Oak Ridge Tennessee. U. S. Atomic Energy Commission Contract Report No. Y-1850, September 1972.

Strengthening mechanisms in U-<1.0w/oTi alloys were determined and studied. Results showed some gain in mechanical properties in the as-cast alloy, higher strength and elongation in the γ-quenched alloy, and increase in hardness and yield strength and decrease in ductility with subsequent aging of γ-quenched alloy. Maximum hardness (511DPH) and maximum strength (145.2 ksi) were produced after aging for 72hrs at 400°C. Continued aging produced growth of precipitates at grain boundaries.

324. Douglass, D. L. and Marsh, L. L., Jr., "Effect of Heat Treatment on the Hardness and Microstructure of U-Ti Alloys," Trans. AIME, 209 (1957), 1260-67.

Hardness and microstructure of U-8.5-50a/oTi alloys were correlated with heat treatment. A direct quench of γ-U-Ti solid solution resulted in the formation of a hard martensitic phase in low-Ti alloys. Subsequent tempering first increased the hardness by the precipitation of U_2Ti but further precipitation with tempering time resulted in softening. isothermal transformation of U-8.5a/oTi at 400°-500°C gave high-hardness levels. The overall response to heat treatment was dependent upon the phases present during solution treatment. Results are interpreted in terms of the phase diagram.

325. Dupont, G. and Dube, A., "Study of the Mechanism of Tempering of a Quenched U-2Mo Alloy." Defence Research Establishment, Valcartier, Quebec. Report No. DREV-R-621/70, September 1970. (AD 880 241)

The mechanism of transformation of the quenched metastable phase (α_b') in a U-2Mo alloy was studied. Isothermal and anisothermal tempering processes were used, including metallography, x-ray diffraction, hardness and dilatometry on quenched samples either during or after tempering. Results indicated the α_b'-phase decomposed in two stages: (1) formation of G. P. zones, (2) formation of peralitic structure $(\alpha+\gamma')$ the matrix impoverished in Mo and hardness reduced. Final stage is analogous to that of normalized or annealed steels.

326. Jackson, R. J. and Miley, D. V., "Tensile Properties of Gamma Quenched and Aged Uranium-Base Niobium Alloys," ASM Trans. Quart., 61 (1968), 336-43.

Tensile test data correlated with metallographic and x-ray studies for U-11, 15, 17, 19a/oNb alloys in the γ-quenched and aged conditions are presented. Aging for 1hr at temperatures <300°C increased the strength of the alloys with no loss in ductility. The alloys are heat treatable and corrosion resistant, have high density, and show promise as an economic engineering material.

327. James, P. F. and Fern, F. H., "Morphology of Precipitation in Alloys of Uranium-Aluminum and Uranium-Iron-Aluminum," J. Nucl. Mater., 29 (1969), 191-202.

TEM of thin foils was used to investigate precipitates formed when dilute alloys of U-Al and U-Fe-Al were γ-quenched and α-annealed. In both alloys intergranular precipitates were identified as UAl_2 and in the ternary alloy large precipitates of U_6Fe formed rapidly at grain boundaries. Evidence for the orientation relationships between these phases is presented and the atomic rearrangements involved in their formation are discussed.

328. May, G. H., "The Annealing of a Quenched Uranium-5 At % Molybdenum Alloy," J. Nucl. Mater., 7 (1962), 72-84.

Three stages were observed in the annealing of γ-quenched u-5a/oMo alloy: (1) age-hardening in the supersaturated α'-phase, (2) over-aging with recrystallization and discontinuous precipitation of nonequilibrium γ, (3) a second recrystallization with re-precipitation to form a pearlite structure. Proposed explanations to account for these reactions are speculative and further work is necessary.

329. Schiesser, R. J., "Improvement of Uranium-Molybdenum Alloys for Gyroscope Wheel Rims by Aging Treatments." Massachusetts Institute of Technology, Instrumentation Laboratory, Cambridge, Massachusetts. Air Force Avionics Laboratory Contract Report No. NP-15334, July 1964.

A compound wheel composed of a Be hub and a U-8%Mo alloy rim increased both the angular momentum and the gyro sensitivity of the wheel. Aging heat treatment provided the U-Mo alloy with the physical properties desired in a gyro wheel rim material. A wheel design for operation at 36,000 rpm was defined.

330. Tomlinson, R. D., Silcock, J. M., and Burke, J., "The Isothermal Decomposition of Gamma-Phase Uranium-Titanium Alloys," J. Inst. Metals, 98 (1970), 154-60.

Isothermal decomposition of the γ-phase in U-12, 20, 25a/oTi alloys was studied by single-crystal and polycrystalline x-ray methods, metallographic observations, microhardness measurements, and limited electrical-resistivity measurements. Single-crystal x-ray studies showed the U-25Ti alloy decomposed during quenching from 1475° to room temperature into a coherent hexagonal phase. In polycrystalline specimens there was continuous precipitation within the grains and a grain-boundary-nucleated discontinuous reaction to $\alpha+U_2Ti$.

331. Wyatt, B. S., Berthiaume, L. C., and Conversi, J. L., "Metallurgical Structures in High Uranium-Silicon Alloy." Atomic Energy of Canada, Ltd., Chalk River, Ontario. Research Report No. AECL-2761, October 1968.

Optical micorscopy, quantitative metallography, and hardness measurements were used to study the effect of fabrication and heat treatment variables on the structure of U-3.96w/oSi alloy. Results showed an optimum temperature below the peritectoid temperature where maximum transformation to U_3Si occurred in a given period of time. The time required is affected by the size of the primary U_3Si_2 particles; at <12μm complete transformation can be achieved in four hours.

Impurity Effects

332. Adamson, P., Orman, S., and Picton, G., "The Effects of Hydrogen on the Tensile Properties of Uranium When Tested in Different Environments," J. Nucl. Mater., 33 (1969), 215-24.

The effect of H, particularly at low concentrations (0-200 ppm) and in different environments (vacuum, air, H_2O), on both the dynamic and static tensile properties of U was studied. At all concentrations the H embrittled the U and caused intergranular fracture. The ductility and tensile strength of the hydrided U decreased in the order vacuum > air > H_2O. Adverse mechanical effects of H were eliminated at temperatures >100°C. Electrolytic etch treatment revealed no preferential hydriding at the grain boundaries.

333. Avery, J. G., "Effect of Alloy Content, Carbon, Oxygen, and Nitrogen on the Mechanical Properties of Uranium-2.2 Wt. % Niobium and Uranium-0.75 Wt. % Titanium Wrought Heat Treated Alloys." Dow Chemical Company, Rocky Flats Division, Golden, Colorado. U. S. Atomic Energy Commission Contract Report No. RFP-1950, March 1973.

A series of U-1.8w/oNb and U-0.75w/oTi alloys with varying amounts of C, O, and N were prepared. The final chemical compositions of the alloys were related to their heat-treated mechanical properties. It was found that C was detrimental to ductility in both alloys but did not affect the yield or ultimate strengths in the U-Ti alloy which exhibited a "gettering" action in which some C was removed by Ti. Variations in the Ti content affected the yield and ultimate strengths.

334. Darras, R. and Caillat, R., "Hydrogen in Uranium." Progress in Nuclear Energy, Series 5. Metallurgy and Fuels, Vol. 2. Edited by H. M. Finniston and J. P. Howe. New York: Pergamon Press (1959), 19-27.

H can be associated with U either in the form of a hydride or dissolved in the metal. Solubility of H in U depends on the allotropic forms of the metal and is greater in molten than solid U. Two types of hydrides, both UH_3, have been identified: (1) α-type, stable at low temperature but completely transformed to β at temperatures >140°C, (2) β-type. Effects of H on the mechanical properties of U are included.

335. Davies, D. M. and Martin, J. W., "The Effect of Inclusions on the Fracture of Uranium," J. Nucl. Mater., 3 (1961), 156-61.

Metallographic study of the nucleation and propagation of tensile fracture in α- range of commercially pure U was made. Crack nucleus appeared to be associated with the inclusions present. The effect of prior annealing in the γ-range on the size-distribution of these inclusions was studied semi-quantitatively.

336. Inouye, H. and Schaffhauser, A. C., "Low-Temperature Ductility and Hydrogen Embrittlement of Uranium-A Literature Review." Oak Ridge National Laboratory, Tennessee. U. S. Atomic Energy Commission Contract Report No. ORNL-TM-2563, July 1969.

A literature review of H embrittlement of U was made. The probable causes of the severe impairment of the ductility at room temperature are threshold concentrations of 0.2-0.5 ppm H present as β-UH_3. The morphology of UH_3 and the microcracks associated with this phase also influence the degree of embrittlement. The reaction of U with H_2O vapor in the annealing media is the source of H in heat-treated U.

337. Meridith, K. E. G. and Waldron, M. B., "Inclusions in Uranium Metal," J. Inst. Metals, 87 (1959), 311-17.

Occurrence and identity of inclusions in U due to the presence of C, N, H, Fe, Si, and Al are discussed. A complex of O, C, and N can exist in normal-purity U because of the isomorphous nature of the individual compounds UO, UC, and UN. The metallic impurity elements Fe, Si, and Al all form U compounds that precipitate on cooling.

