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Report of USDOE/CEA/DEBENE Exchange Meeting on Alternate Steam Generator Structural Materials for Fast Breeder Reactor Service

October 9–10, 1980
St. Petersburg Beach, Florida

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METALS AND CERAMICS DIVISION

Working Group 3, Plant Systems and Components
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REPORT OF USDOE/CEA/DEBENE EXCHANGE MEETING ON ALTERNATE STEAM GENERATOR STRUCTURAL MATERIALS FOR FAST BREEDER REACTOR SERVICE

October 9–10, 1980

St. Petersburg Beach, Florida

C. R. Brinkman, U.S. Chairman

Date Published - May 1981

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CONTENTS

ABSTRACT 1

INTRODUCTION 1

GENERAL OVERVIEW 2

AGREEMENTS AND RECOMMENDATIONS 4

Corrosion 4

Recommended Implementation 5

Mechanical Properties 5

APPROVAL PAGE 8

SUMMARY OF PRESENTATIONS 9

SUMMARY 1 10

Selection of Alternative Steam Generator Materials — J. W. Schinkel, J. Vrijen, and J. K. Van Westenbrugge 10

Waterside Corrosion 11

Sodium Side Corrosion 11

Tensile Properties 12

Creep Properties 12

Fatigue Properties 12

Impact Properties (ISO-V) 12

Fracture Mechanics 13

SUMMARY 2 14

Water-Steam Corrosion on Ferritic Steel — G. Pinard-Legry 14

Future Work 14

SUMMARY 3 16

Sodium-Side Corrosion on EM12 — L. Champeix 16

SUMMARY 4 17

Stress Corrosion in Liquid Metal Fast Breeder Reactor Systems — P. J. Ring, C. N. Spalaris, and T. K. Odegaard 17

SUMMARY 5 19

Steam Generator Materials Development at General Electric Company Advanced Reactor Systems Department, Sunnyvale, California — Prodyot Roy and Charles G. Schmidt 19

SUMMARY 6 21

Basis For Stresses Allowable, Fatigue, Fracture Mechanics, and Dissimilar Metal Weldments — CEA Contribution — M. Aubert 21

EM12 Steel for Steam Generators Tubes 21

2 1/4 Cr-1 Mo Steel for Steam Generator Tubes 21

2 1/4 Cr-1 Mo Steel for Tubesheet 22

SUMMARY 7 23

A Comparison of the Mechanical and Physical Properties of Modified 9 Cr-1 Mo Steel for Advanced Fast Breeder Reactor Systems — V. K. Sikka 23

SUMMARY 8 26

Comparison of the Mechanical Strength Properties of Several High-Chromium Ferritic Steels — M. K. Booker, V. K. Sikka, and B.L.P. Booker 26

SUMMARY 9 27

A Preliminary Analytical Assessment of the Structural Performance of Modified 9 Cr-1 Mo Steel Relative to Other Alloys in Fast Breeder Reactor Applications — R. C. Gwaltney and G. T. Yahr 27

SUMMARY 10 28

A Status Report on Exploratory Time-Dependent Fatigue Behavior of 2 1/4 Cr-1 Mo and Modified 9 Cr-1 Mo Steel — C. R. Brinkman, J. P. Strizak, and M. K. Booker 28

APPENDIX A — AGENDA 31

APPENDIX B — LIST OF PARTICIPANTS 35

APPENDIX C — PAPER TITLES 37

APPENDIX D — QUESTIONS AND ANSWERS 39

REPORT OF USDOE/CEA/DEBENE EXCHANGE MEETING ON ALTERNATE STEAM GENERATOR STRUCTURAL MATERIALS FOR FAST BREEDER REACTOR SERVICE

C. R. Brinkman, U.S. Chairman

ABSTRACT

Representatives of U.S., French, and DEBENE (German, Belgian, and Dutch) organizations met to exchange information on corrosion and mechanical properties of ferritic steam generator alloys. Of concern were steels having from 2 to 12% Cr, 1 to 2% Mo, and in some cases stabilizing elements. The report presents an overview of the meeting, agreements and recommendations, summaries of papers presented, the meeting agenda, a list of participants, and a microfiche supplement with the manuscripts of papers presented.

INTRODUCTION

Alternate structural materials are currently under development by several national and international organizations in support of fast breeder reactor technology. Representatives from several organizations and countries including U.S., CEA (French), and DEBENE (German, Belgian, and Dutch agreement) met in accordance with international fast breeder reactor agreements at St. Petersburg Beach, Florida, on October 9–10, 1980. The objective of the meeting was to accomplish the following:

1. To review and compare properties and behavior of several structural alloys and weldments proposed as possibilities for use as steam generator materials. These alternate alloys are under development by several organizations as follows:

Country or Organization	Material and Heat Treatment
CEA	2 1/4 Cr-1 Mo steel (annealed and normalized and tempered), EM12 (9 Cr-2 MoVNb)
U.S.	9 Cr-1 Mo modified steel (normalized and tempered)
DEBENE	12 Cr-1 MoV (normalized and tempered)

2. To identify areas of common interest for future collaboration if cost and time effectiveness is apparent.
3. To prepare a summary report documenting accomplishments and defining recommendations for collaborative efforts.

It should be noted by the reader that all materials indicated above are ferritic because of the known better stress corrosion behavior of ferritic than austenitic materials. This report summarizes presentations, discussions, and areas for possible collaboration identified at this meeting.

The report is organized as follows:

Appendix A gives the agenda for this meeting. Participants, titles, and organizations represented are listed in Appendix B. Papers presented and/or handed out to participants and observers are listed in Appendix C. Questions and answers summarizing discussion are given in Appendix D. Finally, complete copies of papers and presentations are included with this report as a microfiche supplement.

The next two sections present limited background and recommendations, respectively, for further collaboration in the general areas of corrosion resistance and mechanical properties. Following them is a compilation of summaries of presentations covering known behavior of the above listed materials.

The meeting was chaired by C. R. Brinkman, US-ORNL, with J. W. Schinkel, DEBENE, and M. Weisz, CEA, acting as cochairmen. Finally it is necessary to acknowledge the effort of M. K. Booker, who recorded the dialogue given in Appendix D. Special thanks are also due to Fauna Stooksbury for typing and compilation, Sig Peterson for editing, and P. T. Thornton for the final preparation of this report.

GENERAL OVERVIEW

Reviews of ongoing programs and some available data were presented covering the corrosion behavior and mechanical properties of the following reference and alternate fast breeder reactor structural alloys:

U.S. Materials

2 1/4 Cr-1 Mo base and HAZ*

Transition joints (2 1/4 Cr-1 Mo/ERNiCr-3/Alloy 800*/ 16-8-2/316 stainless)

Modified 9 Cr-1 Mo steel; ferritic-martensitic microstructure

CEA/DEBENE (Alternate Materials)

EM12 (9 Cr-2 MoVNb), ferritic-martensitic microstructure

12 Cr-1 MoV steel, ferritic-martensitic microstructure

2 1/4 Cr-1 MoNb stabilized steel

Bimetallic joints
EM12/2 1/4 Cr-1 Mo

Weldments
EM12/EM12

Material variables included melting practice and heat treatment.

The main corrosion topics discussed reflecting the primary interests of the participants were as follows:

1. general water- and steam-side corrosion,
2. stress-corrosion cracking,
3. corrosion in contaminated sodium, and
4. carbon transport.

Presentations were given of available data and ongoing program plans for development of mechanical properties of the ferritic materials listed above. Properties of interest included tensile, toughness, ductility, crack propagation (static and dynamic), and long-term creep and creep-fatigue for both base and weldment material. It was shown that DEBENE, CEA, and US/DOE each have similar active programs in the area of mechanical properties data generation. Although the use of different materials by DEBENE, CEA, and US/DOE limits the effective exchange of information to some extent, some generic problem areas were identified where mutually beneficial and equitable exchange of information is possible.

One of the generic areas of mutual interest is the problem of creep-fatigue interaction. This is a key area, which can profit from the broadest

*Reference materials.

possible interaction. One benefit is obtaining data for realistic design situations. Such data can be used to establish the adequacy of the various candidate phenomenological creep-fatigue theories such as strain-range partitioning and the damage-rate approach. Another benefit concerns understanding the basic mechanisms of creep-fatigue interaction. All parties indicated that this is an area where cooperative joint planning and testing could be particularly beneficial.

Transition joint analysis and validation testing of transition joints weldments constitute another generic area of mutual interest. Exchange of analysis methodology and test results could again be mutually beneficial. Both the U.S. and CEA identified ongoing experimental and analytic efforts as a part of programmatic efforts while DEBENE indicated an analytical interest in this important area.

