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in Fossil Energy Applications

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Development of technically and economically viable processes for the conversion and utilization of fossil fuels is a major objective of the DOE Fossil Energy program. Many new and different processes are being investigated in areas of coal gasification, improved power generation and advanced combustion. As these processes evolve to the pilot plant stage and beyond, materials selection and component design become increasingly important for reliable and economical operation. The newsletter is intended to serve as a medium for exchange of information and experiences pertinent to the use of materials and components among the communities interested in the development of fossil energy systems.

Update on the European 700°C Steam Program

Since the mid-1990s, the manufacturers and power generators involved in the European power industry have been pursuing the installation of coal-fired power plant technologies capable of increased efficiency. The advances to date have been largely based on the use of 9% chromium steels, starting with P91 (Fe-9Cr-MoNbVCN) for thick walled components (headers and steam lines) as well as improved steel for the steam turbines. Table I summarizes the early European installations employing P91, and shows that the steam parameters used approached 300 bar and 600°C, representing net efficiencies in the range of 45-46% (lower heating value/LHV) for an inland location. The adoption of Japanese developments in ferritic-martensitic steels over P91 (for instance P92, Fe-9Cr-WMoVCN) has allowed tube temperatures to be further increased to 600°C, but it is thought that there is an upper temperature limit on the use of such ferritic steels, which appears to be in the range of 610-630°C, as suggested in Fig. 1. As a result, higher steam conditions will require the use of austenitic steels, or nickel-base alloys, with the latter being preferred (although they are more expensive) because of their higher thermal conductivity, and lower coefficient of thermal expansion, rendering them less prone to thermal fatigue than typical austenitic steels.

Table I. European Plants That Pioneered the Use of P-91 Components

Unit	Start-up	Net Output MW	Main Steam Conditions		Reheat Steam
			P, bar	T, °C	T, °C
Schwarze Pumpe[1]	1997	820	268	547	565
Boxberg[1]	2000	910	266	545	583
Lippendorf[1]	1999/2000	940	267	554	583
Skaerbaek[2]	1997	400	290	582	580
Nordjylland[2]	1998	385	290	582	580

1: German
2: Denmark

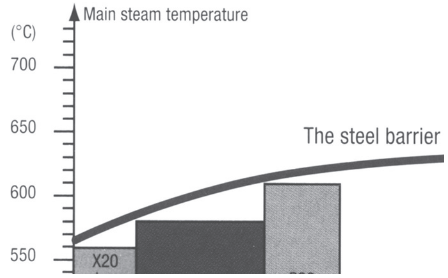

Figure 1. Development of Ferritic Steels, Showing Temperature Limits

Since 1997, the Europeans have been developing the technology and the required materials that will allow main and reheat steam temperatures to be raised into the region of 700°C, with the main steam pressure in the range of 350-375 bar. The net efficiencies forecast for such a plant are over 50% (LHV). Phase I of this work was initiated under the European Fourth Framework Program (FP4) and involved 40 partners from 13 countries, in a project coordinated by Elsam Engineering of Denmark and entitled 'Advanced Supercritical PF Power Plant Operating at 700°C' (or AD700 for short). The project covered both the development of new materials, improved designs, and investigation of the reliability of the AD700 technology.

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The creep strength target for each material was 100,000 hours at 100 MPa at a metal temperature of 750°C for the nickel-based alloys; 700°C for the austenitics; and 650°C for the martensitic steels. The work continued into Phase II under the Fifth Framework program (FP5), and again was coordinated by Elsam Engineering and involved 34 partners from 10 countries. Phase II is due to be completed at the end of 2005. The topics studied are:

- Demonstration of fabricability and manufacturability of materials from Phase I;
- Demonstration and in-plant testing of new materials from Phase I;
- Turbine component prototype manufacturing and testing;
- Preparatory component design;
- Preparatory work for Phase III (component demonstration phase), in particular, the definition of the test facility and identification of a host site; and
- Preparatory work for Phase IV (construction of the full-scale demonstration plant). This effort will include the development of a business plan and continued investigation of the economic viability of the AD 700 technology.

