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COO-3259-29

TRANSPORT AND MAGNETIC PHENOMENA IN
CHROMIUM AND IRON ALLOYS (IV)

Final Report

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March 4, 1969 - June 30, 1973

PREPARED FOR THE U. S. ATOMIC ENERGY COMMISSION
UNDER CONTRACT NO. AT(11-1)-3259

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I. Introduction

The purpose of this research was to investigate the electrical resistivity, thermoelectric power, thermal conductivity, and magnetization of different binary chromium and iron alloys over large temperature ranges (4 to 1700^oK) from the viewpoint of their electronic structures and the interactions among elementary excitations in magnetically ordered metallic systems. Although iron and chromium base alloys are technologically important materials, their physical nature is only partially understood. The present investigation was directed towards a better understanding of these important metallic systems from a fundamental point of view.

The above-mentioned investigation was started on April 1, 1969. Because of the broadness of the proposed research, a selection of initial topics had to be made. It was decided to initiate various studies on the electrical resistivity, thermoelectric power, and magnetization of different chromium and iron base alloys and to start the thermal conductivity studies latter. The reason for this particular selection was primarily the status of the experimental facilities. The achievements of the proposed research are briefly described in the following sections of this report.

II. Results

About 80% of the total time was spent on various proposed research projects using different apparatuses in operating condition. The remaining time was devoted to building additional experimental facilities so that other parts of the proposed research could be carried out. A brief description of these efforts follows.

It is convenient to divide the research work done so far into two groups:

(a) studies completed, including reports and papers, and (b) studies completed but papers yet unwritten.

(a) The following proposed topics have been completed and the results written up since the beginning of the contract (April 1, 1969):

1. Electrical Resistivity of Dilute Chromium-Rich Chromium-Iron Alloys Below 30⁰K. (S. Arajs).

This paper has been published in phys. stat. sol. 37, 329 (1970). A copy of this paper (Report No. COO-3259-1)* is attached to this report as Appendix 1.

2. Antiferromagnetism and Electrical Resistivity of Chromium Alloys Containing Ruthenium and Osmium. (S. Arajs, T. F. DeYoung, and E. E. Anderson).

This paper has been published in J. Appl. Phys. 41, 1426 (1970). A copy of this paper (Report No. COO-3259-2)* is attached to this report as Appendix 2. This paper was also presented at the 15th Annual Conference on Magnetism and Magnetic Materials, held in Philadelphia, Pennsylvania, November 18-21, 1969. This publication is a condensed version of the M. S. thesis of T. F. DeYoung - a graduate student supported by the present contract, who received his degree from Clarkson College of Technology in June 1969 and is presently continuing his studies for the Ph.D. degree.

3. Electrical Resistivity of Dilute Binary Chromium Alloys with Nickel and Manganese. (S. Arajs).

This paper has been published in phys. stat. sol. (a) 1, 499 (1970). It is

* Submitted in previous reports with New York Operations office under contract AT(30-1)-4079.

attached as Appendix 3 (Report COO-3259-3)* to this report.

The above-mentioned three publications constitute the research completed during the first year of the contract.

The following papers listed below resulted from the work done during the second year of the contract.

4. Critical Magnetic Behavior of Nickel Near the Curie Point. (S. Arajs, B. L. Tehan, E. E. Anderson, and A. A. Stelmach).

This paper has been published in phys. stat. sol. 41, 639 (1970). It is attached as Appendix 5 (Report No. COO-3259-7)*. This work was also presented at the American Physical Society March (Solid State Physics) Meeting in Dallas, Texas, March 23-26, 1970 (Report No. COO-3259-5, * Appendix 4).

5. The Critical Exponent for the Spontaneous Magnetization of Iron-Germanium Alloys. (S. Arajs, B. L. Tehan, E. E. Anderson, and A. A. Stelmach).

This paper has been published in Phys. Letters 32A, 412 (1970). It is attached as Appendix 6 (Report No. COO-3259-8)* to this report.