AGREEMENTS AND RECOMMENDATIONS

The following recommendations were made concerning the exchange of information by all parties from ongoing programs.

Corrosion

1. General water and steam corrosion. Exchange of water-and-steam-side corrosion data is recommended, including the effects of cyclic loading, heat flux, and mechanical deformation. Detailed descriptions of test methods and materials would be provided. The U.S. would provide data on evaporator corrosion under DNB conditions, superheat corrosion of 2 1/4 Cr-1 Mo and modified 9 Cr-1 Mo steel. The CEA and DEBENE organizations would provide similar information on 2 1/4 Cr-1 Mo and the high-chromium steels.

2. Stress-corrosion cracking. Information on the effects of faulted environments (chloride or caustic) and other variables including temperature, stress, and concentrations on materials defined above should be exchanged. Results from constant-extension as well as constant-stress tests employing U-bends, C-rings, and capsules are of interest. Again, a detailed description of experimental methods and materials would be included.

3. Hydrogen diffusion. Exchange of hydrogen diffusion data is recommended. This includes detailed experimental methods of measurement. Specifically, the effect of hydrazine additions in the feed water and the effect of hydrogen produced from corrosion and permeation into the intermediate heat transfer sodium are of interest.

4. Sodium-side corrosion (effects due to sodium-water reactions). Specific areas of information exchange in this category include the metallurgical aspects of wastage and corrosion effects due to sodium-water reactions (mainly caustic since high oxygen content is not a problem).

5. Methods for monitoring carbon activity in sodium. An exchange of program plans would occur and include state-of-the-art experimental measurement methods.

Recommended Implementation

1. The parties involved agreed to exchange a list of recent (generated within the last two years) reports believed to be relevant to the above five topical areas. Specific titles and authors would be listed and formally exchanged by March 1, 1981. Complete reports would then be exchanged upon request.

2. It was agreed that all parties should test a common material for resistance to general corrosion as well as stress-corrosion cracking. The objective is to compare results obtained by using somewhat different experimental techniques. The common material selected was the 9 Cr-1 Mo modified material since overall data are lacking for this material. The U.S. agreed to supply material for these tests, and both the CEA and DEBENE organizations agreed to submit their specific needs (tubing, plate, etc.) by November 15. The intent here is that corrosion programs ongoing in the U.S (GE), CEA, and DEBENE would all profit from exchanging specific tests results on a common material.

Mechanical Properties

1. Creep-fatigue interaction damage is probably one of the most significant high-temperature failure modes and is recognized as a key

problem area by all parties. The current level of effort is somewhat diffuse in the characterization of specific materials such as 2 1/4 Cr-1 Mo steel because of the variety of heat treatments (annealed, normalized and tempered) and specifications (chemical, mechanical properties, stabilized versus unstabilized) involved. Further, the level of interest in characterization of 2 1/4 Cr-1 Mo steel is not the same within the participating organizations, (for example, 2 1/4 Cr-1 Mo steel in the normalized and tempered condition is a alternate steam generator material for CEA). Still, collaboration to the extent possible on a common material and heat treatment was recognized as being highly desirable. It was therefore recommended that a joint test matrix be formulated for the characterization of 2 1/4 Cr-1 Mo steel in the normalized and tempered condition. The material would be furnished by the U.S. and have a room-temperature ultimate tensile strength of less than 587 MPa (85 ksi). The agreed upon test plan to be followed by all three participating organizations would be established in the following manner:

a. A specialists meeting would be held early in the Spring of 1981. Available data from all heat treatments and specifications for 2 1/4 Cr-1 Mo steel would be reviewed. Tentative models for data extrapolation and design would be presented. Proposed test plans would be jointly reviewed, and from this critique a joint US-DEBNE-CEA test plan for model(s) verification would be agreed upon.
b. Assignments would then be agreed upon for each of the participating organizations as to accomplishing the test plan. Sufficient latitude would be allowed each organization involved to permit some testing of the specific form of 2 1/4 Cr-1 Mo steel that is of unique interest to that party so as to ensure generalization of the resultant model.

2. Comparative assessment of creep ductility and impact properties is of particular interest for the 9—12% Cr steels for both base and weldment materials. Included in this effort are the following steels:

Modified 9 Cr-1 Mo

EM-12

12 Cr-1 MoV

This assessment will be accomplished in the following manner:

a. ORNL will provide selected creep curves on modified 9 Cr-1 Mo steel for examination by DEBENE/CEA by February 1981.

b. CEA and ORNL will exchange creep-tested specimens (some failed and some unfailed) of modified 9 Cr-1 Mo and EM12 steels. Metallographic examination (optical, SEM, TEM, etc.) will be performed to determine mechanisms of rupture. Specimens will be provided by July 1981.

c. CEA will perform tube rupture tests at several stresses and temperatures (550–700°C) to compare hoop and rupture strains for the above materials. ORNL will provide tubes of modified 9 Cr-1 Mo steel to specifications required by CEA. CEA will supply required tubing dimensions by January 1981 and ORNL will supply tubing by March 1981.

d. A detailed metallographic evaluation will be made at DEBENE and ORNL of the Charpy impact specimens of 12 Cr-1 MoV (DEBENE) and modified 9 Cr-1 Mo (ORNL) in both the aged and unaged conditions. Product form comparisons will be made where possible. Materials will be exchanged for evaluation by March 1981. The intent here is to compare both resultant data and fractured specimens, as well as test methods.

3. Transition joints between austenitic and ferritic metals are present in both the USDOE and DEBENE LMFBR systems and may be used in the CEA systems as well. Transition joint testing is under way by both USDOE and CEA. Detailed analytical assessment of transition joints is under way at all three organizations. "Design and assessment methodology for weldments" was recognized as a high-priority exchange item at the June 1980 Exchange Meeting on Structural Materials Design Methods held in Oak Ridge, Tennessee. Dissimilar-metal welds were included there. It was agreed at the June 1980 meeting that an ad hoc working group (one or two members from each side) should be established, and the group should hold its first meeting in Paris in August 1981. It is recommended that transition joints be given special consideration at that meeting. In particular, plans including time schedules and sufficient experimental details to permit analyses should be exchanged at the August 1981 meeting. A follow-up specialists meeting should be held in late 1982 to jointly compare and discuss the results of the analyses of the transition joints.

APPROVAL PAGE

These agreements and recommendations are submitted by:

For CEA:

For DEBENE:*

For US-DOE:

C. R. Brinkman
Technical Coordinator, Materials

SUMMARY OF PRESENTATIONS

This section contains brief summaries of papers listed in Appendix C. Complete microfiche copies of these papers are attached to this report.

SUMMARY 1

Selection of Alternative Steam Generator Materials

J. W. Schinkel, J. Vrijen, and J. K. Van Westenbrugge

During 1975 a working group was established, consisting of designers and metallurgists of Interatom, Neratoom, Gesellschaft für Kernforschung, and TNO to evaluate the applicability of alternative structural materials for post-SNR-300 reactor systems. Part of this study was the evaluation of materials for the steam generator components.

At the start of this evaluation possible alternatives were listed. The list included 15 types of steel, which could be distinguished into three main classes:

- low- and medium-alloy ferritic chromium-molybdenum steels (including the SNR-300 reference material 10CrMoNiNb910*),
- high-alloy ferritic chromium-molybdenum steels, and
- austenitic stainless steels and alloys.

The evaluation considered a series of properties and other aspects relevant for the application: physical properties, mechanical properties, corrosion performance, wastage, manufacturing aspects, nondestructive testing possibilities, licensing, and material costs. The steam generator design temperatures were assumed identical to those for the SNR-300: 340°C at sodium outlet, 475°C at sodium inlet evaporator, and 525°C at sodium inlet superheater. The design lifetime, however, was for economic reasons, increased to 300,000 h.

The interaction process between designers and metallurgists led to a strong preference for the high-alloy chromium-molybdenum steels, primarily because of their high time-independent as well as time-dependent strength properties. For practical reasons as availability of existing material data, manufacturing experience, licensing possibility the steel type X20CrMoV121† was selected and a research program on this steel was started,

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*2 1/4 Cr-1 Mo niobium stablized with 0.5% nickel.

†12 Cr-1 MoV

including a large number of different heats with varying chemical composition, melting process, thickness, etc. The experimental program, although containing investigations on weldability, brazing, wear, sodium corrosion, etc., is concentrated on two main aspects:

- waterside corrosion and
- mechanical strength and ductility.

It will be continued in the coming years, at least to 1985.

