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METALS AND CERAMICS DIVISION

**TRANSFER OF MODIFIED 9Cr-1Mo STEEL TECHNOLOGY THROUGH
COOPERATIVE PROGRAMS
(1980-1985)**

V. K. Sikka
J. R. DiStefano
P. Patriarca

ORNL--6301
DE86 014397

Date Published - June 1986

Prepared for
DOE Office of Reactor Systems Development and Technology

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

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CONTENTS

ABSTRACT	1
INTRODUCTION AND BACKGROUND	2
OVERVIEW OF DEVELOPMENT PROGRAM	3
STRATEGY FOR OBTAINING ASME CODE APPROVAL	4
STATUS OF WORK BY OUTSIDE ORGANIZATIONS	7
REFERENCES	8
BIBLIOGRAPHY	10
Appendix A. U.S. INDUSTRIES	13
Appendix B. U.S. UTILITIES	27
Appendix C. U.S. UNIVERSITIES	31
Appendix D. U.S. NATIONAL LABORATORIES	39
Appendix E. FOREIGN INDUSTRIES	47
Appendix F. FOREIGN UTILITIES	59
Appendix G. FOREIGN UNIVERSITIES	63
Appendix H. SI METRIC EQUIVALENTS OF ENGLISH UNITS USED IN THIS REPORT	65

**TRANSFER OF MODIFIED 9Cr-1Mo STEEL TECHNOLOGY THROUGH COOPERATIVE
PROGRAMS (1980-1985)***

V. K. Sikka, J. R. DiStefano, and P. Patriarca[†]

ABSTRACT

The principal objective of the United States Department of Energy (DOE) 9Cr-1Mo steel development program has been to provide the data and analyses required by designers for use of the alloy in advanced liquid metal reactors to reduce technical tasks and plant capital costs. It was recognized early that designers would not consider use of any material for nuclear applications unless there was a considerable body of experience already established. Toward this end, the plan has been to get the alloy accepted in Section I (Power Boilers), Section II (Materials Specifications), Section VIII (Pressure Vessels), and Section III (Nuclear Power Plant Components) of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (BPV) Code as logical steps in the process.

To achieve this objective, extensive interaction with the industrial community was considered mandatory. Accordingly, an intensive effort to achieve technology transfer was initiated, which resulted in the involvement of many organizations. This report is a compilation of 47 status sheets describing 35 participating organizations and funding sources, purpose of the interactions, material and product forms utilized, summary of the work completed, findings, and appropriate references. These interactions contributed significantly toward the fulfillment of the program goals.

In May 1981, applications for inclusion of the modified 9Cr-1Mo alloy in specifications of the American Society for Testing and Materials (ASTM) were initiated. Specification ASTM A-213 T91 was the first to receive approval and is now a reference document; ASTM A-307 Grade 91, A-182 F91, A-234 WP91, and A-200 have also been published in the specifications book since that time; and ASTM A-336 F91, A-199 T91, A-369 P91, and A-335 P91 received all necessary Committee and Subcommittee acceptances and are awaiting publication in the specification book.

In July 1983, the material was accepted for use in the ASME BPV Code Section I (Power Boilers) by virtue of approval of Code Case 1943.

In June 1984, the material received all necessary Subcommittee approvals for inclusion in the ASME BPV Code Section VIII (Pressure Vessels) and was approved for use in February 1985 as Code Case 1973.

*Work performed under DOE/RSMT AF 21 30 20 0, BRIM05, 9Cr-1Mo Steel.

[†]Retired from Oak Ridge National Laboratory.

In December 1983, an initial data package was submitted to the appropriate Section III Subcommittee for consideration, and a revised data package was submitted in December 1984. No action has been taken by the Section III Subcommittee pending identification of a user of the alloy for a nuclear application.

INTRODUCTION AND BACKGROUND

A high level of interest in the use of ferritic steels with 9 to 12% chromium content for elevated-temperature service for both nuclear and fossil energy applications has evolved worldwide over the past ten years.¹⁻⁴ In the late 1960s and early 1970s, many U.S. publications⁵⁻⁸ recognized the need for liquid-metal fast breeder reactors (LMFBRs) in the U.S. power generation industry. The scaling up of technology toward large 1000- to 1500-MWe plants and future construction of commercial plants would involve large commitments of capital equipment. The cost of installed components was estimated to be 20 to 25% of the total projected cost of power generation,⁹ and steps that could be taken to improve plant reliability and thereby reduce the overall costs of power production deserved careful consideration. The selection of austenitic stainless steels as the reference structural material for LMFBRs represented sound engineering judgment. However, continued reassessment of future needs was considered necessary to take advantage of recent experience and new developments in materials technology, which might indicate possible merit in replacement of the austenitic steels by other alloys for specific applications. In 1974, a task force was authorized by the U.S. Department of Energy (DOE) to conduct a three-phase study directed at (1) evaluating the deficiencies of the reference structural alloys, types 304 and 316 stainless steel; (2) selecting candidate alloy(s) that gave promise of improved performance; and (3) developing a plan for acquisition of the data base that would support use of an improved alloy in future LMFBRs in the United States.

OVERVIEW OF DEVELOPMENT PROGRAM

Responsibility for the study was assigned to Oak Ridge National Laboratory (ORNL), and the findings⁸ led to a recommendation for development of an improved ferritic steel. The alloy development program recommended by the task force was initially justified by forecast of a significant LMFBR economy in the 1980s.⁹ Subsequent forecasts predict a delay to the 1990s or beyond and a decrease in the rate of introduction of LMFBRs.¹⁰ Despite the slowdown in the U.S. LMFBR program, the very promising results to date on modified 9Cr-1Mo steel strongly suggest that this alloy should find beneficial application not only in advanced liquid-metal reactor programs but also in the other high-temperature energy options, that is, fossil, solar thermal, and fusion systems.

The task force study⁹ (with considerable input from the U.S. industry) identified the need for an improved ferritic steel after considering several alternative materials. Classes considered in the study included ferritic steels (8-14% chromium), austenitic steels, and nickel-bearing solid-solution alloys. A number of commercially available materials in each class were evaluated in accordance with the following criteria: corrosion, welding, fabricability, mechanical properties, engineering code requirements, design costs, and availability. A strong recommendation was made for development of a modified 9Cr-1Mo high-strength steel to offset the difficulties encountered with commercially available steels of the 8 to 12% chromium group. A further incentive for pursuing the 9Cr-1Mo steel development was the importance of conserving critical materials.¹¹ Substitution of 9Cr-1Mo steels for 18Cr-8Ni steels in certain applications will conserve both chromium and nickel.

After review of the task force recommendations, DOE elected to sponsor a research and development effort on development of a modified 9Cr-1Mo alloy, initially for LMFBR steam generator application. It was further recognized that an optimized and commercially available ferritic steel could be considered for application in future LMFBR plants as the sole structural material, thereby eliminating current difficulties associated with piping transition joints used to join stainless steel to ferritic steel.

Early work^{12,13} was conducted at Combustion Engineering, Inc., and then continued under subcontract from ORNL. Other DOE laboratories and several private companies and utilities have also participated in developing a well-rounded data and experience base. Criteria for measuring the degree of success of the modified 9Cr-1Mo steel development program were established early. The most demanding of these criteria was a design allowable stress intensity equal to or higher than that of type 304 stainless steel at 593°C (1100°F). Data generated to date indicate success in meeting this criterion.¹⁴⁻¹⁵

The composition of the alloy, modified by adding 0.06 to 0.10% niobium and 0.18 to 0.25% vanadium¹⁶ to standard 9Cr-1Mo steel, is shown in Table 1.

Table 1. Recommended specifications for modified 9Cr-1Mo steel

Element	Range (wt %)	Element	Range (wt %)
C	0.08-0.12	Mo	0.85-1.05
Mn	0.30-0.60	Ni	<0.40
P	<0.020	V	0.18-0.25
S	<0.010	Nb	0.06-0.10
Si	0.20-0.50	N	0.030-0.070
Cr	8.00-9.50	Al	<0.04

STRATEGY FOR OBTAINING ASME CODE APPROVAL

Although development of modified 9Cr-1Mo steel was undertaken for breeder reactor applications, it was recognized early that designers would not consider use of any material for nuclear applications unless there was a considerable body of experience already established. If modified 9Cr-1Mo steel is to substitute for 2.25Cr-1Mo steel and types 304 and 316 stainless steel in current breeder reactor designs, approval by subcommittees for the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (BPV) Code, Section III, and Code Case N-47 may be

necessary. Toward this end the strategy has been to proceed systematically through Sections I (Power Boilers), II (Material Specifications), and VIII (Pressure Vessels) as logical steps in the process.

To derive the design allowable stresses, ASME requires tensile and creep data on at least three commercial heats. Tensile test data, including both ultimate tensile strength and yield strength, are required at room temperature and at 50°C (100°F) intervals to a temperature at least 50°C (100°F) above the intended use of the material. When creep properties may be expected to limit the allowable stresses, creep and creep-rupture data at temperature intervals of 50°C (100°F) are also required. Such data should be for four or more time intervals, one of which should be longer than 2000 h but shorter than 6000 h, and one of which should be longer than 6000 h. In addition, creep data are also required to establish the effects of variables such as heat treatment, cold work, notch sensitivity, and aging.

The alloy is recommended for use in the normalized and tempered condition [1040°C (1900°F) for 1 h, air cooled to room temperature; 760°C (1400°F) for 1 h, air cooled to room temperature]. The effect of heat treatment and Charpy impact, tensile, and creep properties of the alloy have been determined in detail.^{18,19}

The modified alloy has creep strength that exceeds that of standard 9Cr-1Mo and 2.25Cr-1Mo steels for the temperature range 427 to 704°C (800 to 1300°F). The total-elongation and reduction-of-area values for all test temperatures and rupture times up to 22,500 h exceed 15 and 70%, respectively. The estimated design allowable stresses for this alloy are higher than those for standard 9Cr-1Mo and 2.25Cr-1Mo steel. At 550°C (1020°F) and above, these values are twice those of the other alloys.