338. Adda, Y. and Philibert, J., "Diffusion of Uranium With Some Transition Metals." Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy; Vol. 6, Basic Metallurgy and Fabrication of Fuels. Geneva: United Nations (1958), 72-90.

The intermetallic diffusion characteristics of U with pure metals as Zr, Mo, Ti, and Nb and with the alloys U-30a/oNb and U-30a/oMo were measured. Study of the concentration-penetration curves made it possible to calculate the diffusion coefficients and to draw up the equilibrium diagram in the polyphase field in the U-Zr system. Results were compared by micrographic examination, microhardness measurements, and autoradiography. Diffusion mechanisms were studied by the Kirkendall effect and by calculating the Darken coefficients in the U-Zr and U-Mo systems.

339. Adda, Y. and Philibert, J., "Diffusion of Uranium-Zirconium." Progress in Nuclear Energy, Series 5. Metallurgy and Fuels, Vol. 2. Edited by H. M. Finniston and J. P. Howe. New York: Pergamon Press (1959), 137-47.

The existence of a Kirdendall effect in bcc γ-phase U-Zr alloys is in agreement with recent results and supports an argument in favor of a mechanism invoking lattice vacancies. It has been shown that small concentrations of C can totally inhibit diffusion which leads to a weak bond, at the time of sheathing, between the metal and its sheath. Additions of Zr can fix the C present, and "normal" diffusion does not occur.

340. Harlow, R. A. and Gamba, O., "Diffusion Kinetics Studies in the Al-Ni-U System." Atomics International, Canoga Park, California. U. S. Atomic Energy Commission Contract Report No. NAA-SR-8387, November 1963.

A diffusion couple technique to obtain meaningful data regarding the diffusion kinetics in the Al-Ni-U system was developed and standardized. The technique involved hot pressing under a dynamic vacuum and subsequent isothermal soaking treatments within evacuated quartz tubes for 10-7000hrs at 650°-950°F. The Ni barrier bond formed was metallographically examined and results are presented.

341. Nayar, P. K. K., "Intermetallic Diffusion in Uranium-Aluminum Alloys," Trans. Indian Inst. Metals., 18 (1965), 51-55.

Intermetallic diffusion in U-Al alloys was investigated in the temperature range 300°-600°C using "sandwich"-type couples and employing metallographic and autoradiographic techniques. The growth kinetics of various phases and their relative distribution in the diffusion zone were found to vary with different temperatures. Kinetics of layer growth are discussed in relation to Kidson's analysis. Structural instability of the diffusion couples was attributed to volume changes occurring in the zone as the relative distribution of various phases changed during diffusion.

342. Peterson, N. L. and Ogilvie, R. E., "Diffusion in the Uranium-Niobium (Columbium) System," Trans. Met. Soc. AIME, 227 (1963), 1083-87.

Diffusion measurements were made in the bcc solid solution of U-Nb alloys at all compositions using incremental diffusion couples at composition intervals of 10a/o. Diffusion coefficients were determined by the Matano method from concentration gradients obtained with the electron-probe microanalyzer. The activation energy for interdiffusion showed three distinct areas that seemed to correspond to regions of different atomic order. The frequency factor ($\tilde{D}_0$) and the activation energy ($\tilde{Q}$) for interdiffusion obey the relationship $\log \tilde{D}_0 = a\tilde{Q}+b$.

343. Peterson, N. L. and Ogilvie, R. E., "Diffusion Studies in the Uranium-Niobium (Columbium) System", Trans. Met. Soc. AIME, 218 (1960), 439-44.

Interdiffusion and intrinsic diffusion coefficients using pure element couples were determined with an electron microbeam probe. Due to the large variance of the diffusion coefficient with composition, reliable data were obtained only in the range of 0-10a/oNb. A large Kirkendall effect and considerable porosity in the U-rich areas of the specimen are reported, suggesting that the true diffusion coefficients are somewhat larger.

344. Rothman, S. J., "Diffusion in Uranium, Its Alloys, and Compounds." Argonne National Laboratory, Illinois. U. S. Atomic Energy Commission Contract Report No. ANL-5700, Part C, May 1961.

Third in a series of monographs, "The Physical Metallurgy of Uranium." Laboratory diffusion studies are reviewed and evaluated. Self-diffusion in U, diffusion in γ-U-alloys, layer formation in U-alloys, gaseous diffusion in U, and diffusion in UO_2 are discussed. Extensive bibliography covering the literature to 1960 is included.

345. Smith, T., "Diffusion of Cerium and Zirconium in Molten Uranium." Atomics International, Canoga Park, California. U. S. Atomic Energy Commission Contract Report No. NAA-SR-2628, July 1958.

Diffusion coefficients for Ce in molten U were measured for the temperature range 1170°-1480°. The equation relating the diffusion coefficient and temperature is $D=0.02e^{-15Kcal/RT}$ and D at 1200° is $10^{-4}cm^2/sec$. Solubility of Ce varied from 1-2% by wt at 1140°-1345°C. Experimental error involved in the measurements at high temperature is discussed.

346. Hooper, A. F., George, J. C., and Keller, E. E., "Material-Uranium-Depleted, Pure and Alloyed (2% Molybdenum). Galvanic Behavior in Aqueous Salt Solutions." General Dynamics/Convair, San Diego, California. Aeronautical Systems Division, Wright-Patterson AFB. Contract Report No. 8926-013, August 1960. (AD 286 780)

Solution potentials for U and U-2%Mo alloys measured in 0.1N NaCl solution with a Ag:AgCl reference cell were 0.748 and 0.660V respectively. MIL-P-8585 $ZrCrO_3$-lacquer and $ZrCrO_3$-epoxy primers did not retard galvanic corrosion when used as coatings for galvanic couplings of U and U-alloys with steel and W alloys.

347. Macki, J. M. and Kochen, R. L., "The Galvanic Corrosion Behavior of Uranium Alloys in Hydrochloric Acid and Ocean Water." Dow Chemical Company, Rocky Flats Division, Golden, Colorado. U.S. Atomic Energy Commission Contract Report No. RFP-1592, February 1971.

Galvanic corrosion behavior, in ocean H_2O and HCl, was determined by measuring the gravimetric corrosion rates of galvanically coupled specimens and by constructing a galvanic series for each environment from electrode potential measurements. Gravimetric-galvanic test results showed the following order of increasing nobility in 0.1N HCl at 70°: 7178Al, depleted U, U-4.5Nb, 4340 steel, U-6Nb, U-8Nb, U-7.5Nb-2.5Zr, U-10Mo, Ti-6Al-4V, 304 stainless steel. In 0.1N HCl and ocean H_2O at 25°C the galvanic series, based on electrode potential, are the same as those based on gravimetric-galvanic corrosion tests except for the Ti-6Al-4V alloy.

348. Stephan, E. F., Miller, P. D., and Fink, F. W., "Corrosion of Thorium and Uranium During Long-Term Storage." Battelle Memorial Institute, Columbus, Ohio. U.S. Atomic Energy Commission Contract Report No. BMI-1563, January 1962.

Th, U, U-10w/oMo alloy, bare and organic - or metal coated coupons, and composite assemblies, joined by soldering, welding, or machine screws were evaluated for corrosion behavior during storage for 1 yr. Material was uncovered or in loosely covered metal containers under ambient temperatures in a waterfront building, a roof-top, and an unheated warehouse. In no case was severe corrosion encountered and the U-10w/oMo alloy was the most durable, displaying a relatively uniform tarnish film.

349. Wilkinson, W. D., Uranium Metallurgy, Vol. II: Uranium Corrosion and Alloys. New York: Interscience, 1962.

Corrosion of U by gases, moisture, aqueous media, and nonaqueous media is described. U-alloys are grouped according to type: compound-free, U-nonmetal, low miscibility with intermetallic compounds, and miscibles.

350. U.S. Patent No. 3,089,768. May 14, 1963. Dimensionally Stable, Corrosion Resistant Nuclear Fuel. John H. Kittel to U.S. Atomic Energy Commission.

Method of making U-alloy containing 0-9w/o of an addition of Zr and Nb in the proportions by wt of 10:3 with improved corrosion resistance and dimensionaly stability is described. The alloy is cold rolled, heated to two different temperatures, air-cooled, heated to a third temperature, and quenched in H_2O.

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351. British Patent No. 766,060. January 16, 1957. Improvements In or Relating to Uranium Alloys. United Kingdom Atomic Energy Authority.

Method of improving corrosion resistance of metallic U by adding 0.2-10.0w/oMo (preferably 1.0-6.0w/o). The alloy is formed by melting U and Mo together out of contact with air between 1150°-1400°C and subsequently annealing by heat treatment.

352. British Patent No. 766,061. January 16, 1957. Improvements In or Relating to Uranium Alloys. United Kingdom Atomic Energy Authority.