Waterside Corrosion

It was known from literature sources that, although the uniform corrosion resistance of X20CrMoV121 (12 Cr-1 MoV) under superheater conditions is very good, there would eventually rise a problem of pitting corrosion at evaporator conditions in the presence of chloride impurities. Therefore an experimental program of autoclave tests was performed on several different heats in chloride and caustic environments.

The primary objective was to study the resistance to pitting and stress corrosion under simulated off-normal chemistry conditions of the feed water, especially in nearly dried regions where considerable impurity concentration may occur.

The experiments were carried out at the central laboratory of the Dutch electricity supplier, KEMA, as subcontractor to TNO, as four-point bending tests in high-temperature autoclaves. In addition, several C-ring and U-bend specimens have been (and are) used.

Generally no negative corrosion phenomena have been found, only in concentrated $FeCl_2$ solutions under high mechanical stresses are found localized attack and stress-corrosion cracking. Minor influences of heat treatment procedure and remelting practice were found.

The autoclave experiments will be continued in the coming years. Furthermore long-term exposures under heat-flux conditions will be performed in a special installation at the Hengelo test facility. The duration of these tests will be approximately 10,000 h.

Sodium Side Corrosion

Limited exposure experiments of X20CrMoV121 (12 Cr-1 MoV) under isothermal (550°C) and anisothermal conditions have been performed. These

experiments have shown that under conditions where 2 1/4 Cr-1 Mo steel decarburizes, X20CrMoV121 (12 Cr-1 MoV) will show minor carburization. Under anisothermal downstream conditions the deposition of sodium chromite and chromium carbide on the material surface has been observed. These phenomena are considered of minor importance, so the experimental program has been terminated.

Tensile Properties

Experiments have been carried out on a large number of heats to determine the tensile strength and ductility as functions of melting practice, heat treatment, strain rate, and thermal aging. Only heat treatment shows a significant influence on tensile and yield strength.

Creep Properties

So far very limited creep experiments at 550°C have been performed on one heat to verify its creep strength in relation to the large amount of test data in the literature, especially in the German "Ringbuch" data collection.

In the coming years a program on creep strength and ductility of welded joints and brazed joints will be undertaken.

Fatigue Properties

So far a limited low-cycle fatigue program at 550°C has been carried out to compare the data with those of the SNR-300 material. This program will be extended to a creep-fatigue interaction program.

Impact Properties (ISO-V)

An extensive program on the influence of melting practice, chemical composition, heat treatment, and thermal aging of base metal, heat-affected zone, and weld metal is in progress.

Large effects of heat treatment, aging, and material thickness have been observed. Although the upper-shelf energies normally are above 100 J, large fluctuations in transition temperatures result in large differences of the ISO-V impact value at room temperature. Optimization

of X20CrMoV121 (12 Cr-1 MoV) in this respect will be necessary by adapting chemical composition, melting practice, etc. This will be carried out in the coming years.

Fracture Mechanics

Despite optimization of the impact values as mentioned above, X20CrMoV121 has, because of its high strength, intrinsically a relatively low ductility. A careful consideration and evaluation of this property by means of a fracture mechanics analysis is necessary in the coming years. A start has been made in 1980 by carrying out NDT and crack opening displacement experiments.

SUMMARY 2

Water-Steam Corrosion on Ferritic Steel

G. Pinard-Legry

This program began in 1979 and is related to the corrosion resistance evaluation of EM12. Some tasks include also HT9 (12% Cr) for comparison. Samples are prepared from tubes or rods (mainly ASR). Some of them are cut in a welded region.

The following tests are now in progress:

- Steam. Measurements of the uniform corrosion rate in laboratory tests (loop and static autoclave). Comparison with data from fossil fired plates. Assuming that a parabolic law (found in laboratory) is valid over long times led to a good correlation between the two kinds of data. Extrapolation at 540°C and 200,000 h gives a corroded thickness of 160 to 170 μm.

  Tests under stress are also in progress to assess the risk of stress-corrosion cracking. After 5000 h there is no indication of stress-corrosion cracking.
- Caustic (Sodium Hydroxide). The tests now in progress are done in 10 and 100 kg/m^3 sodium hydroxide solutions at temperatures of 200, 250, and 300°C.

  Samples are U-bends, C-rings, and pressurized capsules. After 3000 to 5000 h (depending on the test) no cracking was observed.
- Chloride. Only one test is now in progress; no cracking occurred after 8000 h at 350°C in deaerated chloride.

Future Work

Steam. Tests will be continued. Attention will be focused on spalling of the oxide layer, especially during thermal transients and deformation of the metal.

Caustic. Investigation of stress-corrosion cracking resistance in more dilute solutions, under various stresses. Constant extension rate test (C.E.R.T.) and electrochemical measurements will be considered.

Chloride. The influence of oxidant will be evaluated (oxygen).

All the experiments will include some welded samples (EM12/EM12 and EM12/2 1/4 Cr-1 Mo). In some cases cyclic stressing at very low frequency will be superimposed on the stress.

SUMMARY 3

Sodium-Side Corrosion on EM12

L. Champeix

In France a limited program is in progress on the behavior of EM12 in contaminated sodium and pure sodium. This material is being considered as an alternative material for LMFBR steam generators. The program includes corrosion in clean or oxygen-contaminated sodium, corrosion in sodium-water reaction products, wastage and self-wastage, and carbon mass transfer.

1. General corrosion, in nominal purity flowing sodium, is very low. The damage resulting from a water leakage in sodium was measured; it appears to be about 5 μm in the worst case.

2. General corrosion rates in sodium containing 0.5, 1, and 10% NaOH are given; no intergranular cracking was found.

A special facility is under construction to study the effects of repeated contamination over a long period in flowing sodium.

3. In wastage experiments, EM12 appears to be inferior to alloy 800 reference material (penetration rate several times higher).

In "self-wastage" tests at 540 and 450°C, no indication of intragranular cracking was found; experiments at 250°C are planned.

4. Static tests on carbon mass transfer are in progress:

- An 8000-h test at 550°C shows a decarburization of type 316L stainless steel and carburization of EM12, respectively, with a rate constant of 1×10^{-12} $g/(m^2 \cdot s^{1/2})$.
- Experiments are in progress at lower temperatures and with the couple EM12, 2 1/4 Cr-1 Mo steel.

In 1981, a special loop will be operated under nonisothermal flowing sodium conditions.

In conclusion, in our program we are trying to answer two general questions concering EM12.

1. Will stress corrosion in sodium occur under certain off-chemistry conditions?

2. Is carbon transfer a problem in reactor conditions?

SUMMARY 4

Stress Corrosion in Liquid Metal Fast Breeder Reactor Systems

P. J. Ring, C. N. Spalaris, and T. K. Odegaard

To a large extent, stress corrosion problems are minimized in LMFBRs, because in the reactor core and intermediate heat transport system the heat transfer medium is sodium. However, the steam generator system and ancillary systems where water is involved introduce the problem of caustic corrosion.

Effort in investigating the risk potential for stress corrosion and in reducing that risk has been concentrated in two principal areas:

1. steam generator modules, especially the tubesheet region, and
2. the sodium water reaction products system.

Work has been carried out to determine the reduction of stress-corrosion cracking susceptibility obtained by the use of remelted rather than air-melted 2 1/4 Cr-1 Mo steel. Both vacuum-arc remelt (VAR) and electroslag remelt (ESR) material have been evaluated. This work has consisted of the testing of 2 1/4 Cr-1 Mo steel specimens in 10 and 20% sodium hydroxide at 232°C (450°F), using an autoclave system with a tensile loading capability.

The work has continued into a determination of stress-corrosion resistance as a function of postweld heat treatment (PWHT) and as a function of the extent of weld repair by remelting.

The second area where attention has been focused is the sodium-water reaction products system. In the eventuality of a steam generator water leak and the resultant sodium-water reaction, this system is designed to accept the mixture of water, sodium, and contaminant reaction products. Methods are now being developed to evaluate the risk of stress-corrosion cracking (caustic embrittlement) and to permit requalification of the system.

Specially designed specimen holders have been installed in the sodium-water reaction products system at the Energy Technology Engineering Center. This system is connected to the large leak test vessel, which

will be used to provide data on the effects of large water leaks in LMFBR steam generator systems. Prototypical materials representing those alloys used for the sodium-water reaction products system are being exposed to determine whether conditions that cause stress corrosion are likely to exist after a large leak. Base material, welded, and welded and postweld heat-treated samples are being tested. In addition, critical regions of the system piping have been ultrasonically inspected to provide baseline data. These regions will be reinspected after each sodium-water reaction event.

