ATTACHMENT 1

UNCLASSIFIED INFORMATION ON TRITIUM EXTRACTION AND PURIFICATION TECHNOLOGY

by

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January 23, 1976

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INTRODUCTION

One item of information requested in a letter from N. Stetson to C. H. Ice, dated November 24, 1975, is a survey of currently unclassified information on tritium separations technology.

To answer this request, recent Nuclear Science Abstracts were searched with the RECON computer system; older abstracts were searched manually. Abstracts of Classified Reports were also searched, because many early reports have been declassified but not yet incorporated into Nuclear Science Abstracts. Classification status of these reports was determined by reference to declassification lists issued periodically by the ERDA Technical Information Center, Oak Ridge, Tennessee.

SUMMARY

Several tritium recovery and purification techniques developed at non-production sites are described in the unclassified and declassified

literature. Heating of irradiated Li-Al alloy under vacuum to release tritium is described in declassified reports of Argonne National Laboratory. Use of palladium membranes to separate hydrogen isotopes from other gases is described by Argonne, KAPL, and others. Declassified KAPL reports describe tritium sorption on palladium beds and suggest fractional absorption as a means of isotope separation. A thermal diffusion column for tritium enrichment is described in a Canadian report. Mound Laboratory reports describe theoretical and experimental studies of thermal diffusion columns. Oak Ridge reports tabulate "shape factors" for thermal diffusion columns. Unclassified journals contain many articles on thermal diffusion theory, experiments, and separation of gas mixtures by thermal diffusion columns; much of these data can be readily extended to the separation of hydrogen-tritium mixtures. Cryogenic distillation for tritium recovery is described in the Mound Laboratory reports. Process equipment such as pumps, valves, Hopcalite beds, uranium beds, etc., are described in reports by ANL, KAPL, and MLM, and in WASH-1269, Tritium Control Technology.

DISCUSSION

Unclassified publications by ERDA installations on tritium technology may be conveniently divided into two types, studies of tritium production technology, and studies of tritium control technology. Production technology research was begun early in the atomic energy program and was directed toward development of tritium recovery processes for Hanford and Savannah River. Unclassified and declassified publications in this category are cited in List 1 below.

In response to adoption in December 1970 of a national policy of keeping radioactive effluents as low as practicable, several installations have conducted research on recovery and containment of very low concentrations of

of tritium in plant effluents. A few of the more significant reports in this category are shown in List 2.

Some of the SRP tritium technology is an adaptation of standard chemical engineering practice as recorded in textbooks, conference proceedings, and technical journals. References to such works are shown in List 3.

In searching the literature, a number of bibliographies on tritium were found. These are presented in List 4.

LIST 1. TRITIUM PRODUCTION TECHNOLOGY

Unclassified and declassified publications are listed below by installation.

Argonne National Laboratory

Studies of tritium extraction from irradiated lithium alloys were carried out by the Tritium Process Development Group of the Chemical Engineering Division at ANL.

Work was first reported in classified memoranda, a series of documents with the ANL-SL prefix. These memoranda were summarized in ANL-4481 (Secret), and subsequent work was reported in formal publications with the ANL prefix which were issued as secret, but later declassified. The same work was also simultaneously reported in summary form in the Quarterly Reports of the Chemical Engineering Division.

- o Chemical Engineering Division Summary Report. N. R. Chellew, (Declassified).

1. ANL-4550, August-October 1950
2. ANL-4608, November-December 1950, January 1951
3. ANL-4660, February-April 1951
4. ANL-4691, May-July 1951
5. ANL-4730, August-October 1951
6. ANL-4827, November 1951-April 1952

   Progress is reported on experiments in which tritium was extracted from irradiated Li-Al slugs by heating in a stainless steel vacuum furnace. Effects investigated included: isotopic yield vs air exposure of targets, extraction efficiency with unclad and aluminum clad slugs, outgassing rate vs heating rate, reuse of furnace tube vs yield and purity of tritium, molten metal fluxes vs yield of tritium.

- o Other ANL documents on tritium production.

7. ANL-4159. Tritium Production Process. N. R. Chellew, J. McGuire, W. Olsen, and A. H. Barnes, May 25, 1948 (Declassified).