The materials efforts in Phases I and II were aimed at:

- Development and initiation of long-term demonstration of nickel-based alloys for components operating at steam temperatures above 650°C. These components include final superheaters and reheaters, final headers, hot-steam lines, turbine valves, inlet section of the turbine casings, and turbine rotors.
- Development and primary demonstration of austenitic steel for sections of superheaters and reheaters operating at steam temperatures in the range of 600-650°C.
- Development and primary demonstration of martensitic steels for headers and interconnecting steam lines operating at steam temperatures in the range of 600-650°C.

Preparatory work for Phase III of the program is well established, but this has proved to be the most difficult phase to start. The key to establishing Phase III was the willingness of nine major European power generators to share the cost of the test facility with the European Commission. This group of power generators, known as the E-max Group, consists of (in alphabetical order): EDF; Electrabel; Elsam; Kraft; EnBW Kraftwerke; ENEL; Energi E2; E.ON Energie; RWE Power; Public Power Corporation; and Vattenfall Europe. The original plan was to establish a test facility that was targeted at full-scale demonstration of furnace walls, superheaters, steam lines with high-pressure (HP) bypass and safety valves, and one HP turbine from each of the turbine manufacturers, Alstom and Siemens. All major components in the steam cycle were to have been demonstrated at full scale, and this approach would have shortened the time to commercial introduction of the AD700 technology by some five years. The planned host plant was Unit 3 at the Danish facility Skaerbaekvaerket. However, this plan was scrapped, because of (unexpected) lack of support of fossil-based technologies in the European FP6 Program.

Nevertheless, funding for a smaller component test facility (CTF) was obtained from an alternative source: the European Commission's Research Fund for Coal and Steel (RFCS); the participating consortium involved in its use consists of the E-max Group, minus ENEL. Other participants in this program (called CONTES 700) are Alstom Power Boiler; Babcock-Hitachi Europe; Burmeister and Wein Energy; and Siemens. The CTF will be established at E.ON's Scholven Unit F Power Plant and will operate at temperatures up to 700°C. The same components will be tested as originally planned, but at a smaller scale and without the turbines. A turbine valve will be installed jointly by Siemens and Alstom. The budget of Phase III is 15m euros, with 40% co-funding from the RFCS. It is planned to operate the CTF over four years. The project will be coordinated by VGB Power Tech. The materials to be tested at Scholven are shown in Table II.

Table II. Materials in the Scholven CTF Tests

Component	Alloy Class	Candidate Alloy
Furnace walls	Steel Nickel-based alloy	T24; HCM12; 617
Superheaters	Austenitics Nickel-based alloy	HR3C; Sanicro 25, DMV310N; 617, 740
Thick walled tubes	Nickel-based alloy	617
Turbine valve	Nickel-based alloy	625

In parallel with CTF, a smaller test rig (ETR), fully funded by the E-max Group, was installed in the summer of 2004 in the boiler of Elsam's Esbjerg Power Station. It is planned to operate this facility over four years, at steam temperatures up to 720°C. Testing will focus on oxidation and high-temperature corrosion phenomena of superheater materials, and is intended to augment the CTF corrosion data. The alloy test list consists of austenitic steels: type 347HFG; HR3C; Sanicro 25; as well as the nickel-based alloys: HR6W; 617; and 740.

This change in the original Phase III plan will probably result in delaying the start of Phase IV from 2008 to 2009. Also, Phases IV and VI are highly dependent not only on the successful outcome of Phase III, but also on renewed funding from the European Commission under FP7, which will run from 2008-2012. As planned, the final Phases (IV and VI) will involve a three-year period of operation of the full-scale demonstration plant (FSDP, approximate output 400 MW), during which experience from the plant will be fed back to the partners. It is expected currently that it is likely that the AD700 technology will be commercially available around 2014.

Abstracted from: *S. Kjaer, J. Bugge, Elsam Engineering, Denmark; and C. Stolzenberger, VGB, Germany, "Europeans Still Aiming for 700° Steam," Modern Power Systems, Vol. 24(11), pp. 19-25 (2004). Used by permission of Wilmington Publishing, Sidcup, Kent.*

Materials Development in the European AD700 Program

While the design of the full-scale demonstration plant for AD700 technology maximizes the use of the 9-12 chromium ferritic/martensitic steels, there was also the need to consider the materials required for operation above the approximately 620° temperature limit of those alloys. As a result, development and qualification work was established for two new alloys: an austenitic steel from Sandvik (Sanicro 25); and a nickel-based alloy from Special Metals, Inc. (alloy 740). Additionally, within the German MARCKO Program, similar qualification work has been undertaken on the nickel-based alloy 617, intended for boiler tubes and steam lines. In fact, preliminary code approval has been available for this alloy since the beginning of 2004 from the Germany Notified Body. As a fall-back position (should there be problems with Sanicro 25 or alloy 740), an existing nickel-based superalloy (C263) has been included in the program. In addition, despite its lower creep strength, alloy 617 also is a candidate for thick-walled sections.