SUMMARY 5

Steam Generator Materials Development at General Electric Company Advanced Reactor Systems Department, Sunnyvale, California

Prodyot Roy and Charles G. Schmidt

The primary objective of the experimental studies described below is to characterize materials, mainly 2 1/4 Cr-1 Mo steel and austenitic stainless steels, to assure that satisfactory compatibility is achieved with LMFBR steam generator environments. These experimental programs are designed to accomplish the following: (1) relate the degree of decarburization of 2 1/4 Cr-1 Mo steel in high-temperature liquid sodium to subsequent effects on mechanical properties; (2) determine the stress corrosion susceptibility of 2 1/4 Cr-1 Mo in water-steam environments of LMFBR steam generators, under both normal and various upset conditions (caustic contamination); (3) determine the rate and extent of carburization and decarburization in a model loop of the intermediate heat transport system (IHTS); (4) determine the fracture toughness properties of 2 1/4 Cr-1 Mo steel base material and weldments with regard to steam generator shell, nozzle, and tubesheet applications, (5) determine the corrosion fatigue properties of 2 1/4 Cr-1 Mo steel in locally faulted evaporator environments to predict fatigue life under departure from nucleate boiling (DNB) conditions, and (6) measure the fatigue crack growth rates and creep rupture and creep ductility properties under IHTS sodium conditions of transition joint regions between 2 1/4 Cr-1 Mo steel and type 316 stainless steel. Significant findings include the following:

- Loss of carbon and thermal aging can independently reduce the ultimate tensile strength of 2 1/4 Cr-1 Mo steel. Comparison of strength degradation of companion specimens (decarburized versus control) demonstrates that thermal aging is an important component.
- Thermal aging and decarburization decreased the short-term 510°C (950°F) creep-rupture properties of 2 1/4 Cr-1 Mo steel. The creep-rupture properties of decarburized 2 1/4 Cr-1 Mo steel were slightly less than those of the thermally aged material.

- The decarburization of ESR and VAR 2 1/4 Cr-1 Mo steels with stable microstructure is not a diffusion-controlled process. Hence, an empirical model for decarburization of 2 1/4 Cr-1 Mo steels does not appear feasible. The previous assumption that the decarburization rate constant K is invariant with time is not correct. Attempts to calculate long-term carbon loss using a constant K value will lead to an erroneous conclusion.
- The carburization results indicate that the activity of carbon in a small bimetallic loop is decreasing with increase in time. The present data do not confirm the assumption that at a given temperature the activity of carbon in a large system will remain constant during the entire service life.
- The room temperature fracture toughness values for 2 1/4 Cr-1 Mo fall above the ASME Code K_{IR} curve for all material conditions.
- Elevated-temperature fracture toughness tests up to 510°C (950°F) decrease the increasing temperature and fall below the current code assumption for the K_{IR} curve at elevated temperature.
- The corrosion fatigue tests in caustic environment at 316°C (600°F) indicate a degradation of fatigue life when compared with data obtained in air in the high-cycle regime. However, the data all fall above the design allowable curve.
- Crack growth rate of a transition joint of 2 1/4 Cr-1 Mo steel and ERNiCr-3 is significantly slower than that of 2 1/4 Cr-1 Mo steel base metal. Tests on transition joints in sodium exhibited crack growth rates that were slower than these in air.

SUMMARY 6

Basis For Stresses Allowable, Fatigue, Fracture Mechanics, and Dissimilar Metal Weldments — CEA Contribution

M. Aubert

We describe the key results obtained and the mechanical properties of the alternative materials for French steam generators, mainly the EM12 and 2 1/4 Cr-1 Mo steels.

EM12 Steel for Steam Generators Tubes

The tensile and creep properties of the tubes made in accordance with nuclear standards agree well with those of the tubes used since 1964 in EDF conventional power plants. In particular, there is no difference between:

- hot- and cold-pilgered products,
- ASV and ESR products, and
- products with high and low chromium contents (between 9 and 10.5 % Cr).

Then, we have established the allowable stresses of EM12 steel, which can be compared with other candidate steam generator tube materials.

The continuous low-cycle fatigue of EM12 steel at 20 and 550°C are in the outer band of 2 1/4 Cr-1 Mo steel.

Aging caused hardening, which was greatest around 475°C and:

- increased the yield stress,
- decreased the tensile ductility, and
- decreased the toughness.

2 1/4 Cr-1 Mo Steel for Steam Generator Tubes

We have compared the allowable stresses and low-cycle fatigue behavior of normalized-and-tempered and annealed steels using

- for annealed materials, the data included in ASME Code Case 1592
- for normalized-and-tempered materials, a statistical analysis including our results and literature results.

We concluded:

1. The allowable stresses of annealed 2 1/4 Cr-1 Mo steel are lower than those of the normalized-and-tempered material up to around 560°C. They are equivalent at higher temperatures.

2. The low-cycle fatigue properties of the normalized-and-tempered material are a little lower than those of the annealed material up to around 10^5 cycles. They are equivalent for a greater number of cycles.

3. A hold period in compression reduces the creep-fatigue properties of normalized-and-tempered 2 1/4 Cr-1 Mo steel.

4. The effect of decarburization on the mechanical behavior of annealed 2 1/4 Cr-1 Mo steel tube has been calculated. The results were given in the Conference held at St. Petersburg, October 6–8, 1980.

2 1/4 Cr-1 Mo Steel for Tubesheet

We have made a thick forging plate in accordance with nuclear standards. It has a homogeneous chemical composition and homogeneous mechanical properties, which are higher than the minimum specified values.

We describe our ongoing programs, including mainly creep and fatigue tests of EM12 steel, mechanical behavior of weld metal and transition welds, and mechanical behavior of a tubesheet made of X20CrMoV121 steel.

SUMMARY 7

A Comparison of the Mechanical and Physical Properties of Modified 9 Cr-1 Mo Steel for Advanced Fast Breeder Reactor Systems

V. K. Sikka

A modified 9 Cr-1 Mo alloy with mechanical properties improved over existing ferritics (2 1/4 Cr-1 Mo, standard 9 Cr-1 Mo, and HT9) and with elevated-temperature creep properties exceeding that of type 304 stainless steel up to 625°C is under development at ORNL and Combustion Engineering (CE). The modified alloy differs from the standard alloy in the amounts of added vanadium and niobium. Silicon is also kept low in this alloy to improve toughness. The alloy is recommended for use in the normalized and tempered condition (1038°C for 1 h and 760°C for 1 h).

The modified alloy has been melted in over 100 experimental heats (ESR and air induction), five intermediate size (2–8 tons) commercial heats and three large (15-ton) heats. Two of the large heats were melted by Cartech and the third was melted by Electralloy. Both Cartech heats were initially melted by the AOD process. Subsequently one-half of the first and all of the second heat were electroslag remelted. The Cartech heats were top poured into ingots. The electrodes of the Electralloy heat will be electroslag remelted during FY 1981. The Cartech heats have been commercially fabricated into hot-forged and hot-rolled plates 25, 50, and 200 mm thick (1, 2, and 8 in.), hot-rolled bar 95 mm (3 3/4 in.) in diameter, and hot-extruded and hot-rotary-pierced tube hollows. In general, the alloy has been fabricated by using conventional equipment and practice. The product yield of plates, bar, and tubes have been high (80–90%). In addition to fabrication from large ingots, tubes were also made by centrifugal casting and cold pilgering. The cold-pilgered and hot-extruded tubes have been cold reduced and cold drawn to tubes of 12 different sizes. Tube wall thicknesses ranged from 2.5 to 0.25 mm (0.1 to 0.01 in.). The smallest tubes passed ultrasonic inspection.

Eight tube lengths were installed in the superheater section of the Tennessee Valley Authority Kingston Plant. They have operated since May 1980. Tubes will be installed in Detroit Edison and American Electric Power Plants during the next three months.

Modified 9 Cr-1 Mo and HT9 tubes were subjected to the ASTM flattening test. Tubes were tested in the normalized-and-tempered condition and after aging for 3000 h at 482, 538, 593, 649, and 704°C. Tubes were also tested after welding and postweld heat-treating. In general, modified 9 Cr-1 Mo tubes in all conditions (aged and welded) flattened until the sides met. The HT9 tubes cracked in all conditions except when aged for 3000 h at 704°C.

Gas tungsten-arc welds were made in several plates. These plates were subjected to U-bend tests both as-welded and postweld heat-treated. The U-bends showed no cracking up to plate thickness of 13 mm (0.5 in.). Modified 9 Cr-1 Mo steel has welded to itself, to type 304 stainless steel, and to 2 1/4 Cr-1 Mo. All welds passed U-bend tests successfully.