   Small-scale production of tritium from irradiated lithium fluoride is described. The process description includes the technique for separating hydrogen isotopes from other gases using a heated palladium membrane. Thickness and dimensions of the membrane are specified. A drawing of a typical Pd diffuser is shown. A "uranium furnace" (uranium bed) for pretreatment of tritium before the palladium diffusion process is described.

8. ANL-SL-284. Report of Tritium Process Development Group, January 1, 1950-April 15, 1950. N. R. Chellew. May 4, 1950 (Declassified).

Knolls Atomic Power Laboratory

Tritium process development at KAPL is reported in a series of monthly reports, P-10 Project Progress Report.

9. KAPL-432 (Declassified) October 1950
10. KAPL-435 (Declassified) November 1950
11. KAPL-443 (Declassified) December 1950
12. KAPL-463 (Declassified) January 1951
13. KAPL-476 (Declassified) February 1951
14. KAPL-497 (Declassified) March 1951
15. KAPL-517 (Declassified) April 1951
16. KAPL-558 (Declassified) May 1951
17. KAPL-574 (Declassified) June 1951
18. KAPL-582 (Declassified) July 1951
19. KAPL-593 (Declassified) August 1951
20. KAPL-608 (Declassified) September 1951
21. KAPL-632 (Declassified) October 1951
22. KAPL-645 (Declassified) November 1951
23. KAPL-658 (Declassified) December 1951
24. KAPL-676 (Declassified) January 1952

Progress is reported on theoretical and experimental studies of palladium black and palladium sponge beds for absorption of hydrogen (protium) and tritium mixed with helium. Although separation of tritium from protium on Pd beds is not suggested in these reports, equilibrium studies for both isotopes were made at various temperatures and pressures, and isotope separation by this method was studied in KAPL-1249 listed below. Separation of hydrogen isotopes from other gases by diffusion through heated palladium membranes was also studied and diffusion equations derived. KAPL-443 contains a drawing of a Pd diffuser. Permeability of construction materials to hydrogen was studied. Results of stainless steel treatments (nitriding, calorizing) are reported in KAPL-476.

KAPL topical reports:

25. KAPL-350. Separation of P-10 by Condensation at Low Temperatures. D. H. Ahmann, May 31, 1950, Declassified.

    Theoretical study of tritium separation from helium by cooling to 4°K. Data on boiling point, vapor pressure, triple point of tritium and deuterium. Isotopic separation by cryogenic distillation is suggested.

26. KAPL-352. Separation of Hydrogen from Helium by Sorption on Palladium Black or Reaction with Uranium. D. H. Ahmann, et al., June 8, 1950, Declassified.

    Experimental studies are reported on separation of hydrogen from helium by absorption on palladium black at -78° and -190°C.

27. KAPL-659. The Diffusion of Hydrogen Through Materials of Construction. P. S. Flint, December 14, 1951, Declassified.

    Experimental investigation of permeability of hydrogen through low carbon steel and several types of stainless steel. Effects of metal plating, ceramic and glass coatings, and calorizing are discussed.

28. KAPL-660. Studies of Hydrogen Sorption on Palladium and the Separation of Hydrogen from Gas Mixture. R. H. Boice, et al., February 10, 1952, Declassified.

    Theoretical and experimental studies are reported of hydrogen absorption from mixtures containing helium and nitrogen in the range -78 to -100°C.

29. KAPL-904. Diffusion Studies. I. The Permeability of Type 347 Stainless Steel to Hydrogen and Tritium. D. Randall and O. N. Salmon, March 17, 1953, Unclassified.

    Permeability of type 347 stainless steel to protium and tritium was measured as a function of temperature and pressure. A diffusion equation was derived and was compared to the equation used in the case of palladium diffusers.

30. KAPL-984. Diffusion Studies. II. The Permeability of Palladium to Hydrogen and Tritium. O. N. Salmon and D. Randall, May 14, 1954, Unclassified.

    The permeability was measured of protium and tritium through a palladium membrane at 200°-600°C temperature and 10^{-3} to 20 cm mercury pressure.

31. KAPL-1036. The Solubility of Hydrogen and Tritium in Palladium Black. R. E. Patterson, et al., April 15, 1954, Unclassified.

    The solubilities of protium and tritium in palladium black were measured between 200° and 400°C. Solubility was found proportional to the square root of equilibrium pressure.

32. KAPL-1097. The Palladium Tritium System at Low Temperature. R. M. Haag, June 1, 1956, Unclassified.

    The palladium-tritium system was studied at 0°, -80°, -100°C using palladium black and palladium sponge.