Industrial operating experience, which aided early approval of the Section I data package for the ASME BPV Code, is being obtained by installing tubes of this alloy in various conventional power plants. The utilities involved are in the United States, the United Kingdom, and Canada.

Installations were completed in the Kingston steam plant Unit 5 of the Tennessee Valley Authority (TVA) in May 1960, the Tanners Creek

Unit 3 plant of American Electric Power Service Corporation in April 1981, the St. Clair Unit 2 plant of Detroit Edison in February 1981, the Agecroft Power Station plant of The Central Electric Generating Board (U.K.) in April 1982, and the Lambton TGS plant of Ontario Hydro (Canada) in May 1983.

In May 1981, an application for inclusion of the modified 9Cr-1Mo alloy in ASTM A213 (Seamless Ferritic and Austenitic Alloy-Steel Boiler, Superheater, and Heat-Exchanger Tubes) was made. The alloy was designated T91 and received Committee and Society ballot approval in 1983. This approval, along with the approval in July 1983 of Code Case 1943 (Seamless Modified 9Cr-1Mo, Section I) requested by Babcock & Wilcox Company, Barberton, Ohio, has resulted in the commercial acceptance of modified 9Cr-1Mo alloy for use in accordance with the ASME BPV Code Section I, Power Boilers.

Other materials specifications that have been published include A-387 Gr 91 (Pressure Vessel Plates, Alloy Steel, Chromium-Molybdenum), A-182 F91 (Forged or Rolled Alloy-Steel Pipe Flanges, Forged Fittings, and Valves and Parts for High-Temperature Service), A-234 WP91 (Piping Fittings of Wrought Carbon Steel and Alloy for Moderate and Elevated Temperatures), and A-200 (Seamless Intermediate Alloy-Steel Still Tubes for Refinery Service).

The ASTM specifications A-336 F91 (Steel Forgings, Alloy, for Pressure and High-Temperature Parts), A-199 T91 (Seamless Cold-Drawn Intermediate Alloy-Steel Heat-Exchanger and Condenser Tubes), A-369 FP91 (Carbon and Ferritic Alloy-Steel Forged and Bored Pipe for High-Temperature Service), and A-335 P91 (Seamless Ferritic Alloy Steel Pipe for High Temperature Service) received all necessary Main Committee and Subcommittee approvals and are awaiting publication.

In February 1985, Code Case 1973 received approval for inclusion of modified 9Cr-1Mo Steel in the ASME BPV Code Section VIII (Pressure Vessels). In December 1983, a data package was submitted to the Working Group on Materials Behavior (SG-ETD)(SC-D) Committee of the ASME BPV Code Section III (Nuclear Power Plant Components) for consideration. A revised data package was then submitted in December 1984, but there has been no ASME action on Section III to date.

STATUS OF WORK BY OUTSIDE ORGANIZATIONS

As discussed earlier, the overall strategy for developing modified 9Cr-1Mo steel has been based on Code approval and commercial acceptance. The LMFBR Base Technology Program has funded the participation of several industries and national laboratories, and data produced from these efforts are documented in a series of 13 periodic progress reports and 10 topical reports, which are listed in the Bibliography of this document.

National laboratories included ORNL, Argonne National Laboratory (ANL), and Hanford Engineering Development Laboratory (HEDL). The facilities and staff of lead reactor manufacturers such as Westinghouse Electric Corporation, General Electric Company, Rockwell International, and Combustion Engineering, Inc., under DOE contract also contributed to the data base. In order to establish an experienced industrial base the program began procurement of the important product forms as soon as the reference specification was established.

Approximately 200 tons of steel have been melted (some of which was later remelted) by several companies including Quaker [argon oxygen decarburization (AOD)], Cartech [electric furnace/electroslag remelt (EF/ESR) and AOD], Electralloy (AOD and AOD/ESR), Combustion Engineering [air induction (AI)], National Forge Company (AOD/ESR), and Special Metals (AOD/ESR).

The Timken Company (AOD), Sumitomo [vacuum induction melting (VIM)], and Nippon Kokan K. K. (VIM) melted material with company funds. The material was made available to the program on a no-cost basis. Information generated by ORNL was then provided to the contributors of the materials.

Wrought products were fabricated from these heats by several companies including Jessop (plates), Cartech (bars), AMAX (tubes), Combustion Engineering (tubes), Timken (tubes), National Forge (forgings), Bethlehem (bar), Phoenix (pipe), Universal Cyclops (plates and bar), and Atlas Foundries (sand castings). Sumitomo (Japan), Nippon Kokan K. K. (Japan), Tube Investments (U.K.), and Valourec (France) made tubes at their own expense. The tubes were made available for testing and evaluation without cost to the program.

These product forms were also made available on request to several other programs, industries, and universities. U.S. Department of Energy Fusion Energy, DOE Fossil Energy, and Nuclear Regulatory Commission programs supported work at national laboratories and universities. Several industrial organizations also expressed an interest in the alloy and used company funds to generate data and fabrication experience. The data were made available to ORNL in exchange for the material.

These contributors are identified by category in Appendixes A through G. Summaries of the work completed or under way are provided by status sheets compiled in those appendixes. (Note: Although the policy of ORNL is to report its work in SI metric units, Appendixes A through G of this report contain English units because some of the status sheets report work done by or for organizations that do not use SI units entirely. The SI equivalents of English units used in those appendixes are listed in Appendix H.)

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Appendix A

U.S. INDUSTRIES

Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed

Organization:

Babcock & Wilcox Company
20 S. Van Buren Avenue
Barberton, OH 44203

Contact:

George H. Harth
Product Line Manager
Fossil Plant Life Extension

Participation Basis: Company funds

Date Action Initiated: April 1982

Date Completed: In progress

Purpose: To conduct fabrication studies and determine mechanical properties of hot-bent tubes after various tempering treatments.

Material Produced or Supplied: ORNL supplied 2-in.-OD x 0.250-in.-wall tubes.

Status of Work Performed: In the first phase of work, the hot-bent tube was tensile tested in the as-bent condition and after heat treatments of 50 h at 1400°F, 25 h at 1400°F, 500 h at 1300°F, and 15 min at 2100°F. Tensile data obtained were compared on the basis of Larsen-Miller parameters, and a letter report was prepared.

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1. J. R. M. Smith, *Evaluation of Hot Bent 9Cr-1Mo Tube*, Babcock & Wilcox Reference No. 832-010210-03, Aug. 30, 1982.
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**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Cameron Iron Works, Inc.
Extruded Products
P.O. Box 1212
Houston, TX 77251

Contact:

Ward Harlan
Sales Representative

Participation Basis: Company funds

Date Action Initiated: June 1983

Date Completed: Work in progress

Purpose: To gain experience in forging a gate valve body from a modified 9Cr-1Mo steel billet and to characterize its mechanical properties.

Material Produced or Supplied: ORNL supplied a 7-7/8-in. (flat to flat) octagon end by 70-in.-long billet (CarTech heat 10148).

Status of Work Performed: Cameron forged a gate valve from the ORNL-supplied billet. The valve was normalized at 1040°C for 1 h followed by a temper at 760°C for 1 h. Cameron proposed to perform the following test program on this valve body:

1. Tensile tests at room temperature and at 350, 500, 750, 1000, 1100, 1200, and 1300°F from four different sections of the valve body.
2. Grain size on unstressed portions of tensile specimens from all different locations.
3. Hardness on specimens from various locations.
4. Charpy impact tests at six temperatures (to be selected by Cameron) on specimens from various locations.

Mechanical property characterization of the gate valve is continuing.

Reference: *Manufacturing Process Instructions*, Cameron Iron Works, Inc., Houston, interim report dated Jan. 16, 1984.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Cameron Iron Works, Inc.
Extruded Products
P.O. Box 1212
Houston, TX 77251

Contact:

Ward Harlan
Sales Representative

Participation Basis: Company funds

Date Action Initiated: March 1984

Date Completed: Work in progress

Purpose: To extrude a 10-ton modified 9Cr-1Mo alloy ingot into a large-diameter heavy-wall pipe for subsequent evaluation by ORNL, Cameron, and Babcock & Wilcox.

Material Produced or Supplied: ORNL supplied Cameron with one Electralloy (ORNL purchase order) 10-ton ingot, 28-in. diam $\times$ 100 in. long.

Status of Work Performed: Cameron will extrude the ingot into 23-in.-OD $\times$ 15-in.-ID (4-in.-wall) $\times$ 20-ft-long pipe. Portions will be evaluated by Cameron, Babcock & Wilcox, and ORNL, and the data will be shared.

Reference: Report to be prepared.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Chicago Bridge & Iron Company
8900 Fairbanks
North Houston Road
P.O. Box 40066
Houston, TX 77040

Contact:

J. E. Sims, Manager
Welding Research and Development

Participation Basis: ORNL purchase
order and company funds

Date Action Initiated: September 1982

Date Completed: December 1982

Purpose: To develop a welding procedure for submerged-arc welding of
thick modified 9Cr-1Mo alloy plates.

Material Produced or Supplied: ORNL supplied the following:

one plate 8 × 14 × 20 in.,
150 lb ER-505 weld wire,
150 lb Oerlikon OP-76 flux.

Status of Work Performed: A welding procedure was developed, and
essential variables were documented. Evaluation was conducted at ORNL.
All results were found acceptable.