Method of producing a ternary alloy with increased corrosion resistance of which major proportion is U containing 0.2-1.0w/o each of Mo and Si. U-metal of customary purity is heated with Mo and Si out of contact with air at 1150°-1400°C and subsequently subjected to stress relief heat treatment.

353. Canadian Patent No. 885,927. November 16, 1971. Uranium-Base Alloys. Brain S. Wyatt to Atomic Energy of Canada, Limited.

Method of optimizing the corrosion resistance of U-alloys containing 3.5-3.7w/oSi, 0.1-1.5w/oAl, balance U and consisting of U_3Si, a minor amount of UAl_2, and isolated small particles of U_3Si_2. The cast alloy is heat treated at 800°C for ∿ 72-144 hrs until the U_3Si is in the δ-phase.

Aqueous Corrosion

354. Burkart, M. W. and Lustman, B., "Corrosion Mechanism of Uranium-Base Alloys in High Temperature Water," Trans. Met. Soc. AIME, 212 (1958), 26-30.

After exposure to high temperature H_2O, γ-phase U-base alloys containing 7-12w/oMo or Nb, failed either by uniform oxidation or by sudden cracking and disintegration of the metal. The disintegration resulted from the oxidation of a second phase, metastable UH_3, which is precipitated during the corrosion process.

355. Draley, J. E., "Problems of Fuel Element Corrosion in Water." Nuclear Fuel Elements. Edited by Henry H. Hausner and James F. Schumar. New York: Reinhold Publishing Corporation (1959), 314-28.

Corrosion behavior of U, U-alloys, Al-alloys, Zr-alloys, and stainless steel in H_2O is described. U-5%Zr and U-5%Zr-1.5%Nb, U-3-6%Nb, U->10%Mo, U-Ti and U-Ti-Nb alloys were investigated.

356. Draley, J. E., Greenberg, S., and Ruther, W. E., "The High-Temperature Aqueous Corrosion Resistance of the Uranium-5% Zirconium-1 1/2% Niobium Alloy," J. Electrochem. Soc., 107 (1960), 732-40.

U-5%Zr-1.5%Nb alloy γ-quenched in H_2O to ∿ 315° showed good corrosion resistance. Optimum heat treatment resulted in a rate of ∿ $6 mg/cm^2/day$ at 290°. Moderate aging at 400°C for 2 hrs resulted in reduced corrosion rates in the early stages of corrosion but corrosion resistance could be destroyed by overaging. Samples failed after extended exposure to H_2O and steam and this is believed to be due to absorbed corrosion product hydrogen.

357. Gerasimov, V. V., "Corrosion of Uranium Alloys in Aqueous Media," in Corrosion of Uranium and Its Alloys. Translated from the Russian by the Joint Publications Research Service, Washington, D. C. Report No. JPRS-31728 (August 1965), 1-24. (N65-33653)

Various methods of increasing corrosion resistance of U in H_2O and steam are discussed with emphasis on alloying and heat treatment. U alloys containing Hf, Ni, Nb, Ti, Zr, Mo, and Si exhibited the highest corrosion resistance and effects of different combinations of these alloys on corrosion resistance are described in relation to heat treatment and exposure to aqueous media. Data for corrosion rates in boiling distilled H_2O, corrosion resistance in H_2O and in H_2O and steam are presented in tabular form. Corrosion rates after various heat treatments are also tabulated.

358. Grieser, D. R. and Simons, E. M., "Aqueous Corrosion of Uranium Fuel-Element Cores Containing 0 to 20 Weight Percent Zirconium," Corrosion, 14 (1958), 313t-18t.

A windowed autoclave system for study of corrosion by pressurized hot H_2O is described. A method by which corrosion rates were calculated from pressure and temperature measurements is given. Corrosion rates for U-5, 10, 15, and 20w/oZr alloys subjected to 600°F H_2O are reported.

359. Jenks, G. H., "Electrochemistry of Uranium and Uranium-Alloys in Aqueous Solutions." Oak Ridge National Laboratory, Tennessee. U.S. Atomic Energy Commission Contract Report No. ORNL-4651, June 1971.

Corrosion of U and U-7.5Nb-2.5Zr alloy in aqueous solution of 0.1MK_2SO_4 at pH5-10 and 0.1NH_2SO_4 at 25°C was studied in order to outline the electrochemistry of these materials in the absence of aggressive ions. Reviews and analyses of literature information pertaining to the electrochemistry of U corrosion in aqueous environments at < 100°C and to certain aspects of pitting, crevice corrosion, and SCC are presented in the Appendixes.

360. Kauer, E. U., "Metal-Water Reactions. A Literature Survey." E. I. DuPont deNemours & Company, Savannah River Laboratory, Aiken, South Carolina. U.S. Atomic Energy Commission Contract Report No. TID-12746, March 1961.

A bibliography listing information on H_2O reactions with U, Zr, and their alloys with references selected from Nuclear Science Abstracts, January 15, 1957 to February 28, 1961.

361. Kishinevskii, V. B., Gomozov, L. I., and Ivanov, O. S., "Corrosion Resistance in Water of Some Alloys of Uranium with Zirconium, Niobium and Molybdenum." Translated from Russian for University of California, Lawrence Radiation Laboratory, Livermore. U.S. Atomic Energy Commission Contract Report No. UCRL-Trans-10455, March 1970.

In the U-Nb-Zr system, the alloys U-20-30a/oNb-20a/oZr proved to be the most corrosion resistant in H_2O at 100° after quenching. After tempering, the alloys U-10a/oZr-10a/oNb, U-30a/oNb, and U-15a/oZr-15a/oNb were the most resistant. Corrosion resistance of quenched U-Nb-Zr alloys in H_2O at 100°C is lower than that of the corresponding binary alloys, but quenched U-15a/oNb-5a/oMo, and U-22.5a/oMo-7.5a/oNb had higher resistance.

362. Leach, J. S. L., "Some Properties of Oxide Films Formed During Aqueous Corrosion," J. Inst. Metals, 88 (1959), 24-30.

Measurements of electrical capacity and conductivity of the surface oxide layers on U-12%Mo alloys indicated that H changed the conductivity without altering the thickness of the layer. The relationship between the conductivity and the rate of corrosion is discussed.

363. Leach, J. S. L. and Nehru, A. Y., "The Corrosion of Uranium, Zirconium, and Some Alloys in Alkaline Solutions," J. Electrochem. Soc., 111 (1964), 781-87.

Corrosion of U, Zr, and U-Zr alloy were studied as a function of potential in some alkaline solutions. Corrosion differed significantly from that in a pH5.4 solution. Difference is ascribed to the formation of oxides other than UO_2 in solutions of high pH.

364. Leach, J. S. L. and Nehru, A. Y., "The Temperature Dependence of the Corrosion of Uranium in Aqueous Solutions," J. Nucl. Mater., 13 (1964), 270-74.

Corrosion of U and U-5-10w/oZr was studied in both acidic and basic environments. Activation energy for aqueous corrosion was found to be considerably lower than that for atmospheric oxidation or diffusion of U and O and was influenced by formation potential of the oxide, alloying with Zr, and pH of the environment. It is suggested that electronic conductivity influences corrosion behavior.

365. Macki, J. M. and Kochen, R. L., "The Corrosion Behavior of Uranium-Base U-Nb, U-Nb-Zr, and U-Mo Alloys in Hydrochloric Acid and Ocean Water." Dow Chemical Company, Rocky Flats Division, Golden, Colorado. U.S. Atomic Energy Commission Contract Report No. RFP-1586, February 1971.

The corrosion rates for several U-alloys were measured in three environments: (1) ASTM ocean H_2O at 26°, showed increased corrosion resistance in the order depleted U (Tuballoy), U-4.5Nb, U-6Nb, U-8Nb, U-7.5Nb-2.5Zr (Mulberry), and U-10Mo, (2) 1N HCl at 26° showed increased corrosion resistance in the order Tuballoy, U-4.5Nb, U-6Nb, U-10Mo, Mulberry, and U-8Nb, (3) 0.1N HCl at 70° showed the positions of U-8Nb and Mulberry are reversed from those given for 1N HCl.

366. Mance, A., "The Anodic Behavior of Low Molybdenum-Uranium Alloys at Higher Electrolyte Temperatures," J. Nucl. Mater., 31 (1969), 252-58.

The effect of the concentrated citric acid solution temperature on the kinetics of anodic dissolution of α-U in the homogenized state and U-0.45w/oMo alloy in the homogenized and in the β-quenched states was investigated. The anodic behavior is represented by means of the Tafel constants, the exchange currents, the dissolution potentials, and by the activation energies.

367. Mihajlovic, A. and Mance, A., "The Potentiostatic Method for Electrolytic Etching of U-Nb Alloys," J. Nucl. Mater., 26 (1968), 267-72.

The electrochemical behavior of U-3.0w/oNb and U-4.0w/oNb alloys with banded martensitic structure in concentrated citric acid was investigated using the potentiostatic method to determine the polarization curves, Tafel constants α and i_0. Fine microstructural details such as dislocations and etch-pits were revealed using low current densities.