33. KAPL-1098. Separation of Tritium from Helium by Sorption on Palladium. R. M. Haag, et al., August 4, 1955, Declassified.

    Experimental measurements were made of the separation of tritium from helium by sorption on palladium in a mockup of the stripping line built for Hanford. An equation was derived describing concentration waves moving through the bed.

34. KAPL-1114. Use of Sorbent Beds for Transferring Hydrogen Gases. D. H. Ahmann, et al., June 17, 1954, Unclassified.

    The use of uranium and palladium black beds for storage of hydrogen isotopes is described. Palladium was found less likely to become poisoned and is more easily reactivated than uranium..

35. KAPL-1227. Diffusion of Gases Through Metals. I. Diffusion of Hydrogen Through Palladium. W. D. Davis, October 1954, Unclassified.

36. KAPL-1249. The Separation of Hydrogen Isotopes by Sorption in Palladium. O. N. Salmon, et al., January 19, 1955, Declassified.

    A theoretical study was made of separating hydrogen isotopes from each other by fractional absorption in palladium beds. Experiments were conducted using protium and deuterium mixtures which yielded separation factors in good agreement with theory.

37. KAPL-1674. Mechanism of Diffusion of Hydrogen Through Active and Inactive Palladium. O. N. Salmon, et al., November 1956, Unclassified.

Los Alamos Scientific Laboratory

38. LAMS-2517. Tabulated Values of Thermal Diffusion Column Shape Factors for the Lennard-Jones (12-6) Potential. B. B. McInteer and M. J. Reisfeld (1961).

Mound Laboratory

Unclassified work applicable to tritium separations technology is found in a series of quarterly Mound Laboratory reports on stable gaseous isotope separation.

Stable Gaseous Isotope Separation and Purification Progress Reports:

39. MLM-1352 (Unclassified) January-March 1966
40. MLM-1353 (Unclassified) April-June 1966
41. MLM-1367 (Unclassified) July-September 1966
42. MLM-1390 (Unclassified) October-December 1966
43. MLM-1409 (Unclassified) January-March 1967
44. MLM-1419 (Unclassified) April-June 1967
45. MLM-1430 (Unclassified) July-September 1967
46. MLM-1455 (Unclassified) October-December 1967
47. MLM-1495 (Unclassified) January-March 1968
48. MLM-1521 (Unclassified) April-June 1968
49. MLM-1529 (Unclassified) July-September 1968
50. MLM-1530 (Unclassified) October-December 1968
51. MLM-1605 (Unclassified) January-March 1969
52. MLM-1608 (Unclassified) April-June 1969
53. MLM-1611 (Unclassified) July-September 1969
54. MLM-1614 (Unclassified) October-December 1969
55. MLM-1728 (Unclassified) January-March 1970
56. MLM-1753 (Unclassified) April-June 1970
57. MLM-1768 (Unclassified) July-September 1970
58. MLM-1793 (Unclassified) October-December 1970
59. MLM-1816 (Unclassified) January-March 1971
60. MLM-1828 (Unclassified) April-June 1971

61. MLM-1861 (Unclassified) July-September 1971

62. MLM-1886 (Unclassified) October-December 1971

63. MLM-1904 (Unclassified) January-March 1972

64. MLM-1943 (Unclassified) April-June 1972

Report title changed to Mound Laboratory Activities for the Division of Physical Research.

65. MLM-2013 (Unclassified) July-December 1972

66. MLM-2068 (Unclassified) January-June 1973

67. MLM-2118 (Unclassified) July-December 1973

68. MLM-2168 (Unclassified) January-June 1974

69. MLM-2198 (Unclassified) July-December 1974

Process development and summaries of process operations are reported in the program for stable isotope separations. One section of each quarterly report records experience in isotopic separation of helium, neon, argon, krypton, and xenon using gaseous thermal diffusion columns. Other sections report isotopic separation of other elements such as calcium, oxygen, carbon, sulfur, and lithium using various other techniques such as distillation, liquid thermal diffusion, and electrolysis. One section reports theoretical studies of gaseous thermal diffusion technology and another section reports experiments in ultra-low temperature technology.