Reference: Letter report, Russell Fuchs to J. W. Hendricks, *Welding
Procedure for Submerged-Arc Welding of Modified 9 Cr-1 Mo Alloy Plate*,
Chicago Bridge and Iron Company, Houston, Dec. 3, 1982.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Climax Molybdenum Company of Michigan
1600 Huron Parkway
Ann Arbor, MI 48106

Contact:

William C. Hagel, Manager
High Temperature Materials
Development

Participation Basis: Company funds**Date Action Initiated:** August 1981**Date Completed:** March 1982**Purpose:** To determine the dissolution temperature of (Nb,V) (C,N) in modified 9Cr-1Mo steel**Material Produced or Supplied:** ORNL supplied Climax with a 6-in. x 6-in. x 1-in. plate (CarTech HT 30394).**Status of Work Performed:** Small specimens of normalized and tempered plate were heated for 0.25 or 1.0 h at selected temperatures between 950 and 1100°C (1740 and 2010°F) and quenched in brine. By examination of extraction replicas, the dissolution temperature of the carbonitrides was found to be approximately 950°C (1740°F).**Reference:** V. Biss, *Dissolution Temperature of Carbonitrides in Modified 9Cr-1Mo Steel*, Report No. J-4747-01, Climax Molybdenum Company, Ann Arbor, Mich., March 23, 1982.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Climax Molybdenum Company of Michigan
1600 Huron Parkway
Ann Arbor, MI 48106

Contact:

William C. Hagel, Manager
High Temperature Materials
Development

Participation Basis: Company funds

Date Action Initiated: September 1981

Date Completed: April 1982

Purpose: To determine the sulfide stress cracking (SSC) resistance of Nb/V-modified 9Cr-1Mo steel tubing.

Material Produced or Supplied: The Timken Steel Company supplied Climax with the following material:

- two lengths 3-in.-OD $\times$ 0.460-in.-wall $\times$ 3-ft tubing (CarTech HT 30394),
- two lengths 3-in.-OD $\times$ 0.460-in.-wall $\times$ 3-ft tubing (CarTech HT 30182).

Status of Work Performed: The Nb/V-modified 9Cr-1Mo steel exhibits moderate SSC resistance in the bent beam and NACE tensile tests with critical stress and threshold stress values of 12×10^4 and 350 MPa (51 ksi), respectively. In the double cantilever beam tests, the steel shows relatively poor sulfide fracture toughness with average $K_{I_{SSC}}$ values of 16.1 and 14.8 MPa $\sqrt{m}$ (14.6 and 13.5 ksi $\sqrt{in.}$) for the two heats tested. A slight compositional dependence of the sulfide fracture toughness was found, the heat with higher molybdenum and silicon contents exhibiting the higher $K_{I_{SSC}}$ value. In the section sizes tested there was no difference in the resistance to SSC between normalized and tempered and oil quenched and tempered heat treatments.

It is likely that improvement in the relatively poor SSC resistance of the steel normalized at 955°C (1750°F) could be realized by increasing the normalizing temperature. Meeting the minimum yield strength of 550 MPa (80 ksi) and a maximum hardness of 22 HRC could be accomplished then by raising the tempering temperature, which also tends to improve sulfide fracture toughness.

Reference: E. J. Vineberg, *SSC Resistance of Nb/V Modified 9Cr-1Mo Steel*, Report No. J-4711, Climax Molybdenum Company, Ann Arbor, Mich., Apr. 20, 1982.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Climax Molybdenum Company of Michigan
1600 Huron Parkway
Ann Arbor, MI 48106

Contact:

William C. Hagel, Manager
High Temperature Materials
Development

Participation Basis: Company funds

Date Action Initiated: July 1981

Date Completed: March 1982

Purpose: Metallographic examination to be conducted on weldments of modified 9Cr-1Mo, 12Cr-1Mo (HT-9), and 2.25Cr-1Mo steels to determine the nature of softening in the heat-affected zones.

Material Produced or Supplied: ORNL supplied Climax with the following weldments:

- PC-45 Modified 9Cr-1Mo, 1 in. x 1 in. x 3.9 in. (CarTech Ht 30394);
- PC-32 Modified 9Cr-1Mo, 1 in. x 1.8 in. x 0.2 in. (CarTech Ht 30182);
- PC-36 Modified 9Cr-1Mo, 1.1 in. x 1.4 in. x 0.2 in. (CarTech Ht 30394);
- PC-49 Standard 9Cr-1Mo, 1.2 in. x 1.8 in. x 0.2 in.;
- PC-48 12Cr-1Mo (HT-9), 0.7 in. x 1.3 in. x 0.2 in.;
- PC-51 2.25Cr-1Mo, 0.8 in. x 1.4 in. x 0.2 in.

Status of Work Performed: The softening was found to be the lowest, 16 DPH points, in 2.25Cr-1Mo steel, and 26 to 27 DPH points in the 9Cr-1Mo steels. The softening was found to be caused by coarsening of carbides due to tempering by the heat from the welding process. The behavior is believed to be a normal process for steels welded by multipass processes. The 12Cr-1Mo (HT-9) steel exhibits a slight hardening in the heat-affected zone, probably due to additional precipitation of fine alloy carbides.

References: V. Biss, *Metallographic Investigation of Soft Regions Near Heat Affected Zones of Modified 9Cr-1Mo, HT-9 and 2.25Cr-1Mo Steel Weldments*, Report No. J-4747, Climax Molybdenum Company, Ann Arbor, Mich., Mar. 8, 1982.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

National Forge Company
Irvine, PA 16323

Contact:

A. K. Khare
Senior Metallurgist

Participation Basis: Company funds

Date Action Initiated: January 1984

Date Completed: August 1984

Purpose: To evaluate properties of a heavy-wall forged pipe of modified 9Cr-1Mo alloy (ASTM A182-F91).

Material Produced or Supplied: ORNL supplied a 30-in.-OD $\times$ 6-in.-wall $\times$ 6-in.-long segment of a forged pipe.

Status of Work Performed: A 30-in.-OD $\times$ 18-in.-ID (6-in.-wall) $\times$ 30-in.-long pipe was forged (ORNL purchase order) from a 5-ton Electralloy ingot. A 6-in. segment was retained for mechanical properties determination by National Forge Company, with remainder shipped to ORNL. Mechanical properties testing included through-thickness tensile tests at room temperature to 1200°F, Charpy V-notch impact, elevated-temperature creep rupture to 3000 h to 1200°F, fracture toughness (J_{1c}), and fatigue crack-growth tests.

References:

1. Letter report, A. J. Laporte to P. Patriarca, Jan. 23, 1984, *Test Matrix for Evaluation of F91 Forging*.
2. V. K. Sikka and A. K. Khare, *Fabrication and Mechanical Properties of a Modified 9Cr-1Mo Alloy (ASTM A182-F91) Forging*, paper presented at the ASTM Forging Conference, Williamsburg, Va., Nov. 20-30, 1984.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Nooter Corporation
125 Rutger Street
St. Louis, MO 63166

Contact:

Maan Jawad, Manager
Engineering Design

Participation Basis: ORNL purchase
order and company funds

Date Action Initiated: October 1983

Date Completed: December 1983

Purpose: To demonstrate the commercial feasibility of backside welding of tube-to-tubesheet joints and to evaluate the strength of such joints in accordance with the ASME BPV Code Section VIII, Div. 1, Appendix A.

Material Produced or Supplied: ORNL supplied Nooter Corporation with the following material:

24-in. × 36-in. × 1-in. plate,
18-in. × 24-in. × 2-in. plate,
0.75-in.-OD × 0.072-in.-wall × 6-in.-long tubing (20 ft),
1/8-in.-diam weld wire (60 lb).

Status of Work Performed: Autogenous backside welding of tube-to-tubesheet joints was demonstrated to be feasible and economical. Welding procedures were developed and evaluated by metallography, Rockwell A hardness traverses, and tensile tests.

Reference: *Tube-to-Tubesheet Backside Welding for Modified 9 Cr-1 Mo Steel*, Nooter Corporation, St. Louis, December 1983.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Rockwell International
Rocketdyne Division
8900 DeSoto Avenue
Canoga Park, CA 91304

Contact:

W. J. Roberts, Director
Engineering and Tests

Participation Basis: Company funds

Date Action Initiated: September 1981

Date Completed: May 1982

Purpose: To develop boreside welding procedures for LMFBR steam generator using CRBRP hockey stick fabrication equipment and technology.

Material Produced or Supplied: ORNL supplied Rockwell with the following material:

four 1-in. × 6-in. × 12-in. plates,
one 1-in. × 0.110-in.-wall × 10-ft tube.

Status of Work Performed: The in-bore tube-to-tube welding program utilizing 1-in.-diam modified 9Cr-1Mo tubing and the equipment and practices of autogenous gas tungsten arc welding of the LMFBR tube-to-tubesheet applications generated a total of 14 welds. At the completion of Weld 10, weld parameters were selected for use on the remaining four welds. The final welds were subjected to metallographic examination, Rockwell DPH traverses, and tensile tests. Radiographic examination was conducted in accordance with the ASME Boiler and Pressure Vessel Code Section III requirements and destructively tested in accordance with Section IX. The results show that the modified 9Cr-1Mo material is readily weldable to ASME Code requirements.

Reference: F. R. Koepenick, *Welding of Modified 9Cr-1Mo Steel Tubes*, Report No. N100T1330003, Rockwell International, Energy Systems Group, Canoga Park, Calif., May 12, 1982 (proprietary).

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Struthers Wells Corporation
1003 Pennsylvania Avenue, West
Warren, PA 16365

Contact:

H. C. Rauschenplat
Chief Mechanical Engineer and
Consultant

Participation Basis: ORNL purchase
order and company funds

Date Action Initiated: April 1982

Date Completed: March 1983

Purpose: To qualify shielded-metal-arc (SMA) welding procedure for
modified 9Cr-1Mo alloy.

Material Produced or Supplied: ORNL supplied the following:

four plates, 1 x 6 x 12 in. (heat 30176);
four plates, 1 x 6 x 12 in. (heat 30394).

Struthers Wells Corporation supplied ER-505 coated electrodes.