368. Uhlmann, W., "The Aqueous Corrosion of Uranium and Some of Its Alloys. A Literature Survey." Information Office, Scientific and Technical Information, Stockholm, Sweden. Report No. VDIT-82, 1963.

A collection of 52 references with abstracts on the aqueous corrosion of U and U-alloys covering the period 1952 to early 1963. Nuclear Science Abstracts, The Review of Metal Literature and current periodicals were used as the sources of information.

369. Waber, J. T., "Aqueous Corrosion of Uranium and Its Alloys." AEC-Euratom Conference on Aqueous Corrosion of Reactor Materials, Brussels, Belgium, 14-17 October 1959. U.S. Atomic Energy Commission, Office of Technical Information, Washington, D.C. Report No. TID-7587 (July 1969), 307-89.

Experimental data for the aqueous corrosion of U and various γ-phase U alloys are provided. A "hydroxide" mechanism theory which incorporates the features of both the hydride and oxide mechanisms is suggested.

Oxidation

370. Antill, J. E. and Peakall, K. A., "Mechanism of the Oxidation of a Uranium-One Weight Per Cent Copper Alloy," J. Electrochem. Soc., 110 (1963), 1146-48.

U-1w/oCu alloy was oxidized in a CO_2 atmosphere at 500°C to determine the effect of Cu on the rate of oxidation. The presence of UCu_5 at the metal/oxide interface increased oxidation resistance of the alloy.

371. Antill, J. E. and Peakall, K. A., "Oxidation of Uranium Alloys in Carbon Dioxide and Air," J. Less-Common Metals, 3 (1961), 239-46.

Weight gain-time curves for U-up to 7.3%Si, U-10%Si, U-10%Ti, U-5%V, U-10%Zr, U-15%Mo, U-10%Nb and U-1%Cu alloys in CO_2 at 500°-1000° and in air at 500°C were obtained. Additions of Ti, Mo, Nb, and Cu reduced attack by CO_2 at 680°-1000° by factors up to 500. None of the elements was found to be markedly beneficial in CO_2 at 500° and Si had a high rate of attack at most temperatures. In air at 500°C, additions of Mo, Ti, and Nb reduced attack by factors up to 200.

372. Baker, L., Jr. and Bingle, D. J., "The Kinetics of Oxidation of Uranium Between 300° and 625°C," J. Nucl. Mater., 20 (1966), 11-21.

Isothermal oxidation studies of U, U-1a/oCu, and U-1a/oAl alloys were carried out at 300°-625° and showed substantially identical self-accelerating reaction rates up to 400°. The effect of oxidation kinetics of the two alloy additives studied were useful in understanding the differences in ignition behavior for binary U-alloys. Empirical equations were formulated for the results of isothermal oxidation studies for pure U above 300°C.

373. Boultinghouse, K. D. and Sallach, R. A., "Oxidation Characteristics of a Quinary Uranium Alloy." Sandia Laboratories, Albuquerque, New Mexico. U.S. Atomic Energy Commission Contract Report No. SC-RR-72-0699, October 1972.

Oxidation of U-0.6w/oMo-0.6w/oZr-0.5w/oNb-0.5w/oTi alloy at 300°-400° in O at pressures of 1-10 torr was studied. Parabolic reactions were found for all conditions except for the aged material at 400°C where reaction curves were "S" shaped and exhibited "breakaway" rates. Oxidation of both the quenched and aged alloys was faster than that of the binary U-6.0-8.0w/oNb alloys.

374. Cathcart, J. V., "Mechanical Properties of Scales and Their Influence on High-Temperature Gas-Metal Reactions." Oak Ridge National Laboratory, Tennessee. U.S. Atomic Energy Commission Contract Report No. CONF-72-0515-1, 1972.

Surface stresses between 10^5-10^6 psi are frequently generated during the oxidation of metals and several stress generating mechanisms are discussed. The influence of such stresses on scale rupture, structure and morphology, diffusion rates within the scales, and on shape change experienced by oxidation specimens is pointed out as is the evidence for extensive high-temperature plasticity in the oxides. The oxidation of U-16.6a/oNb-5.6a/oZr and U-21a/oNb alloys is described to emphasize the importance of the mechanical properties of scales in gas-metal reactions.

375. Cathcart, J. V. and Liu, C. T., "The Mechanical Properties of Two Uranium Alloys and Their Role in the Oxidation of the Alloys," Oxid. Metals, 6 (1973), 123-43.

Tensile and creep properties of U-21a/oNb, U-16.6a/oNb-5.6a/oZr alloys were studied over a temperature range 750°-900°C and creep data were fitted to an equation, $\dot{\varepsilon} = K_{\sigma}^{1n}\exp(-Q/RT)$, which was used to calculate stresses in oxidizing alloy specimens based on elongation measurements. Estimates were made of the average stress in the oxide scale as a function of time. A comparison of the relative stress levels indicated that the major difference in the oxidation properties could be attributed

376. Cathcart, J. V. and Petersen, G. F., "The Low-Temperature Oxidation of U-Nb and U-Nb-Zr Alloys," J. Nucl. Mater., 43 (1972), 86-92.

The oxidation rate data for U-9.4w/oNb and U-7.5w/oNb-2.5w/oZr alloys at 100°-300°C in pure O are presented. Both alloys formed compact, generally protective, oxide films. The reaction appeared to be diffusion controlled and the activation energy, ∿ 13 kcal/mole, suggests the probable importance of short-circuit diffusion modes in the process. Gaseous impurities - H_2O, SO_2, CCl_4 - slightly increased the oxidation rate of the ternary alloy.

377. Cathcart, J. V., Pawel, R. E., and Petersen, G. F., "High Temperature Oxidation of Uranium Alloys." Oak Ridge National Laboratory, Tennessee. U.S. Atomic Energy Commission Contract Report No. CONF-72-0523-1, 1972.

Oxidation charactersitics at 700°-1100°C of U-16.6a/oNb-5.6a/oZr, U-21a/oNb, U-15a/oZr, and U-18a/oMo alloys are discussed. In all cases oxide formation involved the generation of large stresses, $\sim 10^6$ psi, in the oxides that lead to large increases in the lateral dimensions of the specimens. Stress relief processes, including plastic deformation of both the oxide and metal, are discussed.

378. Cathcart, J. V., Pawel, R. E., and Petersen, G. F., "The Oxidation Properties of U-16.6 at %Nb-5.6 at %Zr and U-21 at %Nb," Oxid. Metals, 3 (1971), 497-521.

Oxidation properties of U-base alloys, U-16.6a/oNb-5.6a/oZr and U-21a/oNb at 500°-1000° in O at 0.05 torr are described. At temperatures > 650° both alloys undergo extraordinarily large dimensional changes. Oxidation rate curves were determined at 100° intervals between 500°-1000°C. Activation energy for the process was $\sim$ 15 kcal/mole. Morphology of the oxide scale formed on both alloys is described in full detail. Stresses in the oxide were estimated to be $\sim$ 106 psi. A mechanism for stress generation in the oxide is proposed.

379. Erickson, W. C., Jaynes, G. E., Sandstrom, D. J., Seegmiller, R., and Taub, J. M., "Evaluation of Uranium Alloys." Los Alamos Scientific Laboratory, New Mexico. U.S. Atomic Energy Commission Contract Report No. LA-5002, September 1972.

The oxidation resistance and mechanical properties of 25 U alloys including U-Ti alloys, U-0.5Ni, U-0.5Cr, U-0.5Ni-0.5Cr, U-1.5Mo-0.5Ni-0.5Cr, U-1.5Mo, and U-2Nb-2Ti were evaluated. U-<1w/oTi and U-<2w/oMo alloys had good yield strength (>100,000 psi) and good ductility (>9% elongation). Additions of Nb were required to achieve corrosion resistance and only U-7.5w/oNb-2.5w/oZr (Mulberry) alloy could withstand exposure at 260° but U-4.5w/oNb-2.5Nb-1.7V alloys had excellent corrosion resistance at 120° when hot-rolled. Mechanical properties of U-Ti alloys can be controlled by aging and optimum properties were obtained by aging at 400°C for 4 hrs. Increased homogeneity by thermal processing and mechanical working also increased the corrosion resistance.

380. Gerasimov, V. V., "Corrosion of Uranium and Its Alloys in Non-Aqueous Media for Protective Coatings," in Corrosion of Uranium and Its Alloys. Translated from the Russian for Joint Publications Research Service, Washington, D. C. Report No. JPRS-31728 (August 1965), 25-48. (N65-33654)

Mechanisms of atmospheric corrosion of pure U and U-alloys in relation to the effects of temperature and humidity on the corrosion rates are described. Data for the resistance of various U-alloys under different test conditions are given. The corrosion rates of U in H_2O saturated steam, and Ar, and the free energy of formation of U compounds are presented in tabular form.