Other MLM reports:

70. MLM-1089. Parameters of Thermal Diffusion Columns. G. R. Grove, et al., April 1957.

71. MLM-1104. Isotopic Separation by Thermal Diffusion: Shape Factors for the Extreme Cylindrical Case. M. L. Curtis, V. Wurstner, and G. R. Grove (1961).

72. MLM-1192. Mound Laboratory Progress Report for March 1964. Thermal Diffusion Column Theory (1964).

73. MLM-1389. Tritium Removal from Gases. J. P. Potras, September 30, 1966, Unclassified.

The tritium concentration of a gas mixture consisting primarily of helium was reduced from 10^{-3} mole percent to 2×10^{-12} mole percent. Adsorption experiments on activated charcoal at 77°K and 4.2°K were conducted using various traps and the results compared. The tritium was removed from gas which had been cryogenically adsorbed by the charcoal. This was done by using a catalyst, Hopcalite, heated to 725°C, to form tritiated water which was then adsorbed on a molecular sieve.

Oak Ridge National Laboratory

74. K-1469. Thermal Diffusion Column Shape Factors: Part I. Shape Factors Based on an Inverse Power Repulsion Model. E. Greene, R. L. Hoglund, and E. Von Halle, February 7, 1966.

75. K-1679. Thermal Diffusion Column Shape Factors: Part II. Shape Factors Based on the Lennard-Jones (6-12) Intermolecular Force Model. E. Von Halle, December 27, 1966.

Savannah River Laboratory

76. L. H. Meyer. "Tritium." in Kirk-Othmer Encyclopedia of Chemical Technology. A. Standen, ed., Vol. 6, 2nd Ed., John Wiley and Sons, Inc., New York, 910-918 (1965).

    A general review is given of the occurrence, preparation, properties, and uses of tritium. A section is included on isotopic concentration with reference to methods including electrolysis, thermal diffusion, low-temperature distillation, and elution chromatography.

77. DP-261. Isotopic Purification of Tritium by Electrolysis. B. S. Johnson, et al., May 1958, Declassified.

    An electrolytic refining process was developed to produce tritium of high isotopic purity with negligible loss. The operation is semicontinuous, with multiple stages in cascade. All tritium oxide is handled within the confines of a hermetically sealed enclosure. The mechanical operability of the process was demonstrated in a five-stage prototype line designed to process 15 gram-mols of feed per day. An average separation factor per stage of 5.3 was obtained with a feed of tracer-level tritium. The equipment is described in detail.

78. DP-MS-75-50. "Equilibrium and Kinetic Studies of Systems of Hydrogen Isotopes, Lithium Hydrides, Aluminum, and $LiAlO_2$." J. H. Owen and D. Randall. International Conference on Radiation Effects and Tritium Technology for Fusion Reactors, Gatlinburg, TN, Oct. 1-3, 1975.

    This paper describes measurements of (1) the distribution of tritium and helium throughout both α and β phases of irradiated Li-Al alloy, (2) the migration rate of tritium to the β phase during moderate heating, (3) equilibrium pressures as functions of temperature of H_2, D_2, or T_2 in contact with lithium hydrides + aluminum, Li-Al alloy, or irradiated Li-Al alloy, (4) the equilibrium constant for the reaction $LiH + Al \rightarrow LiAl + 1/2H_2$ as a function of temperature, and (5) extraction rates of tritium from irradiated $LiAlO_2$ targets at elevated temperatures.

79. DP-732. Low Temperature Still for Separation of Hydrogen Isotopes. B. S. Johnson and F. G. Rust, September 1962, Declassified.

Separation of hydrogen isotopes by continuous distillation was demonstrated with hydrogen and deuterium in a pilot-scale still with a packed column two inches in diameter. Theoretical plate heights of one to four inches were observed. Excellent insulation was essential to avoid excessive consumption of liquid hydrogen coolant. A novel method for data evaluation in ternary distillation is presented.

80. DP-771. Analytical Techniques for the Use and Control of Tritium at Savannah River. E. L. Albenesius and L. H. Meyer, September 1962, Unclassified.

Methods of tritium analysis that are used to monitor the potential health hazard and to control processes for tritium production at Savannah River are reviewed. The analytical applications of tritium produced in fission are also discussed.