6. Magnetic Phase Diagram of Chromium-Rich Chromium-Iron Alloys. (S. Arajs).

This paper has been published in J. Less-Common Metals 22, 519 (1970) and is attached as Appendix 7 (Report No. COO-3259-9)*.

7. Power Laws for the Magnetization of Iron. S. Arajs, B. L. Tehan, E. E. Anderson, and A. A. Stelmach).

This paper has been published in Intern. J. Magnetism 1, 41 (1970). It is attached as Appendix 8 (Report No. COO-3259-10)* to this report. The papers 4, 5, and 7 and some yet unpublished results on the Curie points of various nickel alloys are part of the Ph.D. thesis of B. L. Tehan which was supported by the present contract. The Ph.D. degree was awarded to B. L. Tehan in June 1971.

8. Antiferromagnetism and Electrical Transport Properties of Chromium-Alluminum Alloys. (S. Arajs, N. L. Reeves, and E. E. Anderson).

This paper has been published in J. Appl. Phys. 42, 1691 (1971). A copy of it (Report No. COO-3259-12)^{*} is attached as Appendix 10. This paper was also presented at the 16th Annual Conference on Magnetism and Magnetic Materials held in Miami, Florida, November 16-20, 1970 (Report No. COO-3259-11)^{*} Appendix 9. The content of this paper is a brief version of the M. S. thesis of N. L. Reeves who received his degree from Clarkson College of Technology in June 1970.

9. Absolute Thermoelectric Power of Chromium-Silicon Alloys. (S. Arajs, E. E. Anderson, and E. E. Ebert).

This paper was presented at the American Physical Society June Meeting in Winnipeg, Manitoba, June 22-24, 1970 (Report No. NYO-4079-6^{*}, Appendix 11) and has been published in Nuovo Cimento 4B, 40 (1971) (Report No. NYO-4079-13,^{*} Appendix 12).

10. Thermoelectric Power of Antiferromagnetic Chromium-Iron Alloys. (S. Arajs and E. E. Anderson).

This paper has been presented at the American Physical Society February Meeting in New York, New York, February 1-4, 1971 (Report No. COO-3259-14^{**}, Appendix 13) and also has been published in Physica 54, 617 (1971) (Report No. COO-3259-16^{**}, Appendix 14).

11. Electrical Resistivity and Thermoelectric Power of Polycrystalline Uranium at Elevated Temperatures. (S. Arajs, R. H. Flora, and E. E. Anderson).

This paper has been published in J. Nucl. Materials 37, 89 (1970) (AEC Report No. COO-3259-17,^{**} Appendix 15).

^{**} Submitted in previous reports to Chicago Operations Office under Contract AT(11-1)-3259.

12. Seebeck Coefficient of Binary Chromium Alloys Containing Molybdenum and Tungsten. (S. Arajs, E.E. Anderson, and K. V. Rao).

This paper was presented at the American Physical Society March (Solid State Physics) Meeting in Cleveland, Ohio, March 29 - April 1, 1971 (Report No. COO-3259-18, ^{**} Appendix 16) and has been published in J. Less-Common Metals 26, 157 (1971) (AEC Report No. COO-3259-19 ^{**}, Appendix 17).

13. Antiferromagnetism and Electrical Resistivity of Chromium-Iridium Alloys. (S. Arajs, T. F. DeYoung, and E.E. Anderson).

This work has been presented at the 17th Annual Conference on Magnetism and Magnetic Materials, Held in Chicago, Illinois, November 16-19, 1971 (AEC Report No. COO-3259-20 ^{**}, Appendix 18). The paper describing this investigation has been published in AIP Conf. Proceedings No. 5, 517 (1972) (AEC Report No. COO-3259-21, ^{**} Appendix 19).

The following papers listed below resulted from the work done during the fourth year of the contract.