381. Gerrish, M. E. and Stobbs, J. J., "The Oxidation of Uranium-Titanium Alloys in Carbon Dioxide at 450°C," J. Inst. Metals, 95 (1967), 284-86.

Oxidation behavior of U-alloys containing 0.9, 3.6, 8.1 and 18.8a/oTi were studied in pure CO_2, using weight gain, metallographic and x-ray techniques. Only corrosion product identified was UO_2. U_2Ti resisted oxidation by CO_2, and in U-Ti alloys containing < 4a/oTi there was little effect on the oxidation rate but in those containing > 4a/oTi the oxidation rate was increased.

382. Krieg, A. and Napier, J. M., "The Inhibition of Hydrogen Corrosion of Uranium." Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee. U.S. Atomic Energy Commission Contract Report No. Y-1151, December 1957.

The results of a series of qualitative U-H corrosion tests are presented. The effects of surface treatment and inhibitive agents on the corrosion reaction are discussed.

383. Larson, D. T., "Oxidation of a Ternary Uranium Alloy," J. Vac. Sci. Technol., 8 (1971), 80-83.

Using an ellipsometric high vacuum technique, oxidation kinetics (surface oxide thickness up to 2000Å) of U-7.5w/oNb-2.5w/oZr alloy (Mulberry) in air containing H_2O vapor was investigated. The alloy samples were oxidized in dry air, < 5 ppm H_2O, and in air containing H_2O vapor, 15,000 ppm H_2O, at 650 torr in the temperature range 22°-200°. The oxidation followed a parabolic-rate, law, indicating a diffusion-controlled mechanism and the temperature dependence of the reaction was examined by the Arrhenius equation. A difference in the activation energy of the low temperature (22-100°) and the high temperature (100°-200°C) was revealed.

384. Leach, J. S. L., "Some Characteristics of Protective Oxide Films." Proceedings of the Second International Congress on Metallic Corrosion, New York, 11-15 March 1963. Houston, Texas: National Association of Corrosion Engineers (1966), 859-64.

Rate of formation of oxide films and the diffusion rates in these films on U, Zr, and U-Zr alloys are described. The influence of H_2O and H on the protective properties of oxide films was studied.

385. Leach, J. S. L., "Some Properties of Surface Oxide Films on Metals." Properties of Reactor Materials and the Effects of Radiation Damage. Edited by D. J. Littler. London: Butterworths (1962), 383-87.

The presence of a kinetic barrier, usually a surface layer of a reaction product through which the reactants and sometimes the products diffuse, causes some metals to oxidize slowly. In order to understand the factors influencing the diffusion rate the oxide layer was considered not only an inert obstacle to ionic diffusion, but as an electrolyte and semiconductor. Electronic conductivity and H pick up of the metals in the case of oxidation by H_2O or steam as well as oxide thickness and structure were found to be important. The effect of alloying U with Zr on oxidation is used as an example.

386. Lemmon, A. W., Jr., "The Reaction of Steam With Uranium and With Various Uranium-Niobium-Zirconium Alloys at High Temperatures." Battelle Memorial Institute, Columbus, Ohio. U.S. Atomic Energy Commission Contract Report No. BMI-1192, June 1957.

Experimental studies concerned with the measurement of metal-H_2O reaction rates and determining emissivity in order to measure the chemical reaction of steam with U and U-Nb-Zr alloys when contacted at high temperatures in nuclear reactors are reported. Spectral and total emissivities were measured for all materials in the as-rolled condition with O added at 0°-1075°C.

387. O'Rourke, J. A. and Waber, J. T., "Orientation of Oxide Films Formed on Gamma Phase Uranium Alloys," *J. Nucl. Mater.*, *7* (1962), 125-32.

Cold-rolled, γ-phase U-7w/oMo and U-10w/oNb alloys were oxidized in H_2O vapor forming highly oriented oxide films. Dodecahedral planes of UO_2 were formed parallel to the specimen surface. An epitaxial relationship was found between the UO_2 and the Nb alloy.

388. Pawel, R. E. and Cathcart, J. V., "Flexure Measurements on a U-Nb-Zr Alloy During Oxidation and Temperature Cycling," *J. Electrochem. Soc.*, *118* (1971), 1776-81.

Flexure technique was used to observe the stress buildup during oxidation of a U-7.5w/oNb-2.5w/oZr alloy. Measurements indicated that the effective stress in the oxide film approached 10^8 psi and were used to establish a mechanism accounting for the stress generation and relief behavior.

389. Sallach, R. A., "Reaction of Mulberry with Various Gases." Sandia Laboratories, Albuquerque, New Mexico. U.S. Atomic Energy Commission Contract Report No. SC-DR-71-0124, February 1971. (AD 886 274L)

Reaction of U-7.5w/oNb-2.5w/oZr alloy with CO_2, H_2O, N and O gases was surveyed. With CO_2 a linear reaction was found at 600° but with the other gases parabolic reactions were generally found and deviations were attributed to spalling of the reaction product. At 600°C catastrophic reactions were found with H_2O and O. The reactivity of the gases can be ordered as $CO_2 \sim H_2O > N > CO$.

390. Sladky, R. E., "An Ellipsometric Study of the Corrosion of Uranium and Uranium-7.5 Weight Per Cent Niobium-2.5 Weight Per Cent Zirconium Alloy." Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee. U.S. Atomic Energy Commission Contract Report No. Y-1829, May 1972.

The sputter cleaning and oxidation of U and U-7.5w/oNb-2.5w/oZr were studied by an ellipsometric method. The reactive index of both these materials and of their oxides was measured. Corrosion curves were drawn at several different temperatures for films up to 4500Å thickness and equations of the curves were determined. The effect of tensile stress on the ellipsometric data was studied.

391. Terada, K. and Goad, H. A., "X-Ray Study of Oxidation of a Ternary Alloy of U-7.5 Percent Niobium-2.5 Percent Zirconium (Mulberry Alloy)." Dow Chemical Company, Rocky Flats Division, Golden, Colorado. U.S. Atomic Energy Commission Contract Report No. RFP-1485, June 1970.

X-ray diffraction of the oxidation of U-7.5w/oNb-2.5w/oZr alloy was studied at 150°, 200°, 400°, 500°, and 600° in both dry and wet air and with different surface preparations. At 150°-250°, UO_2 was formed, at 400°, U_2O_3 was also formed and at 500°-600°C, U_2O_3 was formed immediately. Results indicated that U_2O_3 does not form under normal storage conditions ($< 200°C$) and therefore played no part in the mechanism of SCC of Mulberry alloy.

Stress Corrosion Cracking (SCC)

392. Bedere, D., Nomine, A. M., Robin, R., and Miannay, D., "Stress-Corrosion Cracking of the U-10Mo Alloy." Translated from the French for Sandia Laboratories, Albuquerque, New Mexico. U.S. Atomic Energy Commission Contract Report No. SC-T-72-2507, May 1972.

Characteristics of slow cracking, in air and in H_2O of U-10w/oMo alloy were studied. The propagation was discontinuous, and the cracking occurred with divergent or non-divergent branching. The fracture faces also exhibited these characteristics. A hypothesis of H embrittlement is advanced.

393. Bullock, J. S. and Condon, J. B., "Electrochemical and Other Studies of a Uranium Alloy Exhibiting Stress-Corrosion Cracking." Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee. U.S. Atomic Energy Commission Contract Report No. Y-1821, February 1972.

Electrochemistry and SCC properties of U-7.5w/oNb-2.5w/oZr alloy were studied. Potential variations were detected on the surface and anodic currents were introduced in air equilibrated moisture films on the alloy. Electrochemistry of the stress-corrosion attack was similar to that of the metal having no oxide film. The SCC was accelerated by Cl ions penetrating the oxide film. Cold-worked alloy was resistant to SCC and the mechanism was unrelated to a pitting-reaction mechanism.

394. Hoeing, S. A. and Sulsona, H., "A Field-Emission Microscope Investigation of the Effects of Ambient Atmospheres on the Stress-Corrosion Cracking of Uranium-Molybdenum Alloys." University of Arizona, Tuscon. U. S. Army Terminal Ballistics Laboratory Contract. Final Report, 1968. (AD 669 252)

Effects of heat treatment and ambient temperatures on the SCC behavior of U-10w/oMo alloys were studied using a field-emission microscope. Cathodic protection, the effect of static electric DC fields, and a special gas shield were investigated as possible protective techniques. It was found that heat treatments influenced the SCC behavior. A tentative critical stress for initiation of SCC was set at 36,500 psi and was strongly dependent upon heat treatments and critical structures. Cathodic protection and electric fields had no effect on the SCC behavior but pure dry N was found to be most effective as a protective shield during cyclic loading. Also reported in Applications of Field-Ion Microscopy in Physical Metallurgy and Corrosion, R. F. Hochman, E. W. Mueller, and B. Ralph, eds.

395. Macki, J. M. and Kochen, R. L., "Stress-Corrosion Cracking Behavior of the U-4.2 wt Percent Nb Alloy Aged 80 Hours at 260°C." Dow Chemical Company, Rocky Flats Division, Golden, Colorado. U.S. Atomic Energy Commission Contract Report No. RFP-1824, March 1972.