Alloy C263 is a precipitation-hardened material that may be difficult to manufacture, whereas alloy 617 is not expected to present problems. Nevertheless, a 5 m-long length of main steam line has been extruded by Scottish Wyman Gordon from an ingot of C263 made by Special Metals, Inc., but additional work is needed to qualify the material. As a result, it will not be included in the CTF testing at the Scholven test rig.

The criterion set in the AD700 Program for alloy strength is 100 MPa creep strength for 100,000 hours at the temperature of interest, so that sufficiently thin-walled pressure vessels can be used with the expectation of minimizing thermal fatigue problems. Figure 2 indicates the 100,000 hour creep rupture stress curves as a function of temperature for a range of alloys, including those selected by the AD700 Program (174 = Sanicro25); the data included for alloys 263 and 740 were extrapolated from values based on 20,000 hours of testing. For Alloy 617, the preliminary value approved by the European authorities is 120 MPa at 700°C, but at the end of the qualification work, public approval of 131 MPa at 700 is expected for this alloy, which still is around 30% below the extrapolated values for alloys 263/740.

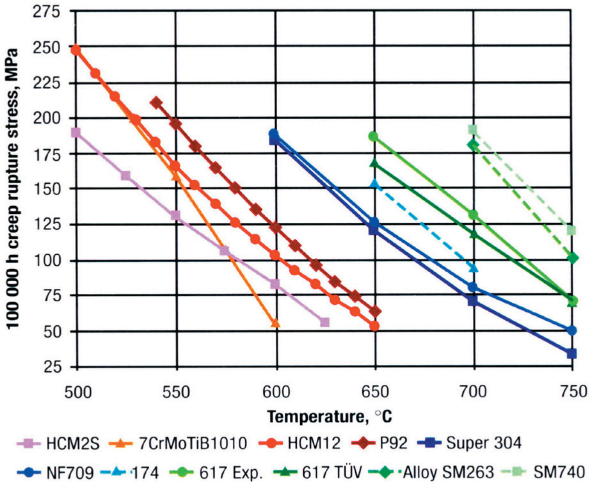

Figure 2. Creep Strength Data for Candidate Alloys

For full qualification of materials for use in boiler tubes and steam piping, the European codes require 30,000 hours of creep testing (which are extrapolated to 100,000 hours). Further, each manufacturer of boiler tubes and steam piping must demonstrate all manufacturing stages, including bending, welding, creep tests on its own melts, in order to secure public approval of the expected strength values. The expected materials suppliers for the AD700 Program are listed in Table III, and the alloy compositions are shown in Table IV.

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Table III. Candidate Alloys for Temperatures >620°C

Component	Alloy	Supplier
Austenitic boiler tubes	Sanicro 25	Sandvik
	HR3C; Super304H; HR6W	Sumitomo
	310N	VDM
Steam piping	Alloy 263	Special Metals, Inc.
	Alloy 617	Vallourec and Mannesmann, Saarschmiede or Foroni
Nickel-based tubes	617	VDM
	740	Special Metals, Inc.
Nickel-based valves and casings	617 or 625	Goodwin Steel Castings (U.K.)
		Voest Alpine (A)
Nickel-based rotors	617 or 625	Saarschmiede; Boehler

Table IV. Alloy Compositions (weight percent)

Alloy	Fe	Ni	Co	Cr	Mn	Mo	W	Si	C	N	Other
Super304H	Bal	9		18	0.8			0.2	0.1	0.1	0.5Nb, 0.1Ti
HR3C	Bal	20		25	2			0.75	0.07	0.2	0.4Nb
HR6W	Bal	43		23	1.2		6	0.4	0.08		0.08Nb & Ti
310N	Bal	21		24.7	1.2			0.75	0.06	0.21	0.45Nb
Sanicro25	Bal	25.5	1.6	22.6	0.5	0.02	3.45	0.25	0.08	0.24	3Cu, 0.4Nb
Alloy 263	0.7	Bal	20	20	0.6	5.8		0.4	0.06		2.6 Al+Ti, 0.2Cu
Alloy 617	3	Bal	13	22	1	9		1	0.1		0.5Cu, 0.6Ti
Alloy 625	5	Bal	1	22	0.5	9		0.5	0.1		3.5Nb+Ta
Alloy 740	2	Bal	20	24	0.3	0.5		0.5	0.07		2Nb, 2Ti