14. Absolute Thermoelectric Power of Chromium-Ruthenium Alloys.

(T. F. DeYoung, S. Arajs, and E.E. Anderson). This paper has been published in J. Less-Common Metals 29, 93 (1972) (AEC Report No. COO-3259-23, Appendix 20).

15. Electrical Resistivity of Chromium-Ruthenium Alloys. (T. F. DeYoung, S. Arajs, and E.E. Anderson). This paper has been published in J. Less-Common Metals 32, 165 (1973) (AEC Report No. COO-3259-24, Appendix 21).

16. Magnetic Susceptibility and Electrical Resistivity of TiCo at Elevated Temperatures. (S. Arajs, A.A. Stelmach, and M.C. Martin). This paper was presented at the American Physical Society March (Solid State Physics) Meeting in San Diego, California, March 19-22, 1973) (AEC Report No. COO-3259-25, Appendix 22) and also been published in J. Less-

Common Metals 32, 178 (1973) (AEC Report No. COO-3259-26, Appendix 23).

17. Determination of Neel Temperatures of Binary Chromium Alloys from Electrical Resistivity Data. (S. Arajs, K. V. Rao, H. V. Astrom, and T. F. DeYoung).

This paper has been accepted for publication in Phys. Scripta (AEC Report No. COO-3259-27, Appendix 24). A part of this paper was presented at the American Physical Society March (Solid State Physics) Meeting in Atlantic City, New Jersey, March 27-30, 1972) (AEC Report No. COO-3259-28, Appendix 25).

(b) The following study has been completed but has not yet been written up in the form of a paper:

18. Magnetic Susceptibility of Iron-Aluminum Alloys in the Paramagnetic State (S. Arajs and E. E. Anderson).

This work has been presented at the American Physical Society April Meeting in Washington, D. C., April 26-29, 1971 (AEC Report COO-3259-22, ** Appendix 26).

III. Significant Differences in the Level of Activity.

The research activities during the four years were carried out approximately as originally expected. A brief description of the personnel and their activities follows.

A. Personnel

The level of activity of the principal investigator and two graduate students was carried out as proposed. In addition the help of few undergraduate and graduate students were used in order to cover larger spectrum of the experimental aspects of the proposed program. One of the sponsored students, B. L. Tehan who received the Ph.D. degree in Physics on his work done for this project in June 1970 stayed at Clarkson for a year and continued studies on various aspects of the project.

Valuable contributions to parts of programs have also been made by Dr. E.E. Anderson, Chairman and Professor of Physics and M. C. Martin, Associate Professor of the Physics Department.

Dr. K. V. Rao, formerly at Dalhousie University, Halifax, Nova Scotia, joined the department as Research Associate between September 1, 1970 and February 28, 1971. He received his D. Phil (Oxon) from Oxford University in 1967 under Prof. Mendelssohn. Dr. Rao supervised the construction of the thermal conductivity apparatus which was successfully completed. However, due to the shortage of time it was not possible to carry out experimental studies in this area.

B. Travel Performed

During the first year of this contract, the principal investigator attended a Symposium on Magnetic Materials at IBM Watson Research Center, Yorktown Heights, New York, November 13-14, 1969 as a part of his related professional activity. Also he attended the 15th Annual Conference on Magnetism and Magnetic Materials, Philadelphia, Pennsylvania, November 18-21, 1969 where two papers (one of them representing studies of this proposal, another related to this proposal) were presented: (1) Antiferromagnetism and Electrical Resistivity of Chromium Alloys

containing Ruthenium and Osmium (Appendix 2), (2) The Critical Exponent for the Magnetization of YIG.

During the second year, the principal investigator attended the following conferences which were covered by the funds of this contract.