Plates of experimental, intermediate, and commercial heats were subjected to Charpy impact, tensile, and creep tests. Testing on the experimental heats was limited as compared with intermediate and large heats. Charpy tests were conducted on normalized-and-tempered and aged plates and on plates made by several different fabrication processes. Hot forging followed by hot rolling and hot forging followed by tempering and cold working produced the lowest transition temperature [68 V (50 ft-lb)]. Aging generally produced small changes in impact properties.

The base metal plates were tensile tested over the range from room temperature (RT) to 760°C. Weldment specimens were tested at RT and 649°C. Creep tests were conducted at 482, 538, 593, 649, 677, and 704°C. Creep rupture time for most heats exceeded the ASME code case minimum rupture curve for type 304 stainless steel up to 649°C. At 677°C, creep times were slightly below the minimum. However, at 704°C, the rupture lives were significantly below the minimum. The reduction of area for creep specimens generally ranged between 70 and 95%. The total elongation values for these specimens generally exceeded 20%. The time to the onset of tertiary creep was about 50% of the rupture time. The minimum creep rate showed a stress exponent of 16 up to 593°C. At higher temperatures, the stress exponent changed from 16 to 4 at lower stresses.

Variable-temperature creep tests (649 and 677°C, 649 and 704°C) showed no damaging effect. In other words, the sum of t/t_r for the entire test exceeded unity.

Tensile tests were conducted on 20% tensile or compressively cold-worked material. Yield and ultimate tensile strengths increased for temperatures up to 538°C. At higher temperatures the yield and ultimate tensile strengths were the same as those of normalized-and-tempered material. The total elongation and reduction of area for the cold-worked material are about the same as observed for the normalized-and-tempered material. Preliminary data showed no effect of 20% cold work on the creep properties.

Continuous-cycling fatigue tests were conducted on an intermediate heat at 525, 538, and 593°C. One test has also been completed on a large heat at 538°C. The large heat showed better fatigue life than the intermediate heat.

Crack growth tests were conducted on one intermediate heat at RT, 316, 427, and 538°C. The crack growth rates of this alloy were about the same as those observed for 2 1/4 Cr-1 Mo and HT9.

A few tensile and creep tests were completed on weldment specimens. Tensile strength properties of weldment specimens were comparable to base metal properties. Ductility values were only slightly lower. Creep data are too limited to permit any conclusions.

Data are available on the steam corrosion response of this alloy up to 25,000 h. A limited amount of information is also available on sodium effects on this alloy.

Work continues in several different areas and we plan to submit the data for this alloy to the ASME code committee for Sections I and VIII approval by the end of 1982 and for Section III by the end of 1985.

SUMMARY 8

Comparison of the Mechanical Strength Properties of Several High-Chromium Ferritic Steels

M. K. Booker, V. K. Sikka, and B.L.P. Booker

A modified 9 Cr-1 Mo ferritic steel has been selected for development by the U.S. Department of Energy as an alternative structural material for breeder reactor applications in which type 304 stainless steel or 2 1/4 Cr-1 Mo steel is currently being used. Different 9 Cr-1 Mo steels are already being used commercially in Britain and the United States, a 9 Cr-2 Mo steel EM12 is used commercially in France, and the 12%-Cr steel alloy HT9 is also often recommended for high-temperature service.

Creep-rupture data for all six of the above ferritic steels were collected and analyzed to yield rupture life as a function of stress, temperature, and lot-to-lot variations in strength. Yield and tensile strength data for the three 9 Cr-1 Mo materials were also examined. All results were compared with the behavior of type 304 stainless steel, and the tensile and creep properties of the modified and British 9 Cr-1 Mo materials were used to calculate allowable stress values S_o and S_m according to the *ASME Boiler and Pressure Vessel Code*. These values were compared with those currently listed in the code for American commercial 9 Cr-1 Mo steel, 2 1/4 Cr-1 Mo steel, and type 304 stainless steel.

The overall conclusion of this work is that the modified 9 Cr-1 Mo steel displays tensile and creep strengths significantly superior to those of the other ferritic materials examined and is at least comparable to type 304 stainless steel from room temperature to about 625°C.

SUMMARY 9

A Preliminary Analytical Assessment of the Structural Performance of Modified 9 Cr-1 Mo Steel Relative to Other Alloys in Fast Breeder Reactor Applications

R. C. Gwaltney and G. T. Yahr

An analytical assessment of the performance characteristics of modified 9 Cr-1 Mo steel relative to those of other alloys in a typical sodium reactor thermal transient environment has been made. The alloys considered included type 304 stainless steel, 2 1/4 Cr-1 Mo steel, alloy 800, 9 Cr-1 Mo (standard U.K.), and modified 9 Cr-1 Mo (U.S.). Although currently available materials data for modified 9 Cr-1 Mo are limited, such comparative analyses are useful for determining the potential usefulness of this material. Furthermore, these analyses indicate where additional research and development will be required.

SUMMARY 10

A Status Report on Exploratory Time-Dependent Fatigue Behavior of 2 1/4 Cr-1 Mo and Modified 9 Cr-1 Mo Steel

C. R. Brinkman, J. P. Strizak, and M. K. Booker

Various aspects of the time-dependent fatigue behavior of 2 1/4 Cr-1 Mo steel were reviewed. Specifically, the role of dynamic strain aging, environmental interaction, and classical creep damage (voidage) were discussed. Examples of results from exploratory tests efforts were presented. They showed the strong waveform-environment synergism that occurs in this material. A test matrix was given for future exploratory tests to provide the basis for determining which method is best for extrapolating time-dependent fatigue data. We presented plans that outline efforts for generating high-cycle fatigue data on 2 1/4 Cr-1 Mo steel in both the annealed and normalized-and-tempered conditions. Specific conclusions from this work were as follows:

1. At temperatures within the range from about 371 to 482°C tensile and fatigue properties of 2 1/4 Cr-1 Mo steel depend upon testing strain rate, primarily because of the effects of dynamic strain aging or interaction solid-solution hardening.

2. Exploratory strain-controlled fatigue tests on annealed 2 1/4 Cr-1 Mo steel in air have shown that considerable degradation in fatigue life in comparison with continuous cycle tests can occur when hold periods are introduced at zero stress or zero relaxation points on the hysteresis loop. The magnitude of the reduction in lifetime depends upon the location of the zero relaxation or stress points, with the most damaging positions on the tension-going side of the hysteresis loop. These effects have been attributed to waveform-oxide interaction that facilitates crack nucleation and accelerates crack propagation.

3. Cyclic lives of specimens of 2 1/4 Cr-1 Mo tested in nonoxidizing environments, such as sodium, do not show the significant waveform dependency effects that are found for similar tests in air. However, slow-fast

triangular waveforms at high temperature reduce cycle lives in sodium, probably from the generation of grain boundary voidage.

4. Comparisons between continuous-cycle fatigue data for standard 9 Cr-1 Mo and modified 9 Cr-1 Mo steel, both normalized and tempered, show the latter to have superior fatigue properties, particularly in the high-cycle range.

5. Limited strain-controlled fatigue data for modified 9 Cr-1 Mo steel at 538°C have shown that compressive hold periods are more damaging than tensile hold periods.

APPENDIX A

AGENDA

ALTERNATE MATERIALS FOR STEAM GENERATOR
SERVICE IN FAST BREEDER REACTOR SYSTEMS

JOINT USDOE/CEA/BMFT EXCHANGE MEETING

Working Group 3
Systems and Components

Don Cesar Hotel
St. Petersburg, Florida

October 9–10, 1980

DATE: October 9, 1980

PLACE: South Terrace Room

Time		
8:30 a.m.	Welcome	C. R. Brinkman
	Introduction	All
	Welcome	J. R. Hunter, DOE-LWR E. E. Hoffman, DOE-ORO
	Meeting Objectives and Format, Miscellaneous Announcements	C. R. Brinkman

Paper Title and Author

9:00 a.m. SESSION I — Materials

"Criteria for Selection of Steam Generator Materials,"
Mr. Schinkel, DEBENE (See Summary 1)
Mr. Spalaris, US-GE, (See Summaries 4 and 5)

10:00 a.m. SESSION II — Corrosion

"Water/Steam-Side Corrosion," Mr. Pinard-Legry, CEA/DEBENE (See Summary 2)

Mr. Schinkel, DEBENE (See Summary 1)

AGENDA (Continued)

"Sodium-Side Corrosion," Mr. Champeix, CEA and Mr. Schinkel, DEBENE (See Summary 3)