Status of Work Performed: A multipass SMA welding procedure was developed and the essential variables documented. The weldment was evaluated in accordance with the ASME BPV Code Section IX including room-temperature tensile strength, yield strength, percent elongation, and reduction in area. Charpy V-notch tests were conducted on the weld and heat-affected zones. Rockwell "B" hardness surveys were also performed. No problems were encountered, and all tests were positive and acceptable.

Reference: R. J. Root, *Welding Procedure for Joining - P #5 Material 9% Chrome - 1% Mo by the Shielded Metal Arc Weld Manual Process*, letter report, Struthers Wells Corporation, Warren, Pa., Mar. 11, 1983.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Struthers Wells Corporation
1003 Pennsylvania Avenue, West
Warren, PA 16365

Contact:

H. C. Rauschenplat
Chief Mechanical Engineer and
Consultant

Participation Basis: ORNL purchase
order and company funds

Date Action Initiated: October 1982

Date Completed: February 1983

Purpose: To qualify submerged-arc (SA) welding procedure for
modified 9Cr-1Mo alloy.

Material Produced or Supplied: ORNL supplied the following:

four plates, 2 in. x 6 in. x 17.5 in.;
100 lb Oerlikon OP-76 flux.

Struthers Wells Corporation supplied ER-505 weld wire.

Status of Work Performed: A multipass SA welding procedure was developed and the essential variables documented. The weldment was evaluated in accordance with the ASME BPV Code Section IX including room-temperature tensile strength, yield strength, percent elongation, and reduction in area. Charpy V-notch tests were conducted on the weld and heat-affected zones. Rockwell "B" hardness surveys were also performed. No problems were encountered, and all tests were positive and acceptable.

Reference: R. J. Root, *Welding Procedure for Joining - P #5 Material 9% Chrome - 1% Mo by the Submerged Arc Weld Automatic Process*, letter report, Struthers Wells Corporation, Warren, Pa., Feb. 14, 1983.

Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed

Organization:

The Timken Company
Canton, OH 44706

Contact:

Tom Burnstad, Manager
Tube Sales
Steel Division

Participation Basis: Company funds

Date Action Initiated: January 1982

Date Completed: In progress

Purpose: To gain experience in fabricating tubes out of the supplied bar stock and to conduct corrosion tests for the use of modified 9Cr-1Mo steel in deep oil well applications.

Material Produced or Supplied: six pieces of 4-1/8-in.-diam × 120-in.-long bar stock.

Status of Work Performed: Tubes were made successfully. Several of the tubes were supplied to Babcock & Wilcox for their welding program. Other tubes are being used for corrosion tests.

Reference: A report is in preparation.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

The William Powell Company
2503 Spring Grove Avenue
Cincinnati, OH 45214

Contact:

Steve Fogle
Laboratory Manager

Participation Basis: Company funds

Date Action Initiated: January 1982

Date Completed: April 1982

Purpose: To evaluate the properties of modified 9Cr-1Mo steel for possible use as valve stem material for sodium pumps.

Material Produced or Supplied: ORNL supplied The William Powell Company with a bar of modified 9Cr-1Mo steel, 1 1/4 in. diam x 25 in. long (heat 10148).

Status of Work Performed: Standard comparative tests were conducted on stems fabricated from modified 9Cr-1Mo and types 303, 316, 316B, and A286 stainless steel. Powell concluded on the basis of the results that modified 9Cr-1Mo was an excellent material for the stem application.

Reference: Minutes of meeting between Rockwell and Powell held at Powell on Apr. 6, 1982, *2 Inch Valve Stem Failure Review*, Powell Transmittal No. 576.

Appendix B

U.S. UTILITIES

Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed

Organization:

American Electric Power Service Corp.
P.O. Box 487
Canton, OH 44701

Contact:

P. E. Haas
Manager, Metals Processing

Participation Basis: Company funds

Date Action Initiated: April 1981

Date Completed: In progress

Purpose: To evaluate the performance of modified 9Cr-1Mo tubes in the Tanners Creek Unit 3 plant (fossil fired) of the American Electric Power (AEP) Service Corporation operating at 593°C (1100°F).

Material Produced or Supplied: ORNL supplied ten tubes, 2.5 in. OD × 0.375 in. wall × 10 ft long.

Status of Work Performed: Combustion Engineering, Inc., attached (ORNL subcontract) type 304 stainless steel safe ends to five of the modified 9Cr-1Mo steel tubes, and AEP completed installation of the test panel in April 1981.

Reference: Letter, G. C. Bodine, Combustion Engineering, Inc., to P. Patriarca, ORNL, June 18, 1982, subject, "Transmittal of Modified 9 Cr-1 Mo Steel Tubes."

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Detroit Edison
2000 Second Avenue
Detroit, MI 48226

Contact:

John E. Schaefer
Principal Engineer

Participation Basis: Company funds

Date Action Initiated: February 1981

Date Completed: In progress

Purpose: To evaluate the use of modified 9Cr-1Mo steel tubes in the St. Clair Unit 2 plant (fossil fired) of Detroit Edison operating at 538°C (1000°F).

Material Produced or Supplied: ORNL supplied two tubes, 2.25 in. OD × 0.290 in. wall × 5 ft long.

Status of Work Performed: Combustion Engineering, Inc., attached (ORNL subcontract) SA213-T9 safe ends to the modified 9Cr-1Mo steel tubes, and Detroit Edison completed installation of the test panel in February 1981.

Reference: Letter, G. C. Bodine, Combustion Engineering, Inc., to P. Patriarca, ORNL, June 18, 1982, "Transmittal of Modified 9Cr-1Mo Steel Tubes."

Appendix C

U.S. UNIVERSITIES

Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed

Organization:

Department of Materials Science
and Engineering
Iowa State University
Ames, IA 50011

Contact:

Prof. O. N. Carlson

Participation Basis: DOE-University

Date Action Initiated: November 1980

Date Completed: June 1983

Purpose: To study the effects of composition and thermal treatment on the bend ductility-transition temperature (BD-TT) of 9Cr-1Mo ferritic steel.

Material Produced or Supplied: ORNL supplied minimal quantities of plates of several commercial heats of modified 9Cr-1Mo steel for graduate-student research projects.

Status of Work Performed: The effect of minor alloy additions or impurities on the ductility of 9Cr-1Mo steel with different thermal treatments was investigated by use of a slow four-point bend test on small notched specimens. The specimens were tested in both the tempered and aged conditions. The change in the BD-TT resulting from changes in composition was determined for both the tempered and aged conditions. Comparative tests were carried out on the ASTM A200 Grade T9 alloy, on a high-purity 9Cr-1Mo base alloy containing controlled individual additions of C, Si, Ni, and Mn, and on modified 9Cr-1Mo of two different Si levels.

Reference: O. N. Carlson and H. Indrawirawan, "Effects of Composition and Thermal Treatment on BD-TT of 9 Cr-1 Mo Ferritic Steels," published in the *Proceedings of the Topical Conference on Ferritic Alloys for Use in Nuclear Technologies, Snowbird, Utah, June 19-23, 1983*, ed. J. W. Davis and D. J. Michel, The Metallurgical Society of AIME, Warrendale, Pa., 1984.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Department of Materials Science
and Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

Contact:

Prof. J. Megusar

Participation Basis: DOE Fusion Energy

Date Action Initiated: June 1981

Date Completed: In progress

Purpose: To study the rapid solidification of 9Cr-1Mo and 2.25Cr-1Mo ferritic steels.

Material Produced or Supplied: ORNL supplied minimal quantities of plates of several commercial heats of modified 9Cr-1Mo steel for graduate-student research projects.

Status of Work Performed: Rapidly solidified foils of 9Cr-1Mo and 2.25Cr-1Mo steels were prepared by melt spinning, with an estimated cooling rate of 10^6 K/sec. The foils were used for structural and mechanical testing. The kinetics for phase transformation were found to be the same for the ingot material and rapidly solidified material. Microstructural studies of rapidly solidified foils have been completed and presented in the paper.

Reference: J. Megusar, D. Imerson, W. Ibrahim, and N. J. Grant, "Rapid Solidification of 9 Cr-1 Mo and 2 1/4 Cr-1 Mo Ferritic Steels," published in the *Proceedings of the Topical Conference on Ferritic Alloys for Use in Nuclear Technologies, Snowbird, Utah, June 19-23, 1983*, ed. J. W. Davis and D. J. Michel, The Metallurgical Society of AIME, Warrendale, Pa., 1984.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Department of Materials Science
and Engineering
Northwestern University
Evanston, IL 60201

Contact:

Prof. J. R. Weertman

Participation Basis: DOE Basic Energy Sciences

Date Action Initiated: August 1981

Date Completed: In progress

Purpose: To study the microstructural changes in modified 9Cr-1Mo steel by using small-angle neutron scattering.

Material Produced or Supplied: ORNL supplied minimal quantities of plates of several commercial heats of modified 9Cr-1Mo steel for graduate-student research projects.

Status of Work Performed: Small-angle neutron scattering (SANS) was used to study the microstructural changes in modified 9Cr-1Mo between the normalized and tempered condition; material aged for 5000 h at 482, 538, 593, 649, and 704°C; material crept for 21,028 h at 649°C; material fatigued at 649°C up to 10,000 cycles; and material fatigued at 649°C up to 7930 cycles with 305 tension holds. The major microstructural changes produced by high-temperature exposure were identified as carbide coarsening, subgrain development, and reduction in dislocation density.

Reference: S. Kim, J. R. Weertman, S. Spooner, C. J. Glinka, V. K. Sikka, and W. B. Jones, "Microstructural Evaluation of a Ferritic Steel by Small-Angle Neutron Scattering," presented at the American Society for Metals Congress, Oct. 2-6, 1983, Philadelphia.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Department of Materials Science and
Materials Research Center
Northwestern University
Evanston, IL 60201

Contact:

Prof. J. R. Weertman

Participation Basis: DOE Basic
Energy Sciences

Date Action Initiated: August 1981

Date Completed: In progress

Purpose: To study the mechanical and microstructural behavior of modified 9Cr-1Mo steel under high-temperature cycling.