Problems in Identifying the Root Causes of Superheater Tube Failures in 9Cr Steels

The choice of materials employed for superheaters and high temperature steam pipework in steam-generating power plants is necessarily conservative, and is largely governed by the appropriate safety licensing codes, as well as practical experience. A new class of materials, the 9% Cr martensitic steels, was introduced into service some ten years ago, and there are hopes that further developments of this class of material can lead to ferritic-martensitic steels being used up to metal temperatures in the range 620-650°C. The first of this new grade of steels to be used was P91 (for headers) and T91 (for tubes). These materials have been in service now for some time, and two related issues are beginning to emerge. Firstly, what techniques are available to predict superheater life, especially if it is suspected that the equipment has been running above the design temperature? Secondly, if over-temperature operation is suspected, can changes in this type of alloy be used to estimate operating temperatures?

Since the introduction of P91, initially for headers, efforts have been made to improve on the performance of this class of alloy. The next alloy in this class that is set to go into service is P92, which has additions of tungsten and molybdenum for solid-solution strengthening, as well as a tighter specification of the precipitate-strengthening elements. The levels of chromium and silicon in P92 also have been tightened up, to ensure a sufficiently wide austenitic phase field for heat treatment. Hence, the oxidation resistance of P92 is recognised to be somewhat poorer than P91, and much inferior to either 12Cr or austenitic stainless steels.

Parametric Strength Issues

Before examining the question of the possibility of using time/temperature/stress parametric equations to estimate whether overheating is occurring, it is worth examining how design stresses for high-temperature components are determined. This is an important question. If the design stress is overestimated, or the alloy is more sensitive to temperature than is recognised, the equipment will fail prematurely. The parametric equations will suggest that the equipment has been running too hot, and needless time could be spent in investigating non-existent furnace problems.

In order to assess the allowable stresses to give a desired design lifetime (100,000 or 225,000 hours) for a new superheater alloy, tests typically are run for a relatively short duration, and extrapolations are applied. A typical way of accelerating such tests is to run them at higher than anticipated service temperatures, and then to extrapolate the results to longer times at lower temperatures using, for instance, a Larson-Miller parametric technique. An alternative is to extrapolate logarithmic plots of stress against time. The main difficulty with such extrapolations is that, at longer times, the curves tend to bend downward in a manner that is difficult to predict. Further, since data typically are collected at specific temperatures (for instance, at every 50°C/90°F), the stresses at other temperatures need to be interpolated, which again results in uncertainties. Different authorities, using different approaches to the extrapolation of long-term strength, have produced a range of strength values for P91, as illustrated in Table V. Since creep life is inversely proportional to the third or fourth power of the stress level at longer times, even an over-estimation of 10% in the design stress could lead superheater failure in less than 3/4 of the expected time. No doubt, as experience builds up with this material, the estimates will come into line.This variation in the estimated long term strengths is quite distinct from any particular shortcomings of a given alloy batch. For instance, interactions of minor additions (such as Al and N) can have a profound effect on the creep strength of a 9Cr steel; as an example, if conditions are such that Al can remove N from solution in the alloy, the formation of the VCN particles used to pin dislocations and subgrain boundaries can be prevented. Such reactions are, in fact, likely during the tempering treatment that these alloys receive after hardening, particularly if the materials are over-tempered. In such cases, the lack of VCN precipitates may be inferred from simple testing, since the hardness of the alloy is likely to be lower than expected. In short, the time to failure is not a very good way of estimating average operating temperature.