"Materials Issues—Intermediate Heat Transport System for CRBRP," Mr. Roy, US-GE (See Summaries 4 and 5)

12:00 noon LUNCH

1:00 p.m. SESSION III — Mechanical Properties (Continued)

"Basis for Stress Allowables, Fatigue Fracture Mechanics, and Dissimilar Weldments," Mr. Aubert, CEA and Mr. Schinkel, DEBENE (See Summaries 1 and 6)

"A Comparison of the Mechanical and Physical Properties of 9 Cr-1 Mo Modified Steel for Advanced FBR Systems," Mr. Sikka, US-ORNL (See Summary 7)

"A Comparison of the Strength Properties of Several High Chromium Ferritic Steels," Mr. Booker, US-ORNL (See Summary 8)

5:00 p.m. COMPLETE DAYS' DISCUSSIONS AND CLEAR ROOM

DATE: October 10, 1980

PLACE: South Terrace Room

8:30 a.m. SESSION III — Mechanical Properties (Continued)

"A Preliminary Analytical Assessment of the Structural Performance of the Modified 9 Cr-1 Mo Steel Relative to Other Alloys in FBR Applications," Mr. Yahr, US-ORNL (See Summary 9)

"A Status Report on Exploratory Time Dependent Fatigue Behavior of 2 1/4 Cr-1 Mo and 9 Cr-1 Mo (Modified) Steel," Mr. Brinkman, US-ORNL (See Summary 10)

AGENDA (Continued)

10:00 a.m. SESSION IV — Meeting Summary

A. Discussion of areas of mutual interest

B. Definition of future collaboration

C. Preparation and approval of recomendations

12:00 noon LUNCH

1:00 p.m. CONTINUATION AS REQUIRED

APPENDIX B

LIST OF PARTICIPANTS

1. M. (Michel) Aubert, Engineer, CEA-SRMA, CEN-Saclay, BP2 91190, Gifsuryvette, France.

2. M. K. (Keith) Booker, Research Staff, ORNL, P.O. Box X, Oak Ridge, Tennessee 37830.

3. C. R. (Chuck) Brinkman, Group Leader, Mechanical Properties, US-ORNL, P.O. Box X, Oak Ridge, Tennessee 37830.

4. L. Champeix, Chef de Section, CEA, CEN CADARACHE, 13115 Saint-Paul-Lez-Durance, France.

5. J. R. DiStefano, Manager, Materials Technology MSTMC, ORNL, P.O. Box X, Oak Ridge, Tennessee 37830.

6. E. E. (Eugene) Hoffman, Branch Chief, US-DOE, Oak Ridge, Tennessee 37830.

7. J. R. (Jim) Hunter, Division Director, US-DOE, Washington, D.C. 20545.

8. G. Pinard-Legry, Chef de Section, CEA, Boite Postale No. 6, 92260 Fontenay Aux Roses, France.

9. P. (Pete) Patriarca, ORNL, P.O. Box X, Oak Ridge, Tennessee 37830.

10. P. (Prodyot) Roy, Manager, General Electric, 175 Curtner Avenue, San Jose, California 95125.

11. J. W. (Jan) Schinkel, Manager, TNO, P.O. Box 541, Apeldoorn, The Netherlands.

12. V. K. (Vinod) Sikka, Research Staff, US-ORNL, P.O. Box X, Oak Ridge, Tennessee 37830.

13. C. N. Spalaris, Manager, General Electric, 175 Curnter Avenue, San Jose, California 92125.

14. J. K. Van Westenbrugge, Coordinator, Steam Generator Development, Neratoom, P.O. Box 93244, Den Haag, Netherlands.

15. J. Vrijen, Head, Materials Development Department, Neratoom, Den Haag, The Netherlands.

16. T. (Terry) Yahr, US-ORNL, P.O. Box Y, Oak Ridge, Tennessee 37830.

17. M. (Michel) Weisz, Chef de Service, CEA, CEA-Saclay, BP2, 91190, Gifsuryvette, France.

APPENDIX C

PAPER TITLES

USDOE/CEA/DEBENE EXCHANGE MEETING
WORKING GROUP 3, SYSTEMS AND COMPONENTS,
"ALTERNATE STRUCTURAL MATERIALS FOR FBR STEAM GENERATORS"

October 9–10, 1980, St. Petersburg, Florida

1. "Selection of Alternative Steam Generator Materials," J. W. Schinkel, J. Vrijen, J. K. Van Westenbrugge.

2. "Water-Steam Corrosion on Ferritic Steel," G. Pinard-Legry.

3. "Sodium Side Corrosion on EM12," L. Champeix.

4. "Stress Corrosion in Liquid Metal Fast Breeder Reactor Systems — LMFBR," P. J. Ring, C. N. Spalaris, and T. K. Odegaard.

5. "Steam Generator Materials Development at General Electric Company Advanced Reactor Systems Department, Sunnyvale, California,"

6. "Basis for Stresses Allowable, Fatigue, Fracture Mechanics and Dissimilar Weldments — CEA Contribution," M. Aubert.

7. "A Comparison of the Mechanical and Physical Properties of 9 Cr-1 Mo Modified Steel for Advanced Fast Breeder Reactor Systems," V. K. Sikka.

8. "A Comparison of the Mechanical Strength Properties of Several High Chromium Ferritic Steels," M. K. Booker.

9. "A Preliminary Analytical Assessment of the Structural Performance of the Modified 9 Cr-1 Mo Steel Relative to Other Alloys in Fast Breeder Reactor Applications," R. C. Gwaltney and T. Yahr.

10. "A Status Report on Exploratory Time Dependent Fatigue Behavior of 2 1/4 Cr-1 Mo and Modified 9 Cr-1 Mo Steel," C. R. Brinkman, J. P. Strizak, and M. K. Booker.

APPENDIX D

QUESTIONS AND ANSWERS

Session I — Materials

"Criteria for Selection of Steam Generator Materials," Mr. Schinkel, DEBENE

1. Q: (Mr. Patriarca) I notice your 12 Cr material has 0.2% C. Don't you have problems with welding?

   A: (Mr. Schinkel) No, we have had no problem.

2. Q: (Mr. Spalaris) Of course, you can prevent problems with well-controlled experimental welds. But what about welds made in the shop under normal conditions?

   A: (Mr. Weisz) We have examined welds made in the shop, and we have no problems with welding.

3. Q: (Mr. Patriarca) I don't quarrel that you can weld tubes, but what about weldability of thick sections? Our experts of Combustion Engineering believe the HT9 family of materials can give some real problems, especially if the level of workmanship is not very high.

   A: (Mr. Schinkel) With careful preheating and proper postweld heat treatment, we have had no problems, even with normal levels of workmanship.

4. Q: (Mr. Brinkman) So your experience doesn't motivate lowering the carbon level?

   A: (Mr. Schinkel) We are motivated to lower it within the specification, say to 0.17, but that's primarily for purposes of ductility, not weldability.

5. Q: (Mr. Hunter) What is your normal preheat?

   A: (Mr. Schinkel) Theoretically it ranges from room temperature for thin sections to 250°C for thick sections, but in practice it's never below 170–180°C.

6. Q: (Mr. Sikka) What is the reason for the carbon level of 0.2%? Is it to get a single-phase material based on the chromium equivalent close to 10?

   A: (Mr. Schnkel) That's one reason; adequate creep strength is another.

7. Q: (Mr. Sikka) But we have low carbon and high creep strength in modified 9 Cr-1 Mo steel.

   A: (Mr. Schinkel) But you have additions of other elements, like niobium and vanadium. We have a material with niobium added, but we don't use it in steam generators.

8. Q: (Mr. Sikka) Because of hot cracking?

   A: (Mr. Schinkel) That may be it.

"Criteria for Selection of Steam Generator Materials," Mr. Weisz, CEA

1. Q: (Mr. Brinkman) We use both annealed and normalized and tempered 2 1/4 Cr-1 Mo material, but we have an upper limit on ultimate strength level of about 590 MPa (85 ksi) on the normalized-and-tempered material. Do you have anything like that?

   A: (Mr. Weisz) Our ultimate strength ranges from 490 to 640 MPa.

2. Q: (Mr. Schinkel) Why does the U.S. have that limit?

   A: (Mr. Brinkman) It's because of the data base used to establish the properties in the code. It consisted mostly of annealed material and some of the lower strength normalized and tempered material.

3. Q: (Mr. Weisz) Does that restriction apply to pressure vessel materials like A 508 class 2?

   A: (Mr. Brinkman) No. There may be some restriction, but I'm not sure what it is.