81. DP-1058 (Del.). Extraction of Tritium from Lithium Aluminate Targets. A. A. Kishbaugh, August 1966, Declassified.

Tritium can be extracted satisfactorily from lithium aluminate targets by heating at 850°C in a vacuum for 10 hours; less than 0.1% of the tritium remains in the residue. Diagrams and photographs of extraction apparatus are shown. Gas treatment using Hopcalite, zeolite and uranium beds is described.

Canadian Report

82. AECL-394 (CRE-481). The Design and Operation of a Thermal Diffusion Column for the Concentration of Tritium Gas. D. L. Prosser, August 1951, Unclassified.

A hot-wire thermal diffusion column which increases the concentration of tritium gas in hydrogen from 20 atom % to 90 atom % is described. The column was designed following the theory of Jones and Furry, using data obtained with 2% tritium gas. The results from four test runs and two production runs using 20 atom % tritium are reported.

British Reports

83. AERE-I/M-47. A Palladium Column for Concentrating Tritium from 2-Litre Mixtures of Tritium and Hydrogen. J. Chadwick, October 1957, Unclassified.

Two-liter batches of a tritium-protium mixture were isotopically separated by fractional absorption on palladium columns. The columns were made of 60 grams palladium, 18 grams asbestos and 45 grams of Dixon rings. Maximum tritium concentration achieved was 99 atom %.

84. AERE-C/R-1847. Gas Chromatographic Separation of Hydrogen Isotopes. E. Glueckauf and G. P. Kitt, February 1956, Unclassified.

A protium-deuterium mixture was experimentally separated by palladium black mixed with asbestos. Elution and breakthrough curves are plotted and a drawing of the apparatus is shown.

LIST 2. TRITIUM EFFLUENT CONTROL TECHNOLOGY

85. L. L. Burger and L. L. Ryan. Technology of Tritium Fixation and Storage. BNWL-1807, Battelle Pacific Northwest Labs, Richland, WA (1973).

The technology of fixation of tritium in a solid form was examined. The principal emphasis was on the storage in solid form of tritium waste from the nuclear fuel cycle with the aim of preventing its significant entry into the biosphere. Sources and routes of tritiated wastes in the fuel cycle were reviewed. It was concluded that the bulk of the tritium produced in the fuel cycle ends up in the fuels reprocessing plant, and with current reprocessing practice, ends up as a very large volume of low-level tritiated water. Alternative practice might produce much smaller volumes. Criteria were established for narrowing the very wide possible choice of tritium fixation methods and the merits of various classes of tritium compounds are discussed. Current tritium fixation technology and fixation research were reviewed. The basic chemical and technical aspects of known and potential fixation methods and the applicability of these methods to specific sources or types of tritiated waste with some estimate of economics are given.

86. C. M. Dube, D. O. Coffin, and R. D. Stoll. Apparatus for the Reduction of Tritium Emissions into the Atmosphere. LA-5303-MS, Los Alamos Scientific Laboratory, Los Alamos, NM (1973).

Equipment and techniques for the removal of tritium from exhaust gases are described. The principle of removal involves the conversion of tritium to tritiated water using a catalyst and collecting the water on molecular sieves. Using a test gas of 0.5% tritium and flow rates of 100 to 500 cc/min, a decontamination or removal factor of 250,000 was obtained.

87. D. G. Jacobs. Sources of Tritium and Its Behavior Upon Release to the Environment. TID-24635, Oak Ridge National Laboratory, Oak Ridge, TN (1968).

This report reviews published information and pertinent factors on the properties of tritium and tritium compounds, sources of tritium production and its release, procedures for tritium enrichment, monitoring practices and instrumentation for the detection and assay of tritium, movement of tritium in the environment, and projected releases of tritium and its impact upon local and worldwide populations. Because of the extremely large number of publications on tritium, this review is not exhaustive but discusses all important aspects of the subject of tritium up to 1968.

88. C. J. Kershner. Quarterly Progress Reports, Tritium Effluent Control Project. Mound Laboratory, Miamisburg, OH.

MLM-2081 (LD) April-June 1973

MLM-2100 (LD) July-September 1973

MLM-2129 (LD) October-December 1973

MLM-2146 (LD) January-March 1974

MLM-2171 (LD) April-June 1974

MLM-2187 (LD) July-September 1974

MLM-2217 October-December 1974

MLM-2235 January-March 1975

MLM-2270 April-June 1975

Research is reported on methods for recovery of tritium from low level effluents by various processes including cryogenic absorption, electrolysis, hydrogen gettering, distillation and selective molecular excitation. Theoretical and experimental results are reported. Reports prior to April-June 1973 appear to be unnumbered internal memoranda. Reports issued prior to October-December 1974 were designated as limited distribution.