Two types of smooth SCC tests - constant deflection 4-point bend tests and static tensile tests - were used to determine the SCC behavior of U-4.2w/oNb alloy aged 80 hrs at 260°C. SCC occurred when the alloy was stressed and exposed to H_2O containing both O and Cl ions. Cracks which nucleated in the Cl ion environment proceeded by an intergranular fracture mode. No failures were observed in dry air containing < 200 ppm moisture or in 100% relative humidity air. Tensile stress required for SCC was < 20,000 psi in O saturated H_2O containing 50 ppm Cl ions.

396. Macki, J. M. and Kochen, R. L., "Stress Corrosion Cracking of Aged U-4.5Wt%Nb," Corrosion, 29 (1973), 153-56.

SCC behavior of U-4.5w/oNb alloy aged 80 hrs at 200°C was investigated using smooth four point bend and static tensile SCC tests. Results showed susceptibility to SCC when stressed and exposed to H_2O containing O and Cl ions. In the aqueous Cl environment SCC proceeded by an intergranular fracture mode. In dry air (< 200 ppm moisture) and in 100% relative humidity no failures were observed. Surface tensile stress required for SCC in O saturated H_2O containing 50 ppm Cl ions was < 20,000 psi.

397. Macki, J. M. and Kochen, R. L., "The Stress-Corrosion Carcking of Underaged and Overaged U-2.3wt%Nb in an Aqueous Chloride Environment." Dow Chemical Company, Rocky Flats Division, Golden, Colorado. U.S. Atomic Energy Commission Contract Report No. RFP-1904, August 1972.

SCC tests using smooth, dead-weight loaded, static tensile specimens which were exposed to O saturated with H_2O containing 50 ppm Cl ions were conducted on a single phase underaged (230°-24 hrs) and on a two phase overaged (430°C-24 hrs) U-2.3w/oNb alloys. Results showed that the underaged alloy was more susceptible to SCC by a transgranular mode and the overaged alloy could fail by corrosion penetration that leads to mechanical failure.

398. Macki, J. M., Mah, G., Kochen, R. L., and Nordin, C. W., "The Stress-Corrosion Cracking of Aluminum-Coated Uranium-4.5wt% Niobium," J. Nucl. Mater., 7 (1973), 173-76.

Room temperature tests showed that vapor deposited Al coatings can protect aged U-4.5%Nb alloy from SCC in aqueous chloride environments. This degree of protection increased with increasing coating thickness and decreased with increasing size of uncoated flaws.

399. McLaughlin, B. D., Stephenson, L. L., and Miglionico, C. J., "Influence of Aging Time and Temperature on the Susceptibility of γ-Quenched U-5wt%Nb Alloy to SCC," Corrosion, 28 (1972), 35-38.

In thermal processing of γ-quenched U-5w/oNb alloy optimum resistance to the initiation of SCC was obtained by aging above 550°. A change in fracture mode from intergranular for low aging temperatures to transgranular, quasi-cleavage, for high aging temperatures was observed. A wire specimen aged for 8 hrs at 600°C had a UTS of ∿ 160 ksi with 17% elongation.

400. Magnani, N. J., "Stress-Corrosion Cracking of Mulberry," Corrosion, 26 (1970), 406-08.

SCC of U-7.5w/oNb-2.5w/oZr alloy was studied by failure mechanics and SEM. Two modes of cracking were observed A transgranular mechanism occured in dry and wet gaseous environments with 0 required for propagation and a $K_{Iscc} \sim 18$ ksi $\sqrt{in}$. An intergranular mechanism occurred in high relative humidity conditions and aqueous environments with H_2O required for propagation and a $K_{Iscc} \sim 5$ ksi $\sqrt{in}$. Cold working inhibited the intergranular mode of failure.

401. Magnani, N. J., "The Effect of Chloride Ions on the Cracking Behavior of U/7.5wt%Nb/2.5wt%Zr and U/4.5wt%Nb," J. Nucl. Mater., 42 (1972), 271-77.

The effect of Cl ions on the SCC behavior of U-7.5w/oNb-2.5w/oZr and U-4.5w/oNb alloys was investigated. Time-to-failure at a given stress intensity decreased in both alloys as the Cl content in aqueous solutions increased (< 2 ppm-50 ppm). Cracking without application of stress when the Cl level reached 500 ppm is attributed to corrosion product wedging. Data indicate that two cracking mechanisms - dissolution and mechanical - are operative.

402. Magnani, N. J., "The Effects of the Environment on the Cracking Behavior of Selected Uranium Alloys." Sandia Laboratories, Albuquerque, New Mexico. U.S. Atomic Energy Commission Contract Report No. SC-R-72-2661, 1971.

Susceptibility to SCC in several environments was determined for U-7.5w/oNb-2.5w/oZr, U-4.5w/oNb, U-10w/oMo, and U-0.5w/oTi alloys. All the alloys listed failed in laboratory air. The humidity in the air did affect the time-to-failure but did not significantly effect the threshold intensities required for cracking. Test environments ranged from < 10%RH air to 100%RH air, pure gases (O, N, H, and CO_2), and aqueous solutions containing < 20 to 500 ppm Cl.

403. Magnani, N. J., Boultinghouse, K. D., and Miglionico, C. J., "Stress Corrosion Cracking Behavior of U-4 1/2 Wt Percent Nb in Laboratory Air." Sandia Laboratories, Albuquerque, New Mexico. U.S. Atomic Energy Commission Contract Report No. SC-RR-71-0426, March 1972.

SCC behavior of U-4.5w/oNb alloy was determined by dry (∿ 10%RH) air using side-grooved tapered double-cantilevered-beam specimens. Crack propagation was monitored using crack opening displacement gages and acoustic emission detection techniques. The threshold stress intensity for SCC was determined to be ∿ 20 ksi $\sqrt{in}$ and the plain strain fracture toughness ∿ 50 ksi $\sqrt{in}$.

404. Magnani, N. J., Romero, H., and Miglionico, C. J., "The Effect of Chloride Ions on the Susceptibility to Stress Corrosion Cracking of U-7 1/2 wt%Nb-2 1/2 wt%Zr and U-4 1/2 wt%Nb Alloys." Sandia Laboratories, Albuquerque, New Mexico. U.S. Atomic Energy Commission Contract Report No. SC-RR-70-860, December 1970.

Effect of Cl ions on the SCC behavior of U-4.5w/oNb and U-7.5w/oNb-2.5w/oZr (Mulberry) alloys was investigated. Both the fracture mode and the critical stress intensity for SCC, K_{Iscc}, were found to be strongly dependent on Cl ion concentration.

405. Magnani, N. J., Romero, H., and Miglionico, C. J., "Stress Corrosion Cracking Behavior of Tungsten Filament Reinforced U-4 1/2 Wt Percent Nb." Sandia Laboratories, Albuquerque, New Mexico. U.S. Atomic Energy Commission Contract Report No. SC-DR-71-0799, November 1971.

SCC behavior of U-4.5w/oNb reinforced with 0, 17, 38, and 51v/oW fibers was studied in 100%RH air. Results indicated that as the W content increases, the susceptibility to SCC decreases to the point that the 51% composite is only slightly susceptible. Fractographic analysis showed that not all the fibers were equally effective in reinforcing the matrix.

406. Magnani, N. J., Romero, H., and Miglionico, C. J., "A Study of the Stress Corrosion Cracking Behavior of Mulberry (U-7.5wt%Nb-2.5wt%Zr)." Sandia Laboratories, Albuquerque, New Mexico. U.S. Atomic Energy Commission Contract Report No. SC-RR-70-371, May 1970.

Two SCC modes of U-7.5w/oNb-2.5w/oZr (Mulberry) alloy were observed: (1) transgranular (quasi-cleavage) which required 0 for propagation and had a critical stress intensity of $\sim$ 20 ksi $\sqrt{in}$; (2) intergranular which occurred both in high relative humidity air and in aqueous environments.

407. Nomine, A. M., Bedere, D., and Miannay, D., "Mechanical Quantities Associated with Stress Corrosion of the U-10Mo Alloy." Translated from the French for Sandia Laboratories, Albuquerque, New Mexico. U.S. Atomic Energy Commission Contract Report No. SC-T-72-2508, May 1972.

The effects of loading rate, stress level, and notch factor on the resistance to stress corrosion of U-10w/oMo alloy in air and at ambient temperatures were studied. In general, the rough-cast material was found to be stronger than the normalized.

408. Nomine, A. M. Bedere, D., Robin, R., and Miannay, D., "Mechanical Study of the Stress Corrosion of a U-10Mo Alloy." Translated from the French for Sandia Laboratories, Albuquerque, New Mexico. U.S. Atomic Energy Commission Contract Report No. SC-T-72-2510, May 1972.