Table V. 100kh Creep Rupture Strengths (MPa) Estimated for P91 Using Different Evaluation Methods

Evaluation Method	500°C	550°C	600°C	650°C
ASME	164	141	98	—
VdTüV	253	162	90	—
EN	258	166	94	48

Nevertheless, in the absence of any other techniques, a failure investigator will normally use a parametric method to estimate service temperatures. The most common extrapolation technique is that of Larson-Miller, where there is a specific parameter (P) for each stress level, which is given by the equation P = T(C + t), where is T is temperature in Kelvin; C is a constant which modifies the impact of time on exposure; and t is the time in hours to failure. The term C does not change with stress, but a reasonably accurate value is needed to assess the amount of overheating. As might be anticipated in view of the spread of creep properties for alloy P91, there is some debate about the relevant value to be used for C. Preliminary extrapolations used a value of C of around 35. This seems to be true for relatively short term tests, as recent work has indicated that a value of 38 is appropriate for tests of up to 20,000 hours. However, the same researchers, from a Japanese institution, consider that for longer times the value should be 20. European studies also suggest that an appropriate short-term value for C would be 31, but for longer-term tests, at lower stresses, the value should be 22. For a complete range of high and lower stresses, a value of 23.9 is suggested.

In a hypothetical failure investigation, we can see what this range to Larson-Miller constants can do to any temperature estimates. Based on the alloy data available to designers in the 1990s, the allowable design stress for 100,000 hours of operation at 600°C would be 65.5 MPa. While the actual time to failure at this stress level and temperature would not be reliably known, it would be on the order of 40 years of continuous operation. An illustration of the differences in calculated temperatures resulting from the use of these different values is given in Table VI. This shows the temperatures that would correspond to failure times of 50, 75, and 100kh, using C values of 23 and 35, respectively. The temperatures for failure times of 225 and 500kh also are given.

Table VI. Estimates of Temperatures Corresponding to Time to Failure at a Stress Level of 65.5 MPa

Failure Time kh	L-M Constant = 23 (parameter = 24921)	L-M Constant = 35 (parameter = 35997)
10	650°C	650°C
50	626°C	633°C
75	621°C	629°C
100	617°C	627°C
225	605°C	619°C
500	595°C	611°C

The effect of the difference in C value is not of great significance if the equipment failed within a relatively short time. Failure causes might then be put down to:

- Outlet steam temperatures higher than design, from excessive flue gas temperatures or low steam flows.
- Formation of a thick oxide scale, especially if the heat transfer rate was high.

However, it will be apparent thay with a C value of 23 at a temperature of around 617°C, the component would last 100kh. If the correct value was 35, the material would have lasted for well over 225kh. In terms of equipment design, this has major implications.

Effect of Exposure Time and Temperature on Hardness

Room-temperature hardness testing could, in principle, be used to detect overheating, although there are practical problems in its application, even with well-understood materials. With the older alloys, precipitate coarsening and the resulting easier movement of dislocations is the major cause of the drop in hardness with time at temperature. However, there tends to be significant scatter in data from in-situ hardness testing. In addition, pre-service values are not always available, and can be distorted by stress relief of weldments. Such sub-optical changes are diffusion controlled, and are stress dependent as well as temperature dependent. With P91 and T91, while precipitate coarsening occurs and leads to a reduction in hardness, recrystallisation of the martensitic structure also reduces the barriers to dislocation movement. These changes appear to be accelerated in P91 by stress, as well as by temperature. As a result, hardness changes are increased in the gage length of test specimens, where the stress is higher than in the specimen shoulders. The magnitude of such effects has been reported to be of the order of 20-25%. Other observations have suggested that this fall-off in hardness is less pronounced as the failure time is increased from -- for instance -- 3,000 to 28,000 hours. Since these observations were made typically from creep tests that were accelerated compared to typical plant exposures, it is unclear how much the hardness will fall in very long exposure times. Nevertheless, the question remains whether, at the stress values used for design purposes, these 9Cr alloys will behave like the material in the head, or in the gage length of the laboratory specimens.

Assessment of Service Lifetime Through Microstructural Change

Of major importance in attempting to assess service life is whether there are significant and easily observable microstructural changes which result from long-term exposure to temperature. The metallurgy of the 9% Cr martensitic steels is quite different from those of the older ferritic steels, such as the carbon-manganese grades and T22 (2.25 Cr-1 Mo). This older class of alloys has either ferrite-pearlite, or ferrite-bainite microstructures in which, after long-term exposure to high temperatures, spheroidisation occurs of the optically visible carbides, as well as coarsening of the submicroscopic carbides, resulting in degradation in creep strength.