89. K. H. Lin. Tritium Enrichment by Isotope Separation Techniques. ORNL-TM-3976, Oak Ridge National Laboratory, Oak Ridge, TN (1972).

A preliminary evaluation of six isotope separation techniques has been carried out to assess their technical and economic feasibility in decontamination of tritiated water containing a trace amount of tritium ($>10^{-3}$ μCi/ml). Two methods that have potential technical and economic feasibility are the dual-temperature water-H_2S exchange process and the cryogenic hydrogen distillation process.

90. A. A. Moghissi and M. W. Carter, eds. Tritium. Messenger Graphics, Phoenix, AZ, 807 pp (1973)(CONF-710809).

This book is a compilation of papers presented at the Tritium Symposium which was held August 28 to September 3, 1971, at Las Vegas, Nevada. It contains 10 chapters covering the subjects or historical and current perspectives, tritium production, detection and measurement, chemical and biological effects of tritium, kinetics of tritium in biological systems, certain environmental aspects of tritium, environmental monitoring techniques, environmental monitoring data, applications of tritium and tritium health physics.

91. T. B. Rhinehammer, et al. Tritium Control Technology. WASH-1269, USAEC, Washington, DC (1973), Unclassified.

Description is given of handling, packaging, analysis, storage, containment, trapping and disposal of tritium at government and private atomic energy installations.

LIST 3. GENERAL PUBLICATIONS ON TRITIUM TECHNOLOGY

92. J. Bardeen. "Concentration of Isotopes by Thermal Diffusion: Rate of Approach to Equilibrium." Phys. Rev. 57, 35 (1940).

93. J. Bardeen. "Concentration of Isotopes by Thermal Diffusion: Rate of Approach to Equilibrium." Letters to the Editor, Phys. Rev. 58, 94 (1940).

94. S. Chapman. "The Characteristics of Thermal Diffusion." Proc. Roy. Soc. (London) A177, 38 (1940).

95. S. Chapman and T. G. Cowling. The Mathematical Theory of Non-Uniform Gases. Cambridge University Press (1939) with Added Notes (1951).

96. S. Chapman and F. W. Dootson. "Thermal Diffusion." Phil. Mag. 33, 248-253 (1917).

97. C. F. Curtiss and J. O. Hirschfelder. "Transport Properties of Multi-component Mixtures." J. Chem. Phys. 17, 550 (1949).

98. S. Danatos, "Unusual Separations." Chem. Eng. 71, 155-168, December 7, 1964.

99. A. S. Darling. "Hydrogen Separation by Diffusion Through Palladium Alloy Membranes," in Proceedings of Symposium on the Less Common Means of Separation, Birmingham, England, 24-26, April, 1963. The Institution of Chemical Engineers, London (1964).

100. P. Debye. "Theory of the Clusius Separation." Ann. d. Physik 36, 284 (1939).

101. G. Dickel. "Does a Pressure Dependence of Thermal Diffusion Exist?" J. Chem. Phys. 60 (1-2), 170 (January-February 1963).

102. S. Dushman. Foundations of Vacuum Technology. John Wiley and Sons, New York, NY (1949).

Chapter 9, "Gases and Metals" treats solubility of hydrogen in palladium and other Group B metals. Pressure-solubility isotherms are shown for chromatographic separation column design.

103. R. Edse and P. Harteck. "The Analysis of Gas Mixture by Means of the Desorption-Thermal Conductivity Method. II." Angew. Chem. 53, 210-215 (1940).

104. W. H. Furry and R. C. Jones. "Isotope Separation by Thermal Diffusion: The Cylindrical Case." Phys. Rev. 69, 459 (1946).

105. W. H. Furry, R. C. Jones, and L. Onsager. "On the Theory of Isotope Separation by Thermal Diffusion." Phys. Rev. 55, 1083 (1939).

106. A. J. Gould, et al. "The Inter-Relations of Hydrogen and Deuterium Molecules." J. Chem. Phys. 2, 362-373 (1934).

107. E. Greene. "Calculation of Thermal Diffusion Column Shape Factors Based on the Inverse Power Law." Report KOA-891 (Thesis), Union Carbide Corp., Oak Ridge, TN, 182 pp (1961).