The stress-corrosion resistance of U-10w/oMo alloy in both the normalized and rough-cast states was studied in air and in H_2O. Crack propagation occurred after an incubation period and the rate was constant. In air, transgranular cracking was observed, but in H_2O both transgranular and intergranular cracking were found.

409. Orman, S., "A Rapid Test for Stress-Corrosion Cracking," Corros. Sci., 9 (1969), 849-51.

A simple rapid test to evaluate the effect of heat treatment on SCC susceptibility of several U-alloys: U-10w/oMo, U-7.5w/oMo, U-7.5w/oNb-2.5w/oZr, and U-6w/oNb, is described. The test had the advantages of speed of assessment and the use of standard laboratory apparatus and results were in agreement with those of longer term tests.

410\. Peterson, C. A. W., "A Stress-Cracking Study of a Gamma Extruded U-8w/oMo-0.50w/oTi Alloy." University of California, Lawrence Radiation Laboratory, Livermore. U.S. Atomic Energy Commission Contract Report No. UCRL-14132, April 1965.

Metastable γ-phase U-8w/oMo-0.50w/oTi alloy was studied during static and low strain-rate loading and exhibited stress cracking in air. The average critical stress observed (60,000 psi with 75 ppm C) was higher than that observed in the U-Mo binary alloy but too low to be acceptable for use under stress except in O free environments. Transformation from the γ to the $\alpha + \gamma$ condition eliminated stress-cracking brittleness.

411\. Peterson, C. A. W. and Steele, W. J., "Delayed Cracking Study in U-7.5%Nb-2.5%Zr." University of California, Lawrence Radiation Laboratory, Livermore. U.S. Atomic Energy Commission Contract Report No. UCID-15256, December 1967.

Two U-7.5w/oNb-2.5w/oZr alloys - one solution treated by quenching from the γ field and the other solution treated and aged for 1 hr at 150°C - were tested to evaluate the delayed cracking propensity. Tests used were sustained loading near yield strength in dry and wet air and dynamic testing to failure at strain rates of 0.05-0.005in/in/min in dry and wet air and in vacuum. Delayed cracking was not observed in the alloys which were finish-machined after heat-treating.

412\. Peterson, C. A. W. and Vandervoort, R. R., "Stress-Cracking in the Uranium-10w/oMolybdenum Alloy." University of California, Lawrence Radiation Laboratory, Livermore. U.S. Atomic Energy Commission Contract Report No. UCRL-7767, March 1964.

U-10w/oMo alloy was found to be subject to delayed failure in air due to O. Critical or threshold stress was as low as 37,000 psi but increased with decreasing C content. The offset yield strength in the dynamic tensile test was typically 125,000 psi.

413\. Pridgeon, J. W., "Stress Corrosion Cracking in Uranium-Molybdenum Alloys." Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee. U.S. Atomic Energy Commission Contract Report No. Y-1417, August 1963.

The cause of cracking in U-4-5w/oMo alloys was investigated. Studies showed that cracking could be eliminated by testing tensile specimens in a He atmosphere. Results of various experiments on both U-4w/oMo and U-5w/oMo alloys showed that cracking was transgranular, occurred only in tension, and was caused by SCC due to the presence of O in the atmosphere. Increasing the temperature above 25° increased the rate of cracking and in the U-5w/oMo alloy, no cracking was observed below 10°C.

414. Stephenson, L. L., "A Survey of Factors Which Influence Stress Corrosion Crack Initiation in Several Uranium Base Alloys." Sandia Laboratories, Albuquerque, New Mexico. U.S. Atomic Energy Commission Contract Report No. SC-DR-70-718, October 1970.

The effect of various metallurgical and electrochemical variables on the initiation of SCC in U-7.5Nb-2.5Zr, U-4.5Nb, U-6.5Nb, and U-8.5Nb alloys was determined. Passivation behavior of U-7.5Nb-2.5Zr alloy was determined in several different solutions using a potentiostat. Bend specimens, immersed in aqueous solutions and and held at constant potentials, were used to investigate the SCC initiation of the various alloys. The effect of potential on crack initiation in U-7.5Nb-2.5Zr alloy in 10^{-4}M KCl was determined.

415. Sulsona, H., "The Field-Emission Microscope Investigation of the Effects of Ambient Atmospheres on the Stress-Corrosion Cracking of Uranium-Molybdenum Alloys." Unpublished Ph.D. dissertation University of Arizona, 1968.

Field emission microscopy was used to study the effects of heat treatment and ambient temperatures on the SCC behavior of U-10w/oMo alloys. Cathodic protection, the effect of static DC fields, and a special "gas shield" protective technique were investigated. SCC behavior was influenced by heat treatments. Susceptibility was reduced by a γ-homogenization and quench followed by a tempering treatment. Tentative critical stress for initiation of SCC, strongly dependent upon heat treatment and internal structure, was set at 36,500 psi. Cracking was found to be intergranular, transgranular, or both depending on the particular atmosphere.

416. Weirick, L. J., "The Effect of Heat Treatment Upon the Stress-Corrosion Cracking of Mulberry (U-7.5Nb-2.5Zr)." Sandia Laboratories, Livermore, California. U.S. Atomic Energy Commission Contract Report No. SLL-73-5015, November 1973.

Representative microstructures of U-7.5w/oNb-2.5w/oZr alloy specimens heat treated at selected temperatures (150°-600°C) were obtained from both SCC and mechanical property data. Results showed that, in general, mechanical strength and resistance to SCC increase as the aging temperature increases, particularly when a two-phase microstructure is produced. Polarization curves indicated that the general corrosion resistance was not significantly affected by heat treatment.

417. Weirick, L. J. and Schoenfelder, C. W., "The Effect of Oxygen, Chloride Ion and Water Vapor on Crack Initiation in U-7 1/2 Wt%Nb-2 1/2 Wt%Zr (Mulberry)." Sandia Laboratories, Livermore, California. U.S. Atomic Energy Commission Contract Report No. SCL-DC-72-0103, March 1973.

The effect of O, Cl and H_2O vapor on U-7.5w/oNb-2.5w/oZr alloy, in particular on susceptibility to initiation of SCC, was studied. Results indicated that when the Cl present was < 2 ppm, a smooth specimen with or without Ni couples did not exhibit crack initiation during a 3 year period. Also in a Cl environment that would otherwise be detrimental, crack initiation was prevented if the O is reduced to a very low but indeterminable amount.

418. Whitlow, G. A., "Stress Corrosion of Uranium Alloys." Atomic Weapons Research Establishment, Aldermaston, England. Report No. AWRE-0-49/66, 1966.

SCC in U-10w/oMo and U-6.0w/oMo alloys and the effect of moisture on U-7.5w/oNb-2.5w/oZr alloy have been investigated. Initial results indicated that moisture not 0 effected the stress corrosion of the binary alloys and that cracking in the 6w/oMo alloy was intergranular not transgranular as reported by others. High humidity also caused intergranular cracking in the binary alloy.

Protective Coatings

419. Anderson, P. D. and Coronado, P. R., "Electroplating Uranium with Nickel." Sandia Laboratories, Livermore, California. U.S. Atomic Energy Commission Contract Report No. SCL-DR-67-43, July 1967.

A reliable method for providing an adherent and protective electroplate of Ni on U was developed. A method for evaluating specimens and the detailed results are presented. A plated specimen with an exposed U-Ni interface was subjected to a H_2O saturated atmosphere at 200-250°F. Specimens can be soldered and give the full strength properties of other good soldered joints. The plate cannot be peeled or chipped with a chisel.

420. Baque, P., Koch, P., Dominget, R., and Darras, R., "Protection of Uranium by Metallic Coatings." Translated from the French for Los Alamos Scientific Laboratory, New Mexico. U.S. Atomic Energy Commission Contract Report No. LA-4363-TR, 1968.

Inhibiting or limiting the oxidation of U by CO_2 at high temperatures by means of protective metallic coatings was investigated. Surface films containing intermetallic compounds or solid solutions of U with Al, Zr, Cu, Nb, Ni, or Cr were formed. Processes recommended are direct diffusion starting from a thin sheet or tube, vacuum deposition, and immersion in a molten bath of suitable composition. Conditions were optimized as a function of the protective effect obtained in CO_2 at 450° or 500°C. Only Zr and Al based coatings were satisfactory, and provided the U good protection against atmospheric corrosion.

421. Beel, R. T., "Aluminum Ion Plating of Uranium-Molybdenum Alloy Fast-Burst Reactor Elements." Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee. U.S. Atomic Energy Commission Contract Report No. Y-1617, June 1968.

U-10w/oMo alloy fast-burst reactor parts were ion plated with thin ($< 2\times10^{-4}$in) Al coatings to protect the alloy from oxidation and as a means of containing the fission products. These coatings were compared with Ni coatings. At fissions $> 10^{17}$ and temperatures > 700°C the Ni plating spalled severely while the Al and the U-Al intermetallics formed during the process remained adherent to the alloy.

422. Bland, R. D., "A Parametric Study of Ion-Plated Aluminum Coatings on Uranium," Electrochem. Technol., 6 (1968), 272-78.