Material Produced or Supplied: ORNL supplied minimal quantities of plates of several commercial heats of modified 9Cr-1Mo steel for graduate-student research projects.

Status of Work Performed: Work is under way to conduct fatigue and creep-fatigue tests on unaged and aged specimens of modified 9Cr-1Mo steel. Tested specimens were examined with electron microscopy. Several environments were used in this test program.

Reference: S. Matsuoka, S. Kim, and J. R. Weertman, "Mechanical and Microstructural Behavior of a Ferritic Stainless Steel under High-Temperature Cycling," published in the *Proceedings of the Topical Conference on Ferritic Alloys for Use in Nuclear Technologies, Snowbird, Utah, June 19-23, 1983*, ed. J. W. Davis and D. J. Michel, The Metallurgical Society of AIME, Warrendale, Pa., 1984.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Metallurgy Department
University of Connecticut
Storrs, CT 06268

Contact:

Prof. A. J. McEvily

Participation Basis: University funds

Date Action Initiated: March 1980

Date Completed: In progress

Purpose: To study the influence of processing on elevated-temperature low-cycle fatigue properties of modified 9Cr-1Mo steel.

Material Produced or Supplied: ORNL supplied minimal quantities of plates of several commercial heats of modified 9Cr-1Mo steel for graduate-student research projects.

Status of Work Performed: Strain-controlled fatigue tests were performed at 538°C on hot-forged and hot-rolled base metal plates and on an electron-beam (EB) welded plate. Fatigue-tested specimens were subjected to extensive microstructural analysis. The hot-rolled material was found to have better fatigue-life resistance than hot-forged material. The fatigue life of EB welded specimens was the same as that of hot-rolled material up to 10⁶ cycles.

Reference: Gunter Ebi, "Influence of Processing on Elevated-Temperature Low-Cycle Fatigue Properties of a 9 Cr-1 Mo Steel," Master's Thesis, University of Connecticut, June 1982.

Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed

Organization:

Corrosion Research Center
University of Minnesota
Minneapolis, MN 55455

Contact:

Prof. Yang Ki Hong

Participation Basis: University funds

Date Action Initiated: August 1982

Date Completed: In progress

Purpose: To study the effect of gamma radiation on the corrosion of 9Cr-1Mo ferritic stainless steel in deionized water and chloride-ion-containing solution.

Material Produced or Supplied: ORNL supplied minimal quantities of plates of several commercial heats of modified 9Cr-1Mo steel for graduate-student research projects.

Status of Work Performed: Experiments involving anodic electrochemical polarization and open-circuit potential measurements were conducted on modified 9Cr-1Mo steel in Cs¹³⁷ radioactive source providing a radiation dose rate of 7×10^5 rad/h and in the absence of radiation. The electrolytes for these purposes were deionized water and the various concentrations of chloride ion. Various tools were used to perform surface analysis of these specimens. A paper was prepared describing the influence of gamma-radiation pitting corrosion, open circuit potential, and oxide-film change.

Reference: Yang Ki Hong, "The Effect of γ -Radiation on the Corrosion of 9Cr-1Mo Ferritic Stainless Steel in Deionized Water and Chloride-Ion Containing Solution," published in the *Proceedings of the Topical Conference on Ferritic Alloys for Use in Nuclear Technologies, Snowbird, Utah, June 19-23, 1983*, ed. J. W. Davis and D. J. Michel, The Metallurgical Society of AIME, Warrendale, Pa., 1984.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Department of Chemical, Metallurgical
and Polymer Engineering
University of Tennessee
Knoxville, TN 37996-2200

Contact:

Prof. C. D. Lundin

Participation Basis: DOE Fossil Energy

Date Action Initiated: January 1980

Date Completed: In progress

Purpose: To investigate the transformational characteristics and weldability of modified 9Cr-1Mo steel.

Material Produced or Supplied: ORNL supplied minimal quantities of plates of several commercial heats of modified 9Cr-1Mo steel for graduate-student research projects.

Status of Work Performed: Transformational characteristics, cold-cracking sensitivity, and stress-relief cracking sensitivity of several heats of modified 9Cr-1Mo steel were investigated. Results were compared with those on 2.25Cr-1Mo, 9Cr-1Mo, and HT9 steels. Microstructural work was carried out to understand the observed response.

Reference: M. W. Richey, "The Weldability of Cr-Mo Steels for Fossil Energy Applications," Master's Thesis, University of Tennessee, June 1984.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Department of Metallurgy and
Metallurgical Engineering
University of Utah
Salt Lake City, UT 84112

Contact:

Prof. C. H. Pitt

Participation Basis: Utah Energy Consortium**Date Action Initiated:** September 1979**Date Completed:** In progress

Purpose: To study the corrosion behavior of selected metal alloys in Utah geothermal waters.

Material Produced or Supplied: ORNL supplied minimal quantities of plates of several commercial heats of modified 9Cr-1Mo steel for graduate-student research projects.

Status of Work Performed: A potentiodynamic polarization technique was applied to characterize the corrosion behavior of type 316L, modified 9Cr-1Mo steel, Inconel 625, and mild steel in Utah geothermal waters. The effect of temperature on pitting potential and corrosion rate was measured. Corrosion rate for the selected metal alloys was affected greatly by temperature. The pitting potentials decreased with increasing temperature. The paper gives measurements of corrosion rate, pit density, maximum pit depth, and polarization resistance.

Reference: Y. K. Hong and C. H. Pitt, "Corrosion of Selected Metal Alloys in Utah Geothermal Waters," *J. Mater. Energy Systems* 5(2), 77-83 (September 1983).

Appendix D

U.S. NATIONAL LABORATORIES

Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed

Organization:

Materials Science and Technology
Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

Contact:

O. K. Chopra
Senior Metallurgist

Participation Basis: DOE Fusion Energy

Date Action Initiated: January 1981

Date Completed: In progress

Purpose: To study the compatibility of ferritic steels with sintered Li_2O pellets in a flowing helium environment.

Material Produced or Supplied: ORNL supplied minimal quantities of plates of several commercial heats of modified 9Cr-1Mo steel.

Status of Work Performed: The interaction between sintered Li_2O pellets and ferritic HT9 alloy and modified 9Cr-1Mo steel was investigated at 550°C in a flowing helium environment containing known amounts of moisture and hydrogen. Alloy specimens, approximately $10 \times 10 \times 0.4$ mm in size, were sandwiched between two pellets of Li_2O about 2.4 mm thick and mounted in a specimen holder such that the surfaces of the ceramic pellets were exposed to the flowing gas environment. A separate nickel foil (without Li_2O pellets) was placed downstream from the couples to study the deposition behavior. The results indicated that both ferritic steels develop a uniform scale that consists of an iron-rich outer layer and a chromium-rich subscale.

Reference: O. K. Chopra, T. Kurasawa, and D. L. Smith, "Compatibility of Ferritic Steels with Sintered Li_2O Pellets in a Flowing Helium Environment," published in the *Proceedings of the Topical Conference on Ferritic Alloys for Use in Nuclear Technologies Snowbird, Utah, June 19-23, 1983*, ed. J. W. Davis and D. J. Michel, The Metallurgical Society of AIME, Warrendale, Pa., 1984.

Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed

Organization:

Hanford Engineering Development
Laboratory
P. O. Box 1970
Richland, WA 99352

Contact:

D. S. Gelles
Senior Metallurgist

Participation Basis: DOE Fusion Energy

Date Action Initiated: January 1981

Date Completed: In progress

Purpose: To study the fracture behavior of unirradiated HT9 and modified 9Cr-1Mo welds.

Material Produced or Supplied: ORNL supplied minimal quantities of plates of several commercial heats of modified 9Cr-1Mo steel.

Status of Work Performed: Fracture toughness tests on HT9 weld and heat-affected-zone samples and on modified 9Cr-1Mo weld samples were performed at 93, 205, 427, and 538°C. In this work, circular compact tension specimens were fabricated from these welds with notch orientation parallel to the fusion line. It was shown that the toughness of HT9 and 9Cr-1Mo was not significantly reduced by welding. However, the bearing modulus of the welds was lower than that of the base metal, indicating that the alloys become less resistant to crack propagation as a result of welding.

Reference: F. H. Huang and D. S. Gelles, "Fracture Behavior of Unirradiated HT9 and Modified 9 Cr-1 Mo Welds," published in the *Proceedings of the Topical Conference on Ferritic Alloys for Use in Nuclear Technologies, Snowbird, Utah, June 19-23, 1983*, ed. J. W. Davis and D. J. Michel, Metallurgical Society of AIME, Warrendale, Pa., 1984. Metallurgical Society of AIME, New York.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Hanford Engineering Development
Laboratory
P.O. Box 1970
Richland, WA 99352

Contact:

D. S. Gelles
Senior Metallurgist

Participation Basis: DOE Fusion Energy

Date Action Initiated: January 1980

Date Completed: In progress

Purpose: To study the microstructure of HT9 and modified 9Cr-1Mo steel specimens irradiated in EBR-II.

Material Produced or Supplied: ORNL supplied minimal quantities of plates of several commercial heats of modified 9Cr-1Mo steel.

Status of Work Performed: The microstructures of HT9 and modified 9Cr-1Mo were examined before and after irradiation in EBR-II to a fluence of 2.5×10^{22} n/cm² at temperatures from 400 to 500°C. The precipitate structure of unirradiated HT9 consists of M₂₃C₆, which forms at martensite lath and prior austenite grain boundaries. The 9Cr-1Mo shows much less M₂₃C₆ at grain boundaries, but it contains finely dispersed (Nb,V,Cr)C within grains.