4. Q: (Mr. Brinkman) We have three materials here: 2 1/4 Cr-1 Mo, EM12, and 12 Cr-1 Mo. Is there any compelling reason to chose one over the other from what we know now?

   A: (Mr. Weisz) We are still studying it. You must realize that many criteria are involved, including some, such as nondestructive examination, that won't even be discussed today.

"Fabrication and Inspection Experience in Support of FBR Steam Generator Development," Mr. Spalaris, US-GE

1. Q: (Mr. Weisz) Will you test only one steam generator unit for the Clinch River Plant, or will you test them all?

   A: (Mr. Spalaris) There are nine units in the plant. Eleven are being made. The two extras are prototypes for testing. We will not test the actual plant units.

2. Q: (Mr. Weisz) Have you done any testing in polluted sodium?

   A: (Mr. Spalaris) No. We have not studied off-chemistry effects.

3. Q: (Mr. Weisz) Your tests will be instrumented?

   A: (Mr. Spalaris) Instrumentation will be provided — thermocouples, strain gages, and so on.

4. Q: (Mr. Weisz) So you use plain 2 1/4 Cr-1 Mo steel in the Clinch River steam generator?

   A: (Mr. Spalaris) Plain 2 1/4 Cr-1 Mo, but with VAR or ESR. The VAR-ESR material is much cleaner and is very resistant to stress-corrosion cracking. You should see Peter Ring's paper from earlier this week.

5. Q: (Mr. Weisz) We have it. Can you get VAR material for a big tubesheet forging, which is 0.56 m (22 in.) thick and 1.5 m (5 ft.) in diameter?

   A: (Mr. Spalaris) Yes. Two vendors in this country can supply our tubesheet forging, which is 0.56 m (22 in.) thick and 1.5 m (5 ft.) in diameter.

6. Q: (Mr. Weisz) Isn't the material very expensive?

   A: (Mr. Spalaris) By the time the tubesheet is delivered there are so many other costs that the difference in material costs is an inconsequential part of the total.

7. Q: (Mr. Weisz) And normal material has problems with stress corrosion cracking?

   A: (Mr. Spalaris) Yes. The air-melted material cracks.

8. Q: (Mr. Shinkel) In your transition joint life tests you selected conditions to give failure in a given time. How did you make that analysis?

   A: (Mr. Spalaris) It was very detailed. We got a lot of materials properties from ORNL, and Al Dalcher and Tom Yang at GE did the inelastic and elastic analysis. They predicted the conditions that would give cracking after 120 cycles. For practical considerations, though, we increased the transients to get cracking sooner, and we did get it.

9. Q: (Mr. Weisz) What is the stress in that test relative to the yield strength, say, of the 316?

   A: (Mr. Spalaris) It's below the yield strength, but it's high enough to give us a significant amount of creep damage. We calculated that our damage at failure was 75% creep and 25% fatigue.

10. Q: (Mr. Schinkel) Where were the cracks you saw?

A: (Mr. Spalaris) They were on the 2 1/4 Cr-1 Mo side, near the fusion line with the ERNiCr-3.

11. Q: (Mr. Patriarca) Let me ask Mr. Weisz: You have a pool type reactor. Does that mean you have no transition joint problem?

A: (Mr. Weisz) No, not necessarily. The intermediate heat exchanger can be in the pool, but the joint can be anywhere. We can still have a transition joint.

12. Q: (Mr. Schinkel) Your experiment is like a validation of the stress analysis. Shouldn't there be a meeting of stress analysts about it? Maybe it was discussed in their meeting.

A: (Mr. Spalaris) I don't think it was part of their recent meeting.

A: (Mr. Weisz) But it was discussed at the Oak Ridge meeting.

13. Q: (Mr. Weisz) What additional transition joint tests are you planning?

A: (Mr. Spalaris) We plan to test two identical spools, but with smaller temperature gradients. We will also use these to demonstrate our nondestructive examination techniques.

14. Q: (Mr. Schinkel) You have spoken only about 2 1/4 Cr-1 Mo. What about your alternate materials, like the modified 9 Cr-1 Mo?

A: (Mr. Brinkman) Vinod Sikka will discuss that tomorrow. Perhaps he could give a brief history of the program now, though.

A: (Mr. Sikka) We had an alternate materials task force a few years ago headed by Roy King. That started with a wide range of possibilities and then narrowed it down to the family of 9—12 Cr ferritic alloys. Since 1975 we have studied the 9 Cr-1 Mo.

A: (Mr. Hoffman) I should point out that in 1973 or 1974 Dr. Cunningham, now the Head of Nuclear Energy at DOE, gave ORNL a three-phase task: first, to explore problems with the austenitics; second, to consider some alternate; then finally to lay out a qualification program for the alternates. We worked on both alloy 800 and 9 Cr-1 Mo for a while, then we dropped the alloy 800 about 2.5 years ago.

Session II — Corrosion

"Water/Steam-Side Corrosion," Mr. Pinard-Legry, CEA

1. Q: (Mr. Spalaris) Your corrosion rates are based on oxide thickness measurement? Our results show that those do not mean anything because of the spalling.

   A: (Mr. Pinard-Legry) In our laboratory tests we have looked at both oxide thickness and weight change, and the results agree very well. Our field data from plants involved only the oxide thickness measurements of course. Our tests may not have gone out far enough yet to see the spalling effect.

2. Q: (Mr. Brinkman) Most of the tests you showed were short term, but your work is still in progress. How long will your tests continue?

   A: (Mr. Weisz) At least to 10,000 h.

3. Q: (Mr. Brinkman) Your results show that the corrosion resistance of EM12 is excellent. Do you have 2 1/4 Cr-1 Mo data for comparison?

   A: (Mr. Pinard-Legry) The only data we have for comparison is in a high concentration of NaOH, where EM12 has never been found to crack but where 2 1/4 Cr-1 Mo cracks easily.

4. Q: (Mr. DiStefano) Do you have steam tests for comparison?

   A: (Mr. Pinard-Legry) Not yet. Those tests are in progress.

5. Q: (Mr. DiStefano) Your silicon concentration seems to improve the corrosion resistance. How does it affect the other properties?

   A: (Mr. Weisz) We don't know exactly. We think the effect is small.

"Sodium-Side Corrosion," Mr. Champeix, CEA

1. Q: (Mr. Brinkman) The EM12 has a higher wastage rate than Alloy 800 in sodium?

   A: (Mr. Champeix) Yes.

2. Q: (Mr. Spalaris) You are testing in flowing sodium?

   A: (Mr. Champeix) No, static. We are setting up a special loop to test in flowing sodium next year.

3. Q: (Mr. Spalaris) Do your tests indicate that we should be worried about carburization of EM12 in sodium?

   A: (Mr. Champeix) Not necessarily.

Session III — Mechanical Properties

"Basis for Allowable Stresses, Fatigue, Fracture Mechanics, and Dissimilar Weldments," Mr. Aubert, CEA

1. Q: (Mr. Brinkman) Are you worried about the decrease in creep ductility of EM12 with time.

   A: (Mr. Aubert) Certainly we are concerned about it. We are studying it.

2. Q: (Mr. Brinkman) Wouldn't the ductility be even lower for weldments?

   A: (Mr. Weisz) Perhaps, but that's just a guess.

3. Q: (Mr. Hunter) You showed a lot of data on the older version of EM12. How different is that from the nuclear grade material?

   A: (Mr. Weisz) From the data we have, they seem quite similar. We believe the data on the older material are therefore useful to estimate minimum strength, ductility, and so on.

4. Q: (Mr. Brinkman) Do your aging results bother you?

   A: (Mr. Weisz) A little, yes. We don't like it when the properties of materials change with time. It's apparently some sort of precipitation process, but we certainly have to evaluate the effect further.

5. Q: (Mr. Brinkman) How would the 2 1/4 Cr-1 Mo Nb-stabilized compare with the regular 2 1/4 Cr-in terms of allowable stress?

   A: (Mr. Vrijen) It's not very different.

6. Q: (Mr. Brinkman) Why is CEA not studying the stabilized material?

   A: (Mr. Weisz) Our carbon transport data show that we don't really need it at temperatures below 500°C, and above that the creep strength is too low. There are some weldability problems, too. There is some of the material in Phenix, but we don't really have much interest.

7. Q: (Mr. Brinkman) How extensive is the creep-fatigue testing program you plan for the 2 1/4 Cr-1 Mo material.

   A: (Mr. Weisz) It depends on the cooperation with you. It's only a backup material, so it is secondary in our plans. We would be glad to share the testing with you.

8. Q: (Mr. Sikka) Do you have hold-time tests on the EM12?

   A: (Mr. Weisz) No, but we plan to do some.