Ion-plated Al coatings provide excellent corrosion protection on unalloyed depleted U when exposed in an accelerated corrosion test (100°C - 1 atom H_2O vapor pressure). Processing parameters which influence corrosion protection were determined to be substrate precleaning, amount of gaseous contamination in the glow discharge, sputter cleaning voltage and pressure, filament contamination, deposition rate, and amount of U-Al interdiffusion, either during plating or in subsequent vacuum heat treatment. A diffusion layer consisting of U-Al intermetallic compounds is believed to provide corrosion protection in this system.

423. Bland, R. D., McDonald, J. E., and Mattox, D. M., "Ion Plated Coatings for the Corrosion Protection of Uranium." Sandia Laboratories, Albuquerque, New Mexico. U.S. Atomic Energy Commission Contract Report No. SC-DR-65-519, October 1965.

Coating of depleted U with thin Al coatings ($< 5x10^{-4}$in) using the ion plating process provided corrosion protection of U exposed to a condensed H_2O vapor at 950°C for up to 95 hrs. Surface preparation and deposition parameters are discussed. Vacuum deposited coatings did not provide corrosion protection.

424. "Depositing Metals on Uranium," Prod. Finish., 27 (1963), 158, 160-61.

Methods of depositing metals, e.g. Zn, on U to inhibit corrosion were investigated. Anhydrous plating with zinc acetate-formamide gave good adhesion but an oxide film was formed between the U and the coating. A method of depositing Zn, having an appreciable vapor pressure, directly on U showed promise but additional experiments are necessary. A simple method for determining the porosity on the electroplated coatings on U was developed.

425. Dini, J. W. and Coronado, P. R., "Electroplating Uranium with Nickel (Supplement)." Sandia Laboratories, Livermore, California. U.S. Atomic Energy Commission Contract Report No. SCL-DR-67-44, July 1967.

Improvements in the process for plating U with an adherent and protective Ni coating are reported (see entry No. 419). A superior pretreating solution using NiCl rather than SnCl and a new method for cleaning pieces to be plated are described.

426. Dini, J. W. and Coronado, P. R., "Preparation of Uranium for Electroplating with Nickel." Sandia Laboratories, Livermore, California. U.S. Atomic Energy Commission Contract Report No. SCL-DC-68-50, October 1968.

A process for reliably protecting unalloyed depleted U with an adherent corrosion-resistant electroplated deposit was developed. The key to the process was treatment of U with a metal chloride/HNO_3 solution (preferably $SnCl_2$ or $NiCl_2$) before plating. Plated parts, pretreated with any metal chloride solutions were capable of withstanding exposure to a H_2O saturated atmosphere at 200°F for > 90 hrs without deterioration. Plated parts pretreated in the $SnCl_2$ solution showed no signs of deterioration after five years of outdoor exposure.

427. Macki, J. M. and Kochen, R. L., "The Corrosion and Stress-Corrosion Cracking of Painted U-4.2wt%Nb." Dow Chemical Corporation, Rocky Flats Division, Golden, Colorado. U.S. Atomic Energy Commission Contract Report No. RFP-1891, August 1972.

Salt spray (fog) and SCC tests were conducted on an aged U-4.2w/oNb alloy having a sprayed paint coating consisting of an epoxy primer with a polyurethane cover coat. Results showed some protection from corrosion in a 3.5w/oNaCl salt fog environment but when subjected to appropriate surface tensile stresses failure by SCC occurred at flaws or scratches in the paint coating.

428. McLaughlin, B. D. and Panousis, N. T., "Protective Metallic Coatings for γ-Quenched U-5wt%Nb Alloy," J. Nucl. Mater., 43 (1972), 343-46.

The incubation time for the initiation of SCC in γ-quenched U-5w/oNb alloy was extended by coating the alloy with Cd or Al. Coatings of 10-25 m thickness were deposited by electroplating with Cd and by plasma spraying, PVD, CVD, and electroplating with Al. No attempt was made to develop continuous impermeable coatings. Coating type, aging times and temperatures, time-to-failure, test environment, and gap size data are presented in tabular form.

429. "Metal Deposition on Uranium to Inhibit Corrosion," Corros. Technol., 10 (1963), 43, 36.

Procedures for depositing metals on U were investigated by the National Bureau of Standards. Plating Cr, Ni, Cu from aqueous baths was not satisfactory but plating of Al and Zn from anhydrous baths prevented the formation of a black oxide film between the base and plating metals. A simple method for determining porosity in the U-plated specimens stored 24 hrs in an evacuated vessel is to partially refill with H and heat to ∿ 200°C. Any U exposed through a pore in the plate is attacked by the H.

430. Orman, S., Owen, L. W., and Picton, G., "The Corrosion Behavior of Nickel-Plated Uranium," Corros. Sci., 12 (1972), 35-44.

The corrosion behavior of U electroplated with Ni was investigated. Due to loss of adhesion the protective quality of the plating decreased as exposure to aqueous environments increased due to the formation of UH_3 which resulted from H penetration at the Ni-U interface. Corrosion could be inhibited if the H generated were free to escape. A mechanism for the corrosion of U beneath the Ni plate is proposed.

431. Panousis, N. T., "Protective Coatings for Uranium-Niobium Alloys." Bendix Corporation, Kansas City, Missouri. U.S. Atomic Energy Commission Contract Report No. BDX-613-615, December 1971.

Both Al and Cd coatings on U-5.0w/oNb alloy significantly reduced susceptibility to SCC. Unprotected samples under a static tensile stress of 44,000 psi failed in less than 30 min exposure to 10^{-4}N KCl solution but the coated samples lasted 1-4 mos under similar conditions. Results indicated that the Al and Cd coatings sacrificially protect the base alloy. Four methods of applying the coatings are described.

432. Weirick, L. J., "Electrochemical Determination of Porosity in Nickel Electroplates on a Uranium Alloy." Sandia Laboratories, Livermore, California. U.S. Atomic Energy Commission Contract Report No. SLL-73-5316, November 1973.

The change in corrosion potential as a function of the changing U-alloy area fraction in galvanically connected Ni-U alloy couples in KCl electrolytes was determined. The technique was calibrated so that the exposed base metal area fractions of U-alloy specimens plated with Ni could be estimated.

433. U.S. Patent No. 3,573,120. March 30, 1971. Uranium Etchant and Method.
Forrest B. Waldrop and Max J. Bezik to the U.S. Atomic Energy Commission

Method of preparing articles of U and U-alloys for the reception of a protective metal coating by immersing the article in an etching bath consisting of an aqueous solution of either $FeCl_3$ or $FeCl_3$ and $NiCl_2$ for ∿ 10-15 min at 30°-60°C, rinsing it in H_2O, and then immersing it in a solution containing an Fe solvent to remove the surface Fe.

434. U.S. Patent No. 3,668,084. June 6, 1972. Process for Plating Uranium with Metal.
George S. Petit and Ralph R. Wright to U.S. Atomic Energy Commission.

Method for providing a U-metal article with a tenaciously adhering metal plating deposited from an aqueous solution. Oxides and other contaminants are removed from the surface and the article is then heated in vacuum under selected conditions to form thereon a very thin and highly protective oxide film which is non-wettable by H_2O but may be made wettable by H_2O by contact with a basic wetting solution. The resulting wettable, oxide-coated article is then electroplated with metal in an aqueous metal-plating bath.

435. U.S. Patent No. 3,674,655. July 4, 1972. Surface Preparation of Uranium Parts.
Louis de Vaulchier du Deschaux, Alain de Fouchier, Emmanuel de Vaucelles, and Louis Facquet to Commissariat a l'Energie Atomique.

Method of surface preparation of U and U-base alloys prior to electroplating parts. Preliminary procedures involve chemical degreasing, electrolytic degreasing, and if necessary chemical etching and an anodic electrolytic treatment in an aqueous solution of an organic salt or a Li and/or Mg sulphate.

436. British Patent No. 1,132,808. November 6, 1968. Electroplating Process. Guy Chauvin, Louis Facquet, Alain de Fouchier, and Louis de Vaulchier du Deschaux to Commissariat a l'Energie Atomique.

Method of electrodepositing metallic coatings on parts fabricated of U and U-alloys is described. A first coating, containing at least one metal layer, is heated under vacuum at 350°-400°C for 1-3 hrs to degas the metal coating, then mechanically treated by cold-working to close the surface defects of the first coating. A second coating, containing at least one metal layer, is electrodeposited to provide an impervious composite coating. At least one of the coatings must be formed by successive deposition of layers of different metals.

437. British Patent No. 1,184,393. March 18, 1970. Method of Electroplating.
Guy Chauvin, Louis Facquet, and Louis de Valuchier du
Deschaux to Commissariat a l'Energie Atomique.

Method of electroplating articles the surface of which consists of U-alloys and others. A first layer of metal is electrodeposited followed by a second layer (55μm) of Sn, Zn, Pb, or In which is impervious to outside agents. Plated articles to be primarily used in plating rods or plates of alloyed U for nuclear fuels.

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