Reference: D. S. Gelles and L. E. Thomas, "Microstructural Examination of HT9 and 9Cr-1Mo Contained in the AD-2 Experiment," pp. 343-61 in *Alloy Development for Irradiation Performance, Semiannual Progress Report for Period Ending March 31, 1982*, DOE/ER-0045,'8, September 1982.

Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed

Organization:

Hanford Engineering Development
Laboratory
P.O. Box 1970
Richland, WA 99325

Contact:

D. S. Gelles
Senior Metallurgist

Participation Basis: DOE Fusion Energy

Date Action Initiated: January 1980

Date Completed: In progress

Purpose: To provide fractographic data for Charpy specimens of the irradiated ferritic alloys HT9 and modified 9Cr-1Mo in order to provide improved understanding of toughness degradation as a result of irradiation for the ferritic alloy class.

Material Produced or Supplied: ORNL supplied minimal quantities of plates of several commercial heats of modified 9Cr-1Mo steel.

Status of Work Performed: Fracture surface topologies were examined by scanning electron microscopy for 20 selected half-sized Charpy impact specimens of HT9 and modified 9Cr-1Mo steel. Specimens were irradiated in EBR-II at 390, 450, 500, and 550°C. Results showed that irradiation hardening due to G-phase formation at 390°C was responsible for a large shift in the ductile-to-brittle transition temperature (DBTT) in HT9. At higher temperatures delta-ferrite was responsible for reduction in DBTT. Reduction in toughness as a consequence of irradiation in modified 9Cr-1Mo was attributed to in-reactor precipitation of (V,Nb)C and $M_{23}C_6$.

Reference: D. S. Gelles and W. L. Hu, "Fractographic Examination of HT9 and 9 Cr-1 Mo Charpy Specimens Irradiated in A0-2 Test," pp. 178-219 in *Alloy Development for Irradiation Performance, Semiannual Progress Report for Period Ending September 30, 1982*, DOE/ER-0045/9, February 1983.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Hanford Engineering Development
Laboratory
P.O. Box 1970
Richland, WA 99352

Contact:

W. L. Hu
Senior Metallurgist

Participation Basis: DOE Fusion Energy

Date Action Initiated: January 1980

Date Completed: In progress

Purpose: To conduct Charpy impact tests on HT9 and modified 9Cr-1Mo specimens irradiated in EBR-II to determine the effect of neutron irradiation.

Material Produced or Supplied: ORNL supplied minimal quantities of plates of several commercial heats of modified 9Cr-1Mo steel.

Status of Work Performed: Charpy impact tests were conducted at temperatures from -65 to 250°C on specimens of HT9 and 9Cr-1Mo steels irradiated in EBR-II to a peak exposure of about 13 dpa at temperatures of 390, 450, 500, and 550°C. Results showed lowering of upper-shelf energy and an upward shift of DBTT due to irradiation.

Reference: W. L. Hu, "Miniature Charpy-Impact Test Results for Irradiated Ferritic Alloys," pp. 255-71 in *Alloy Development for Irradiation Performance, Semiannual Progress Report for Period Ending March 31, 1982*, DOE/ER-0045/8, September 1982.

Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed

Organization:

Metals and Ceramics Division
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, TN 37831

Contact:

R. L. Klueh
Senior Metallurgist

Participation Basis: DOE Fusion Energy

Date Action Initiated: January 1981

Date Completed: In progress

Purpose: Nickel-doped ferritic (martensitic) steels for fusion reactor irradiation studies: tempering behavior and unirradiated and irradiated tensile properties.

Material Produced or Supplied: ORNL supplied minimal quantities of plates of several commercial heats of modified 9Cr-1Mo steel.

Status of Work Performed: Heats of modified 9Cr-1Mo and HT9 were irradiated in the High-Flux Isotope Reactor (HFIR) at about 50°C. The modified 9Cr-1Mo was tensile tested at room temperature and at 300°C. For the 9Cr-1Mo steel, irradiation at 50°C resulted in an increase in yield and ultimate tensile strength at both test temperatures. The increased strength was accompanied by decreased ductility. These effects were attributed to irradiation hardening that resulted from displacement damage.

References: R. L. Klueh, J. M. Vitek, and M. L. Grossbeck, "Nickel-Doped Ferritic (Martensitic) Steels for Fusion Reactor Irradiation Studies: Tempering Behavior and Unirradiated and Irradiated Tensile Properties," in *Effects of Radiation on Materials*, proceedings of the Eleventh International Symposium, Scottsdale, Arizona, June 28-30, 1982, ed. H. R. Brager and J. S. Perrin, ASTM STP 782, American Society for Testing and Materials, Philadelphia, 1982.

Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed

Organization:

Metals and Ceramics Division
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, TN 37831

Contact:

R. L. Klueh
Senior Metallurgist

Participation Basis: DOE Fusion Energy

Date Action Initiated: January 1981

Date Completed: 1983

Purpose: To study the tensile properties of ferritic steels (2.25Cr-1Mo, 9Cr-1Mo, and HT9) after low-temperature irradiation.

Material Produced or Supplied: ORNL supplied minimal quantities of plates of several commercial heats of modified 9Cr-1Mo steel.

Status of Work Performed: The irradiated tensile properties of 9Cr-1Mo and HT9 were determined along with those 2.25Cr-1Mo and 20% cold-worked type 316 stainless steel. All steels were irradiated at about 55°C to about 1.3×10^{26} n/cm². Tensile tests were conducted at room temperature and at 300°C. Results indicated that irradiated tensile properties of 2.25Cr-1Mo, modified 9Cr-1Mo, and HT9 were similar and comparable to those of 20% cold-worked type 316 stainless steel.

Reference: R. L. Klueh and J. M. Vitek, "Tensile Properties of Three Commercial Ferritic Steels After Low-Temperature Irradiation," published in the *Proceedings of the Topical Conference on Ferritic Alloys for Use in Nuclear Technologies, Snowbird, Utah, June 19-23, 1983*, ed. J. W. Davis and D. J. Michel, The Metallurgical Society of AIME, Warrendale, Pa., 1984.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185

Contact:

W. B. Jones
Senior Metallurgist

Participation Basis: Nuclear Regulatory Commission

Date Action Initiated: December 1980

Date Completed: October 1981

Purpose: To study the effects of mechanical cycling on the substructure of modified 9Cr-1Mo steel.

Material Produced or Supplied: ORNL supplied minimal quantities of plates of several commercial heats of modified 9Cr-1Mo steel.

Status of Work Performed: Transmission electron microscopy was used to study the microstructure of fatigue and creep-fatigue tested specimens of modified 9Cr-1Mo steel. Results showed that a 1000-h exposure at 538°C produced little change in microstructure. However, cycling at the same temperature rearranged the microstructure to equiaxed subgrains with large MC and $M_{23}C_6$ carbides. At this point, the strengthening mechanism was suggested to occur by solid-solution strengthening.

Reference: W. B. Jones, "Effects of Mechanical Cycling on the Substructure of Modified 9 Cr-1 Mo Ferritic Steel," pp. 221-35 in *Ferritic Steels for High-Temperature Applications*, proceedings of ASM International Conference on Production, Fabrication, Properties, and Applications, Warren, Pa., October 6-8, 1981, A. K. Khare, ed., American Society for Metals, Metals Park, Ohio, 1983.

Appendix E

FOREIGN INDUSTRIES

Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed

Organization:

Novatome
La Boursidiere-R.N. 186
92357 Le Plessis-Robinson Cedex
France

Contact:

A. Gelpi
Senior Structural Designer

Participation Basis: Company funds

Date Action Initiated: May 1984

Date Completed: In progress

Purpose: To evaluate properties of a heavy-wall forged pipe of modified 9Cr-1Mo alloy (ASTM A182-F91).

Material Produced or Supplied: ORNL supplied one quadrant of a 30-in.-OD x 6-in.-wall x 6-in.-long segment of a forged pipe.

Status of Work Performed: The forging was evaluated in accordance with a test matrix that included hardness, tensile, creep, fatigue, toughness, fracture mechanics, stress corrosion, aging, and welding studies.

Reference: Letter, A. Gelpi, Novatome, to P. Patriarca, ORNL, "Test Matrix for Modified 9Cr-1Mo Steel. National Forge Company Forging," June 14, 1984.

Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed

Organization:

Vallourec
Recherches et Developpement
Aciers Speciaux
21500 Montbard
France

Contact:

D. Vuillaume
Senior Scientist

Participation Basis: Company funds

Date Action Initiated: February 1984

Date Completed: In progress

Purpose: To compare fabrication and mechanical properties of T91 (U.S.), EM12 (French), and X20 (German) tubes for fossil-energy boiler applications.

Material Produced or Supplied: ORNL supplied one hexagonal billet (heat 10148) 7 3/4 in. x 70 in. long.

Status of Work Performed: Vallourec has extruded the T91 billet along with similar billets of EM12 and X20 into tubes 2-in. OD x 40-in. wall x 20-ft lengths. Two lengths of tubes of each grade are to be evaluated by ORNL and Vallourec and the results shared.

Reference: Letter, D. Vuillaume, Vallourec, to V. K. Sikka, ORNL, "Test Matrix for Comparative Evaluation of T91, EM12, and X20 Tubes," Feb. 10, 1984.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

NIRA S.p.A.
Largo Renzo Tasselli - Via del
Pescatori 35
16129 Genova (Italia)
Casella Postale N. 1166 - 16100 Genova
Italy

Contact:

Salvatore Di Leo
Director

Unita Techiche Specialistiche

Participation Basis: Company funds

Date Action Initiated: July 1983

Date Completed: In progress

Purpose: To determine weldability and properties of tube-tubesheet joints of modified 9Cr-1Mo, T91, and F91 steel.

Material Produced or Supplied: ORNL supplied the following:

one quadrant of 30-in.-OD $\times$ 6-in.-wall $\times$ 6-in.-long segment of a
forged pipe,
one tube 0.75-in. OD $\times$ 0.1-in. wall $\times$ 7 ft long.