The situation with respect to the aging characteristics of the 9Cr alloys is not so simple, because there are no real changes in the optical microstructure over the service lifetime of these materials that can be observed by the usual techniques. Typically, the microstructure of alloys P91 and P92 continues to have a distinct, martensitic appearance even after long-term, high-temperature exposures. It has been suggested that, although there are changes in the crystal structure of the laths of martensite (from body-centered tetragonal structure, to a new body-centered structure, to ferritic structure) cannot be used to indicate temperature, even though these changes in the crystalline structure of the martensite reduce its strength. There are changes in the size, composition, and distribution of the sub-optical precipitates, but these changes can only be detected using thin-foil transmission electron microscopy. This is hardly a practical technique for evaluating superheater life. Furthermore, as will be seen, as with hardness changes in this material, there are questions about whether stress affects the rate of change.

More importantly, unlike the lower-alloyed materials, it seems to be extremely difficult to detect the formation of creep cavities in P91 until it is very close to the end of its creep life. Nevertheless, this technique might be helpful when attempting to assess the life of weldments.

Oxide Thickness for Estimating Temperature

Measurement of the steam-side oxide thickness is quite widely used to assess the average operating temperature of superheater tubes of low-alloy steels such as type T22. Such measurements often can be made using nondestructive ultrasonic techniques on the tubing in situ. However, there is a major problem in applying this technique to the class of 9Cr martensitic steels, since the oxidation rate of these alloys is changed significantly by relatively minor changes in alloy chromium content. Figure 3 illustrates the rapid decrease in oxidation rate in steam at 650°C, as a function of relatively small changes in chemical composition of 9Cr-type alloys, including P92 and developmental alloys containing cobalt. Similar trends have been observed at 600°C. Even where the alloy chromium content can be held close to 9%, very small variations in the second-order elements (such as silicon) can have sufficient effect on the corrosion rate that the technique of using oxide thickness measurements for estimating average metal temperature is rendered, at best, semi-quantitatively. Nevertheless, where all the tubes in a given section of superheater are from the same alloy batch, the oxide-dating technique could be used to determine whether there were tube-to-tube variations in temperature, and so point out variations in steam flow or flue gas flow, or local tube blockages.

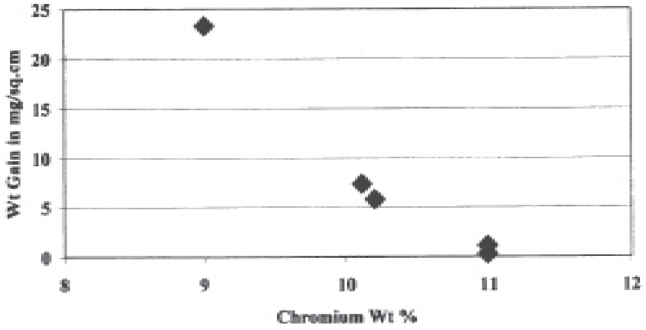

Figure 3. Effect of Chromium Content on Oxidation Rate of P92 (and Developmental Alloys Containing Co) in Steam at 650°C, after 2,650 h of Exposure

It will be also appreciated that compared to many alloys the steam side oxidation resistance of P91 alloys is relatively high. The insulating effect of this oxide can, in superheater tubes under conditions of high heat transfer, lead to increases in tube temperature. It can also be postulated that this increase in temperature, cause a further increase in oxidation rate, so that a mild runaway effect may result. Such a problem would increase the difficulties for the failure investigator in determining tube life.

Conclusions

The author of the original article has commented that with respect to P91, the situation is similar to that described by a well known American politician who has said that there are “the known knowns, the known unknowns and the unknown unknowns”. However, there clearly are a number of potential problems in the identification of the root cause of creep failures in superheater tubes made from 9Cr alloys. None of the current approaches is very effective, and it is necessary to marshal these in coming to conclusions about whether the cause was the alloy or some problem related to the furnace. However, when relying on alloy-related evidence which might point to overheating, it is vital to take into account the questions relating to the Larson-Miller parameter, estimates of design strength, and how small changes in alloy composition might affect hardness and oxidation resistance.

It is certainly advisable to examine furnace operational records to assess whether heat transfer rates are excessive or steam flows are below design. Here, the fact that most modern plants are well instrumented will help. From this information and comments by operating staff, it would be possible to show, for example, that high flue gas temperatures could indicate problems such as furnace slagging; high levels of excess air; too much flue gas recirculation; over firing; etc.