1. The Fordham Conference on Critical Phenomena, June 9-11, 1970, held at Fordham University Campus, New York, New York.
2. The American Physical Society Meeting in Winnipeg, Manitoba, June 22-24, 1970, where a paper on "Absolute Thermoelectric Power of Chromium-Silicon Alloys" (Appendix 11) was presented. (Bull. Am. Phys. Soc. 15, 361 (1970)). Another paper co-authored by the principal investigator and related to the present project was also given at this conference: "The magnetization of Lutetium Iron Garnet Near the Critical Point", E.E. Anderson A.A. Stelmach, S. Arajs, and B. L. Tehan, Bull. Am. Phys. Soc. 15, 78 (1970).
3. Gordon Research Conference - Chemistry and Physics of Solids, Kimball Union Academy, Meriden, New Hampshire, August 10-14, 1970.
4. The American Physical Society Meeting in New York, New York, February 1-4, 1970, where a paper "Thermoelectric Power of Antiferromagnetic Chromium-Iron Alloys" (Appendix 13) was presented.
5. The Annual March Solid State Physics Meeting of the American Physical Society in Cleveland, Ohio, March 29- April 1, 1971, where a paper entitled "Seebeck Coefficient of Binary Chromium Alloys Containing Molybdenum and Tungsten" (Appendix 16) was given.

The principal investigator also attended the following meetings, paid by the Department of Physics or other sources, where results obtained associated with the present contract were presented and discussed.

6. Department of Physics, Dalhousie University, Halifax, Nova Scotia, April 8-9, 1970, where a colloquium talk entitled "Manifestations of Magnetic Moments in Metallic Systems", were presented.

7. Department of Metallurgy, Syracuse University, Syracuse, New York, July 7, 1970, where a colloquium talk "Magnetic Moments in Metallic Systems" was presented.
8. 1970 Fall Meeting of the New York State Section, The American Physical Society, Canton, New York, October 2-3, 1970. Title of the conference: Fluctuations and Critical Phenomena.

During the third year, the principal investigator attended meetings paid by the funds of this contract.

1. The American Physical Society Cleveland (Solid State Physics) Meeting held in Cleveland, Ohio, March 29-April 1, 1971, where a paper entitled "Seebeck Coefficient of Binary Chromium Alloys Containing Molybdenum and Tungsten" [Appendix 16; Bull. Am. Phys. Soc., 16, 423 (1971)] was presented.
2. 17th Annual Conference on Magnetism and Magnetic Materials, Chicago, Illinois, November 16-19, 1971 where a paper entitled "Antiferromagnetism and Electrical Resistivity of Chromium-Iridium Alloys" (Appendix 18) was presented. Another paper co-authored by the principal investigator and related to the present project was also given at this conference: "The Critical Exponents for the Magnetic Properties of Europium Iron Garnet".
3. The American Physical Society Atlantic City (Solid State Physics) Meeting, New Jersey, March 27-30, 1972, where a paper entitled "The Néel Temperatures of Binary Chromium Alloys" (Appendix 25) was presented.

The principal investigator also attended the following other meetings paid by Physics Department or other sources, where some results associated with the present contract were presented and discussed:

4. The American Physical Society New York Meeting held in New York, New York, February 1-4, 1970, where a paper on "Thermoelectric Power of Antiferromagnetic Chromium-Iron Alloys" (Appendix 13) was presented [Bull. Am. Phys. Soc., 16, 143 (1971)].

5. Department of Physics, McGill University, Montreal Quebec, Canada, March 24, 1971, where a colloquium talk entitled "Manifestations of Magnetic Moments in Solids" was presented.
6. Toronto Conference on Antiferromagnetism of Chromium, held in Toronto, Ontario, Canada, March 26 and 27, 1971.
7. Edgar C. Bain Laboratory for Fundamental Research, United States Steel Corporation, Monroeville, Pennsylvania, April 2, 1971 where two seminar talks "Critical Phenomena in Ferromagnets" and "Macromolecules, Genetic Control, and Life" were presented.
8. 1971 Spring Meeting of the New York State Section, The American Physical Society, Corning, New York, April 23 and 24, 1971.
9. Gordon Research Conference - Science and Technology of Biomaterials, Holderness School, Plymouth, New Hampshire, August 2-6, 1971.
10. 1971 Fall Meeting of the New York State Section, The American Physical Society, Geneseo, New York, September 30 - October 1, 1971.