Status of Work Performed: The forging and tubes have been received at NIRA, and specimen preparation is in progress.

Reference: Letter, S. Di Leo, NIRA, to P. Patriarca, ORNL, "Request for Forging and Tube Materials for Welding Program," Mar. 23, 1984.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Mitsubishi Heavy Industries, Ltd. (MHI)
5-1 Marunouchi 2 Chome
Chiyoda-Ku
Tokyo, Japan

Contact:

H. Haneda, Manager
Boiler Development Group

Participation Basis: Company funds

Date Action Initiated: June 1982

Date Completed: March 1983

Purpose: To conduct welding studies on modified 9Cr-1Mo steel tube and plate.

Material Produced or Supplied: Material supplied by Sumitomo. Weld wire and coated electrodes of modified 9Cr-1Mo steel were supplied by Combustion Engineering, Inc., Chattanooga, Tennessee.

Status of Work Performed: MHI of Japan is very interested in the use of modified 9Cr-1Mo (Super 9Cr-1Mo) steel in their supercritical plant. To become familiar with the material, they conducted welding studies. The specific studies described in report ML-1869 deal with the making and testing of tungsten inert gas (TIG) and shielded metal arc (SMA) welds. The TIG weld was made in a 1.2-in.-thick plate, and the SMA weld was in a 0.4-in.-thick tube. The TIG weld was subjected to post-weld heat treatment and to microhardness, bend, and Charpy impact testing. The tube weld by the SMA process was subjected to a room-temperature tensile test. The TIG weld passed all of the ASME BPV Code Section IX test requirements. The welded tube failed in the heat-affected zone during the tensile test. The fracture surface was examined by optical metallography and by scanning electron microscopy.

Reference: *Investigation Results of Welded Super 9Cr*, ML-1869, Mitsubishi Heavy Industries, Ltd., Tokyo, March 1983.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

NKK America Inc.
450 Park Avenue
New York, NY 10022

Contact:

Sotoaki Tokui
Vice President

Participation Basis: Company funds

Date Action Initiated: October 1981

Date Completed: March 1983

Purpose: To melt a 5-ton heat of modified 9Cr-1Mo steel, fabricate it into tube and plate, and perform mechanical property characterization on those products.

Material Produced or Supplied: NKK produced a 5-ton heat and fabricated the following:

2.0-in.-OD $\times$ 0.25-in.-wall $\times$ 13.3-ft tube,
3.0-in.-OD $\times$ 0.50-in.-wall $\times$ 10.0-ft tube,
10.4-in.-OD $\times$ 1.0-in.-wall $\times$ 1.0-ft tube.

Status of Work Performed: A 5-ton heat of modified 9Cr-1Mo steel was produced in a vacuum-induction electric furnace. The fabrication procedure of this heat into tube and plate is described. Tubes and plates were subjected to chemical analysis and to tensile, Charpy impact, creep, weldability, and weldment tensile properties tests. The following conclusions are possible from this work:

1. Chemical analysis of this heat was within the specifications for the modified 9Cr-1Mo steel for all elements including residuals.
2. Tensile properties were consistent with the ORNL results.
3. The 50 ft-lb transition temperature for the plate and tubes was between -50 and -75°C.
4. The cold cracking susceptibility of modified 9Cr-1Mo steel was similar to that of standard 9Cr-1Mo steel.
5. A total of 15 creep tests were conducted. Their results were consistent with ORNL data.

References:

1. *Test Results of ORNL Modified 9Cr-1Mo Steel*, Nippon Kokan K.K., Fukuyama, Japan, March 1983.
2. *Test Results of ORNL Modified 9Cr-1Mo Steel (ASME SA213-T91)*, Nippon Kokan K.K., Fukuyama, Japan, February 1984.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Sumitomo Metal America Inc.
420 Lexington Avenue
New York, NY 10170

Contact:

Y. Hayase
Technical Manager

Participation Basis: Company funds

Date Action Initiated: October 1981

Date Completed: November 1982

Purpose: Study the effect of chromium enrichment layer on the tube surface by various mechanical and corrosion tests.

Material Produced or Supplied: Sumitomo produced tubing, 1.8-in. OD x 0.51-in. wall x 20-ft length.

Status of Work Performed: This investigation deals with the effect of tube surface finish of modified 9Cr-1Mo steel on the mechanical, corrosion, and oxidation response. Tubes were tested in the as-fabricated condition and after removing a 0.004-in.-thick layer from the inside and outside surfaces. Tubes were subjected to flattening and flaring tests and corrosion tests in 30% H₂SO₄, 5% HCl, and 10% HCl for periods ranging from 4 to 24 h. Tubes were also tested in steam at 600, 650, and 700°C. Results of these tests showed that the tubes as delivered and after machining the surfaces had similar responses.

References:

1. *Test Results of Modified 9 Cr-1 Mo Steel Tube*, 802 F-No. 779, Sumitomo Metal Industries, Ltd., Amagasaki, Japan, April 1982.
2. *Test Results of Modified 9Cr-1Mo Steel Tube*, 802 F-No. 923, Sumitomo Metal Industries, Ltd., Amagasaki, Japan, November 1982.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Sumitomo Metal America Inc.
420 Lexington Avenue
New York, NY 10170

Contact:

Y. Hayase
Technical Manager

Participation Basis: Company funds

Date Action Initiated: October 1981

Date Completed: March 1993

Purpose: To melt 2- and 50-ton heats of modified 9Cr-1Mo steel, fabricate boiler tubing, and characterize mechanical properties of these tubes.

Material Produced or Supplied:

Melted 2-ton heat and fabricated 2-in.-OD $\times$ 0.250-in.-wall $\times$ 13.3-ft tubes and 3-in.-OD $\times$ 0.50-in.-wall $\times$ 13.3-ft tubes.

Melted 50-ton heat and fabricated 2.15-in.-OD $\times$ 0.15-in.-wall $\times$ 11.6-ft tubes and 1.8-in.-OD $\times$ 0.22-in.-wall $\times$ 13.3-ft tubes.

Status of Work Performed: Melting of 2- and 50-ton heats is described. Steps used in the fabrication of tubes are given as a flow diagram. All tubes were subjected to chemical analysis and to tensile, Charpy impact, steam oxidation, and high-temperature corrosion tests in ash-containing sulfates and oxides. The following conclusions are drawn from this investigation:

1. No problems were encountered in meeting the chemistry specifications for all elements.
2. Tube fabrication did not require unusual practice.
3. Tensile properties of all tubes were above the specified values for Grade T91. The elevated-temperature values were consistent with those observed for heats melted and fabricated in the United States.
4. The 50 ft-lb transition temperature for these tubes was below -60°C .
5. Creep data on these tubes were consistent with ORNL data.

6. Steam oxidation resistance at 600 and 650°C was much better than that of 2.25Cr-1Mo steel and slightly better than that of standard 9Cr-1Mo steel and Sumitomo Alloy HCM9M (9Cr-2Mo alloy).
7. High-temperature corrosion in ash environment was significantly better than that of 2.25Cr-1Mo steel and nearly similar to that observed for standard 9Cr-1Mo and HCM9M.

Reference: Report, *Properties of Super 9Cr Steel Tube (ASTM A213-T91)*, 803 F - No. 1023, Sumitomo Metal Industries, Ltd., Amagasaki, Japan, March 1983.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Sumitomo Metal America Inc.
420 Lexington Avenue
New York, NY 10170

Contact:

Y. Hayase
Technical Manager

Participation Basis: Company funds

Date Action Initiated: October 1981

Date Completed: March 1983

Purpose: To analyze elevated-temperature tensile and creep data on modified 9Cr-1Mo steel tubes and pipe.

Material Produced or Supplied: Sumitomo produced tubes and pipe and also performed the tests.

Status of Work Performed: Tensile and creep data generated at Sumitomo on tubes and pipe produced by Sumitomo were analyzed and compared with the parametric model developed by ORNL. The creep rupture and creep strength data were used to develop the design allowable stresses. These stresses were found to be in excellent agreement with those developed by ORNL using the data generated on commercial heats produced and fabricated in the United States. The allowable stresses developed on modified 9Cr-1Mo steel were also compared with those developed on HCM9M. Consistent with the ORNL analysis, the modified 9Cr-1Mo steel was superior to that of HCM9M.

References:

1. *Elevated Temperature Strength of Super 9Cr Steel Tubes*, 803 F-No. 1027, Sumitomo Metal Industries, Ltd., Amagasaki, Japan, March 1983.
2. *Properties of 9Cr Steel Tubes and Pipe*, 804 F-No. 1194, Sumitomo Metal Industries, Ltd., Amagasaki, Japan, February 1984.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Sumitomo Metal America Inc.
420 Lexington Avenue
New York, NY 10170

Contact:

Y. Hayase
Technical Manager

Participation Basis: Company funds

Date Action Initiated: June 1982

Date Completed: March 1983

Purpose: To fabricate a large-diameter modified 9Cr-1Mo pipe and characterize its mechanical properties.

Material Produced or Supplied: The material produced was 18.8-in.-OD x 6-in.-wall x 6.7-ft pipe.

Status of Work Performed: A large-diameter pipe was fabricated out of a 50-ton heat (electric furnace plus vacuum oxygen deoxidized) melted at Sumitomo. The pipe was subjected to chemical analysis and to tensile, Charpy impact, creep, and weldability tests, and a continuous cooling transformation diagram was developed. The following conclusions are possible from this investigation.