108. K. E. Grew. "Thermal Diffusion in Hydrogen-Deuterium Mixtures." Proc. Roy. Soc. (London) 178A, 390 (1941).

109. K. E. Grew, F. A. Johnson, and W. E. J. Neal. "The Thermal Diffusion Factor and Temperature." Proc. Roy. Soc. (London) 224A, 513 (1954).

110. K. E. Grew and A. E. Humphreys. "Thermal Diffusion in Some Binary Mixtures of the Hydrogen Isotopes." J. Chem. Phys. 45, 4267 (1966).

111. K. E. Grew and T. L. Ibbs. Thermal Diffusion in Gases. Cambridge University Press (1952).

112. R. Haase. "Über die Druckabhängigkeit des Thermodiffusionsfaktors." Zeit. für Phys. Chem. 196, 219 (1950).

113. E. Von Halle. "Evaluation of the Performance of Thermal Diffusion Columns." J. Chim. Phys. 60 (1-2), 187 (January-February 1963).

114. P. Harteck and G. A. Melkonian. "Über das Auftreten des Tunneleffektes bei Ad-und Desorption der Wasserstoffisotope." Naturwissenschaften 37, 450 (1950).

115. W. J. Hauback, Jr. Separation of the Isotopes and Spin Isomers of the Molecular Hydrogens by Preferential Adsorption at Low Temperatures. Ph.D. Thesis, Ohio State University (1963).

The theory of chromatographic separation is reviewed and experiments described. Experimental work used gamma-alumina as the chromatographic absorbent. Tests were run using protium, deuterium and tritium mixtures, and varying conditions to determine effects on separation factors.

116. H. R. Heath, T. L. Ibbs, and N. E. Wild. "The Diffusion and Thermal Diffusion of Hydrogen-Deuterium with a Note on the Thermal Diffusion of Hydrogen-Helium." Proc. Roy. Soc. (London) 178A, 380 (1941).

117. E. J. Hellund. "Generalized Theory of Diffusion II." Phys. Rev. 57, 328 (1940).

118. R. G. Hickman. "Tritium in the Fusion Engineering Research Facility." in Proceedings of the 8th Symposium on Fusion Technology, Noordwijkerhout, Netherlands, June 17-21, 1974. CONF-740630-1 (UCRL-75354), May 17, 1974 Unclassified.

The Lawrence Livermore Fusion Engineering Research Facility is described. The facility includes palladium diffusers for hydrogen purification and a cryogenic still for deuterium-tritium separation.

119. J. O. Hirschfelder, et al., eds. Molecular Theory of Gases and Liquids. John Wiley and Sons, New York, NY, 1954.

120. A. J. Howard and W. W. Watson. "Isotope Separation by Thermal Diffusion." J. Chem. Phys. 40, 1409 (1964).

121. P. Hugony, et al. "Tritium Production in France." Bull. Inform. Sci. Tech. (Paris) No. 178, 3 (February 1973)(in French). (For translation see ERDA-tr-286.

Most of the tritium producing facilities in France are found at Marcoule: the two Celestin reactors and the tritium extraction and purification plant. The two heavy water reactors started up in 1967 and 1968 are fed with plutonium or enriched uranium. The standard type of element irradiated is an enriched lithium target. These targets are unloaded and transferred to the processing plant; the tritium is extracted by fusion, purified, and finally subjected to thermal diffusion process in which almost all the traces of hydrogen and deuterium are removed. Another plant exists at Grenoble for recovering the tritium formed in the heavy water of the high flux reactor of the Laue Langevin Institute.

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2. Fractional distillation of the deuterium which eliminates HD at the head and DT at the foot of the column.

Heavy water coming from the reactor is evaporated, superheated, and mixed with deuterium to pass through the catalytic reactor where isotopic exchange occurs. It is then recondensed, separated from the deuterium, and transferred to the second and third stage of the catalytic exchanger.

Deuterium coming out of the catalytic exchanger is dried, purified, and sent into a Sulzer-packed distillation column. Purified deuterium coming out of the column returns to the catalytic exchanger through an expansion vessel. The deuterium hydride drawn off at the head is sent to a burner. The tritiated deuterium at the foot of the column is sent to a second column with Dixon packing, at the bottom of which the pure tritium is drawn off.

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