During the fourth year, the principal investigator attended the American Physical Society San Diego (Solid State Physics) Meeting in California, March 19-22, 1973 where two papers were presented. One of them, entitled "Magnetic Susceptibility and Electrical Resistivity of TiCo at Elevated Temperatures" is briefly described in Appendix 22.

IV. Technical Articles Prepared

The following papers, resulting from the work done on the present project, have been published or have been accepted for publication:

1. S. Arajs, Electrical Resistivity of Dilute Chromium-Rich Chromium-Iron Alloys Below 30°K , phys. stat. sol. 37, 329 (1970).
2. S. Arajs, T. F. De Young, and E.E. Anderson, Antiferromagnetism and Electrical Resistivity of Chromium Alloys Containing Ruthenium and Osmium, J. Appl. Phys. 41, 1426 (1970).
3. S. Arajs, Electrical Resistivity of Dilute Binary Chromium Alloys with Nickel and Manganese, phys. stat. sol. 1(a), 499 (1970).
4. S. Arajs, B. L. Tehan, E.E. Anderson, and A. A. Stelmach, The Critical Exponent for the Spontaneous Magnetization of Iron-Germanium Alloys, Phys. Letters, 32A, 412 (1970).
5. S. Arajs, B. L. Tehan, E.E. Anderson, and A. A. Stelmach, Critical Magnetic Behavior of Nickel Near the Curie Point, phys. stat. sol. 41, 639 (1970).
6. S. Arajs, Magnetic Phase Diagram of Chromium-Rich Chromium-Iron Alloys, J. Less-Common Metals 20, 519 (1970).
7. S. Arajs, B. L. Tehan, E.E. Anderson, and A. A. Stelmach, Power Laws for Magnetization of Iron, Int. J. Magnetism 1, 41 (1970).
8. S. Arajs, N. L. Reeves, and E.E. Anderson, Antiferromagnetism and Electrical Transport Properties of Chromium-Aluminum Alloys, J. Appl. Phys. 42, 1619 (1971).
9. S. Arajs, E.E. Anderson, and E.E. Ebert, Absolute Thermoelectric Power of Chromium-Silicon Alloys, Nuovo Cimento 4B, 40 (1971).
10. S. Arajs and E.E. Anderson, Thermoelectric Power of Antiferromagnetic Chromium-Iron Alloys, Physica 54, 617 (1971).

11. S. Arajs, R. H. Flora, and E. E. Anderson, Electrical Resistivity and Thermo-Electric Power of Polycrystalline Uranium at Elevated Temperature, J. Nucl. Materials 37, 89 (1970).
12. S. Arajs, E. E. Anderson, and K. V. Rao, Seebeck Coefficient of Binary Chromium Alloys Containing Molybdenum or Tungsten, J. Less-Common Metals 26, 157 (1971).
13. T. F. DeYoung, S. Arajs, and E. E. Anderson, Antiferromagnetism and Electrical Resistivity of Chromium-Iridium Alloys, AIP Conf. Proceedings No. 5, 517 (1972).
14. T. F. DeYoung, S. Arajs, and E. E. Anderson, Absolute Thermoelectric Power of Chromium-Ruthenium Alloys, J. Less-Common Metals 29, 93 (1972).
15. T. F. DeYoung, S. Arajs, and E. E. Anderson, Electrical Resistivity of Chromium-Ruthenium Alloys, J. Less-Common Metals 32, 165 (1972).
16. S. Arajs, A. A. Stelmach, and M. C. Martin, Magnetic Susceptibility and Electrical Resistivity of TiCo at Elevated Temperatures, J. Less-Common Metals 32, 178 (1973).
17. S. Arajs, K. V. Rao, H. V. Åström, and T. F. DeYoung, Determination of Néel Temperatures from Electrical Resistivity Data, Phys. Scripta (accepted for publication).