1. All elements of this heat were within ASTM specifications for the modified 9Cr-1Mo (Grade T91) steel.
2. Room-temperature tensile properties at 0.25-, 0.50-, and 0.75-in. thickness were identical and well above the ASTM specified values for Grade T91. The elevated-temperature tensile properties of the large pipe were similar to those observed for the thin-wall tubing fabricated from the same heat.
3. The 50 ft-lb transition temperature for the pipe was between -7 and -30°C.
4. The creep properties of the pipe were consistent with the ORNL data on tubes and plates of U.S.-melted commercial heats. Creep data on this pipe were also similar to those observed for 12.7-mm-thick tubing made from the same heat.
5. Cold-cracking test results on the modified alloy were similar to those observed for the standard 9Cr-1Mo steel.

Reference: *Properties of Super 9Cr Large Diameter Pipe*, 803 F-No. 1024, Sumitomo Metal Industries, Ltd., Amagasaki, Japan, March 1983.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Sulzer Brothers, Ltd.
Begründer, Sulzer
Aktiengesellschaft, CH-8401
Winterthur, Switzerland

Contact:

H. Beutler
Deputy Vice President
Materials Research and
Development

Participation Basis: Company funds

Date Action Initiated: August 1982

Date Completed: May 1983

Purpose: To gain experience with modified 9Cr-1Mo steel and to compare data generated in the laboratory with data on HT9 (FRG X20).

Material Produced or Supplied: Three pipes 9-in. OD × 1-in. wall × 12 in. long, two plates 2 in. × 6 in. × 12 in. long. All pieces were from heat 10148 in the normalized and tempered condition (1040°C/1 h/760°C/1 h).

Status of Work Performed: Tensile, creep, and Charpy impact tests were conducted on ORNL-supplied material, and results were compared with those from HT9. Charpy impact tests were conducted in the normalized-and-tempered and aged condition. It was concluded that the modified 9Cr-1Mo offers a strength and toughness advantage; however, additional long-term data are needed to determine if the extrapolated values will hold up.

Reference: B. Walser, *Comparison Between and Behavior of Different High-Temperature Materials*, Paper J-1, Sulzer Brothers, Ltd., Winterthur, Switzerland.

Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed

Organization:

Tube Investments Chesterfield, Ltd.
Stainless Steel Division
P. O. Box 21
West Midlands WS2 7BW
England

Contact:

Trevor Thursfield
General Manager

Participation Basis: Company funds

Date Action Initiated: September 1981

Date Completed: December 1981

Purpose: To gain experience in fabricating boiler tubes of an ORNL-supplied billet of modified 9Cr-1Mo steel and to provide some of the tubes for installation in Agecroft Power Plant of the Central Electricity Generating Board (CEGB), U.K.

Material Produced or Supplied: ORNL supplied a 9-in.-diam $\times$ 72-in.-long billet from Electralloy heat 11148. The material produced was 2-1/8-in.-OD $\times$ 0.372-in.-average-wall tubes.

Status of Work Performed: Tube fabrication was successfully completed. On the basis of this experience, Tube Investments was ready to accept any commercial orders for the manufacturing of boiler tubing of modified 9Cr-1Mo steel. Tubing fabricated at Tube Investments was later installed in the Agecroft Power Plant of the CEGB, U.K.

References:

1. Trip Report, G. C. Bodine, Combustion Engineering, Inc., *Extrusion of Modified 9 Cr-1 Mo Alloy Billets, T. I. Stainless Tubes, Ltd., Chesterfield, Derbyshire, England*, Nov. 27, 1981.
2. *The Extrusion of 9%Cr-1%Mo Modified Grade Agecroft Power Station Trial*, Report No. Trial No. 34D, Tube Investments Chesterfield, Ltd., Chesterfield, Derbyshire, U.K., Dec. 17, 1981

Appendix F

FOREIGN UTILITIES

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Ontario Hydro
700 University Avenue
Toronto M5G 1X6
Ontario

Contact:

Duncan Sidey
Technical Supervisor

Participation Basis: Company funds

Date Action Initiated: May 1983

Date Completed: In progress

Purpose: To evaluate the use of modified 9Cr-1Mo steel tubes in the Lambton TGS plant (fossil fired) of Ontario Hydro operating at 538°C (1000°F).

Material Produced or Supplied: Sumitomo Metal Industries, Ltd., supplied nine tubes, 2 1/8 in. OD × 0.148 in. wall × 10 ft long; and nine tubes, 2 1/8 in. OD × 0.148 in. wall × 9 ft long.

Status of Work Performed: As part of an ORNL subcontract, Combustion Engineering, Inc., attached type 304 stainless steel safe ends on nine tubes and SA213-T9 safe ends on nine tubes. Ontario Hydro completed installation of the test panel in May 1983.

References:

1. Letter Report, D. Sidey, Ontario Hydro, to V. K. Sikka, ORNL, *In-Service Testing of Modified 9 Cr-1 Mo Boiler Tubing*, Mar. 10, 1982.
2. Letter Report, G. C. Bodine, Combustion Engineering, Inc., to V. K. Sikka, ORNL, *Fabrication of Safe Ends on Sumitomo Tubes*, July 16, 1982.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Ontario Hydro
700 University Avenue
Toronto M5G 1X6
Ontario

Contact:

Duncan Sidey
Technical Supervisor

Participation Basis: Company funds

Date Action Initiated: April 1984

Date Completed: In progress

Purpose: To evaluate the performance of modified 9Cr-1Mo steel tubes in Nanticoke TGS plant (fossil fired) of Ontario Hydro operating at 538°C (1000°F).

Material Produced or Supplied: Sumitomo Metal Industries, Ltd., supplied 11 tubes, 1 3/4 in. OD × 0.215 in. wall × 12 ft long.

Status of Work Performed: As part of an ORNL subcontract, Combustion Engineering, Inc., attached type 321 stainless steel safe ends on selected tubes. Ontario Hydro completed installation of the test panel in April 1984.

References:

1. Letter Report, D. Sidey, Ontario Hydro, to V. K. Sikka, ORNL, *In-Service Testing of Modified 9 Cr-1 Mo Boiler Tubing*, Mar. 10, 1982.
2. Letter Report, G. C. Bodine, Combustion Engineering, Inc., to V. K. Sikka, ORNL, *Fabrication of Safe Ends on Sumitomo Tubes*, July 16, 1982.

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Central Electricity Generating Board
Berkeley Nuclear Laboratories
Berkeley, Gloucester GL89PB
England

Contact:

Peter Marshall
Senior Research Scientist

Participation Basis: Company funds

Date Action Initiated: April 1982

Date Completed: In progress

Purpose: To evaluate the performance of modified 9Cr-1Mo steel tubes in the Agecroft Power Plant (fossil fired) of CEGB operating at 593°C (1100°F).

Material Produced or Supplied: Tube Investments Chesterfield, Ltd., provided six tubes, 2 1/8 in. OD × 0.372 in. wall × 6 ft long.

Status of Work Performed: Installation was completed in April 1982, replacing 2.25Cr-1Mo steel tubes in the test panel.

Reference: Trip Report, G. C. Bodine, Combustion Engineering, Inc., *Extrusion of Modified 9 Cr-1 Mo Alloy Billets, T. I. Stainless Tubes, Ltd., Chesterfield, Derbyshire, England, Nov. 27, 1981.*

**Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed**

Organization:

Tennessee Valley Authority
Chattanooga, TN 37401

Contact:

W. Goins
Senior Metallurgist

Participation Basis: Company funds**Date Action Initiated:** May 1980**Date Completed:** In progress

Purpose: To evaluate the performance of modified 9Cr-1Mo steel tubes in the Kingston plant (fossil fired) of TVA operating at 593°C (1100°F).

Material Produced or Supplied: ORNL supplied eight tubes, 2 in. OD × 0.320 in. wall × 8 ft long.

Status of Work Performed: Combustion Engineering, Inc., attached (ORNL subcontract) type 347 stainless steel safe ends on the tubes, and TVA completed installation of the test panel in May 1980. In May 1983, ORNL and TVA conducted an in-service inspection and found the tubes to be sound; a decision was made to resume the test.

References:

1. Memorandum, R. T. King, ORNL, to L. E. McNeese, ORNL, "Interagency Agreement Between DOE and TVA on Exposure of 9 Cr Steel in TVA Boilers," Sept. 25, 1978.
2. Letter, E. E. Hoffman, DOE, to L. B. Kenney, TVA, May 3, 1980, "In-Service Inspection of Test Panel."

Appendix G

FOREIGN UNIVERSITIES

Summary of Modified 9Cr-1Mo Steel Specimens or Product Forms
Produced or Supplied and Status of Work Performed

Organization:Contact:

Department of Metallurgical Engineering Prof. K. P. Singh
Indian Institute of Technology
Kanpur-208016, U. P.
India

Participation Basis: Funded by

Department of Atomic Energy, India

Date Action Initiated: January 1982

Date Completed: In progress

Purpose: To study the effects of prior oxidation on mechanical properties of modified 9Cr-1Mo alloy.

Material Produced or Supplied: ORNL supplied minimal quantities of plates of several commercial heats of modified 9Cr-1Mo steel for graduate-student research projects.

Status of Work Performed: Specimens of modified 9Cr-1Mo alloy were oxidized at 650°C (1200°F) in oxygen at one atmosphere. Oxidized specimens were subjected to tensile, creep, low-cycle fatigue, and creep-fatigue tests. Data showed the following:

1. Tensile properties were not affected.
2. Fatigue strength was lowered with increased oxygen content.
3. Creep and creep-fatigue strength increased with increasing oxidation time.

Reference: M. K. Maheshwari, *Effect of Oxidation on Mechanical Properties of Modified 9Cr-1Mo Steel at High Temperature*, Master's Thesis, Indian Institute of Technology, Kanpur, May 1984.

Appendix H

SI METRIC EQUIVALENTS OF ENGLISH UNITS USED IN THIS REPORT

<u>English unit</u>	<u>SI equivalent</u>
inch	25.4 mm
foot	0.3048 m
pound	0.43 kg
ton	907.18 kg
foot-pound	1.36 J
°F	°C = (5/9)(°F - 32)

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