9. Q: (Mr. Hunter) What do you mean when you say "automatic deposit" welding?

   A: (Mr. Weisz) Submerged arc.

10. Q: (Mr. Brinkman) What is the difference in the composition of the nuclear grade of EM12 and the older grade?

    A: (Mr. Weisz) Some of the specifications are a little tighter, but the primary differences are fabrication procedures (cold rather than hot) and melting practice (ESR rather than air-melt.)

11. Q: (Mr. Brinkman) Do you worry about a degradation in toughness with time?

    A: (Mr. Weisz) No, we don't worry much about toughness.

12. Q: (Mr. Brinkman) What about things like notch sensitivity? We worry about that.

    A: (Mr. Weisz) I agree that notch sensitivity and notch ductility are important, but not toughness itself.

13. Q: (Mr. Spalaris) On the EM12 and 2 1/4 Cr, are we talking ESR, air-melt, VAR, or what?

    A: (Mr. Weisz) We are using ESR, but we could go to VAR. We're not totally satisfied. These 9–12 Cr steels can give some problems, such as cracking in the insides of the tubes during fabrication. I think we have grain growth and an orange peel effect. The inside surfaces of the tubes are not very good.

14. Q: (Mr. Sikka) Will you be testing weld metal or actual weldments in your weld tests?

    A: (Mr. Weisz) We are running some preliminary tests on weld metals of different compositions. When we choose one, we will test weldments.

15. Q: (Mr. Sikka) Are your data all on tubing?

    A: (Mr. Weisz) The fatigue is on bar. Most of the rest is on tube.

16. Q: (Mr. Yahr) Do you have tests on internally pressurized tubes, or just axial tensile loads?

    A: (Mr. Aubert) Just tensile loads.

17. Q: (Mr. Brinkman) Are your fatigue specimens uniform gage or hourglass?

A: (Mr. Aubert) Hourglass.

"A Comparison of the Mechanical and Physical Properties of Modified 9 Cr-1 Mo Steel for Advanced Fast Breeder Reactor Systems," Mr. Sikka, US-ORNL

1. Q: (Mr. Weisz) Why exactly did you modify each chemical element as you did?

A: (Mr. Sikka) The compositions result from many creep, fatigue, and Charpy tests on a large number of heats of various compositions. We plotted carbon plus nitrogen versus chromium equivalent and found an area that gave us high strength, ductility, and toughness. It's very qualitative, but that's how we arrived at our composition. I think it's a good guide.

2. Q: (Mr. Schinkel) What was the duration of the creep tests used in that evaluation?

A: (Mr. Sikka) Most were less than 1000 h, but we have data almost to 30,000 h, and it is still consistent.

3. Q: (Mr. Weisz) How did you determine your heat treatment? We have found the properties to be very sensitive to the austenitizing temperature.

A: (Mr. Sikka) We primarily tried to optimize the toughness. We still need to study the effects on creep properties.

4. Q: (Mr. Weisz) What is your austenitizing temperature?

A: (Mr. Sikka) 1040°C.

5. Q: (Mr. Weisz) Is that high enough to dissolve the carbides?

A: (Mr. Sikka) The $M_{23}C_6$ is dissolved, and the NbC seems to be dissolved, too. At least we can't find any after heat treatment. Normally that would take a higher temperature, but I enough.

6. Q: (Mr. Weisz) What about the rate of cooling? Is that important?

A: (Mr. Sikka) I don't think we have to worry for thicknesses up to 4 in.

7. Q: (Mr. Weisz) Do you have any residual austenite in your material?

A: (Mr. Sikka) We haven't seen any. We have seen up to 3% ferrite.

8. Q: (Mr. Weisz) Your creep ductility shows no decrease with time, but most of your data are for less than 10^4 h. EM12 doesn't begin to drop off in reduction of area until beyond 10^4 h. So you still need to study that further.

   A: (Mr. Sikka) Yes, but again our data out to 30,000 h still show reduction in area of about 80%.

9. Q: (Mr. Weisz) What is the difference between the allowable stresses in Sections I, VIII, and III?

   A: (Mr. Sikka) Those in Sections I and VIII are the same. Those in Section III involve much more detailed considerations of the creep properties.

10. Q: (Mr. Weisz) What is the state of the development of your weld wire?

    A: (Mr. Sikka) Most of our welding to date has been GTA, although we have done some SMA and SAW. We still have some work to do, but I think we will wind up with the same composition in our weld wire as in our base metal.

11. Q: (Mr. Hunter) Of course with SAW you have to be careful: The fluxes and all can change the composition.

    A: (Mr. Sikka) Right.

12. Q: (Mr. Weisz) Have you done any stress corrosion testing?

    A: (Mr. Sikka) No, but there was some previous work on the standard 9 Cr-1 Mo.

13. Q: (Mr. Weisz) What about wastage in sodium?

    A: (Mr. DiStefano) There are plans for stress corrosion testing, but we have not really planned for wastage testing.

14. Q: (Mr. Weisz) But is not that an important factor?

    A: (Mr. Hoffman) Yes, but we think it is similar to 2 1/4 Cr.

15. Q: (Mr. Weisz) How do you know that?

    A: (Mr. Hoffman) Granted, it is a guess. But we have funding limitations, and we can only do so much.

16. Q: (Mr. Weisz) Do you have the facilities for wastage testing?

    A: (Mr. Hoffman) I'm not sure.

17. Q: (Mr. Weisz) We might be able to run some tests in our facilities. By the way, have you developed a continuous cooling diagram for the modified 9 Cr-1 Mo?

    A: (Mr. Sikka) That work is under way at Climax Molybdenum. We might have it next month.

18. Q: (Mr. Weisz) What about studies of the microstructural changes during creep, cavitation, and that sort of thing?

    A: (Mr. Sikka) We have looked at most of the specimens, but we have seen no cavitation so far.

19. Q: (Mr. Schinkel) Was the transition temperature lowered by aging?

    A: (Mr. Sikka) It is within the scatter band.

20. Q: (Mr. Schinkel) Have you studied the effect of strain rate in your tensile tests?

    A: (Mr. Sikka) We are doing that, but up until now we have concentrated on a single strain rate to get baseline data.

"A Comparison of the Mechanical Strength Properties of Several High-Chromium Ferritic Steels," Mr. Booker, US-ORNL

1. Q: (Mr. Schinkel) Why have you looked at comparison with HT9 but not our 12 Cr MoV material?

   A: (Mr. Sikka) Because our fusion energy program has selected HT9 as an alternate structural material. Currently the 12 Cr MoV is not being used in the U.S.

2. Q: (Mr. Weisz) Why is the creep strength important above 550°C?

   A: (Mr. Booker) It may not be important for breeder applications, but we are considering use of the modified 9 Cr-1 Mo steel in a variety of systems.

3. Q: (Mr. Weisz) Do you plan to develop isochronous stress-strain curves for this material?

   A: (Mr. Booker) Yes, that will be part of our Code Case N-47 package.

4. Q: (Mr. Weisz) Are all your creep tests instrumented for strain measurement?

   A: (Mr. Booker) Yes.

"A Preliminary Analytical Assessment of the Structural Performance of the Modified 9 Cr-1 Mo Steel Relative to Other Alloys in Fast Breeder Reactor Applications," Mr. Yahr, US-ORNL

1. Q: (Mr. Weisz) I don't understand why your creep damage for alloy 800H is so high.

   A: (Mr. Yahr) I think that is an anomolous effect. We used material properties compiled by GE for their transition joint test, and the alloy 800H in that test had an unusually high yield strength.

"A Status Report on Exploratory Time Dependent Fatigue Behavior of 2 1/4 Cr-1 Mo and Modified 9 Cr-1 Mo Steel," Mr. Brinkman, US-ORNL

1. Q: (Mr. Weisz) You say the linear damage summation approach does not work, but can you prove it? You get voidage in sodium.

   A: (Mr. Brinkman) We have a lot of data that convince us that it doesn't work, but we definitely need more data in protective environments like sodium.

2. Q: (Mr. Weisz) How do you propose to treat creep-fatigue in this material?

   A: (Mr. Brinkman) In the short term we are working on approximations for the code that may be similar to linear damage. In the long term, we will develop improved models, but we need more data.

3. Q: (Mr. Weisz) Stainless steels are not stable metallurgically and they can have environmental effects, yet linear damage works for them. What is so special about the ferritics.

   A: (Mr. Brinkman) Nothing really. It is just that the magnitudes of the environmental and metallurgical effects are larger. Again, we have a lot of data, such as those at zero stress, that strongly indicate that linear damage will not work for this material.

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