In the case where a tube has failed by creep, where the heat transfer investigations or other indications indicate that there has been little or no overheating, the implication would be that the creep strength of the material was too low. Such a condition may have resulted from the original heat treatment, which could be reflected in the original hardness value. The as heat-treated hardness also can be affected by compositional differences, such as high aluminium levels, as mentioned earlier. Nevertheless, it appears possible that, even when the alloys are made exactly to specification, it is probable that the strength of P91 may have been over-estimated due to difficulties in the extrapolation of data from accelerated stress rupture tests.

Abstracted from: F. Starr, European Technology Development, Ltd.; J. Castle and R. Walker, University of Surrey, U.K., "Potential Problems in the Identification of the Root Cause of Superheater Tube Failures in 9Cr Martensitic Alloys," Materials at High Temperatures, 2(3), 147-160 (2004). Used by permission of Science Reviews, St. Albans, Herts.

Progress in Direct Firing of Gas Turbines with Coal

The development of Ultra-Clean Coal (UCC) as a substitute for fuel oil was started in the 1980's in Australia under the auspices of the Cooperative Research Center for Black Coal Utilization, the Commonwealth Scientific Industrial Research Organization (CSIRO), Division of Energy Technology, and the Australian Coal Association Research Program. The first formulation of UCC was a coal/water slurry containing approximately 0.5% ash. Continued research in the intervening period has resulted in a solid, powder fuel with ash levels between 0.1 and 0.2% that can be directly injected into a gas turbine. Development of this technology is currently being pursued by UCC Energy Pty., Ltd., a wholly-owned subsidiary of White Mining, Ltd., in co-operation with CSIRO.

The process to produce UCC involves a series of steps in which the minerals are removed from the coal by dissolution in both acid and alkali, and are then precipitated as calcium sulfates and calcium aluminum silicates, which can then readily be separated out. The by-products from the process are gypsum, and silicate materials that can be used in the production of ceramics. The process involves a closed-loop system for sodium hydroxide and water, and more closely resembles a chemical plant than a conventional coal-washing facility. Since one third of the process costs relate to the chemical feedstocks, the use of a higher-quality coal feed containing less silicate and aluminum compounds can lead to significantly-reduced costs. Extensive efforts have been devoted to developing the control system for the process, and its successful implementation has paved the way for a full-scale demonstration project.

There are several substantial benefits claimed for UCC: direct firing in a gas turbine combined cycle is expected to result in an overall thermal efficiency of approximately 53%, and its use allows coal to supply energy as a peaking fuel, previously the exclusive domain of gas and liquid fuels. In terms of effects on greenhouse gas emissions, it is estimated that the combined operation to produce UCC (coal mining plus UCC processing) produces 185 kg/MWh of CO_2, while combustion of the UCC in a gas turbine combined cycle produces a further 607 kg/MWh, giving a total of 792 kg/MWh of CO_2. This compares to 71 kg/MWh of CO_2 for conventional mining, plus 794 kg/MWh for a conventional coal-fired power plant, for a total of 865 kg/MWh, representing a reduction in greenhouse gas emissions of up to 20%, compared to a conventional coal-fired plant.

The projected cost of UCC is $3 to 3.5 dollars per GJ, compared to natural gas at approximately $4.95 per GJ (currently prices) in the U.S., or liquid fuels at $3.96-6.44 per GJ. Since the UCC process is suited to most bituminous coals, it is potentially of great importance to developing countries.

Gas Turbine Trials

The Japanese Center for Coal Utilization arranged for the participation of Mitsubishi Heavy Industries (MHI), Idemitsu Kosan Co. Ltd., and the Kyushu Electric Power Co. Inc., in the assessment of UCC as a directly-fired gas turbine fuel. Idemitsu Kosan Co. Ltd. and the Kyushu Electric Power Co. Inc. were involved in the preparation, testing, and economic evaluation of the fuel, and MHI performed combustion trials using a modified MHI model 501G gas turbine at its Takasago facility. The MHI fuel specification included an ash content of less than 0.2%, with a particle size of less than 5μm in order to avoid turbine hot section damage by erosion, and the combustor and fuel injection system of the turbine were modified to accept UCC fuel instead of natural gas.

The UCC produced for the first gas turbine trial had an ash content of 0.28% (Table VII), slightly below the target level of 0.2%, while the particle size of the ask was < 4 μm. The softening point of the ash was 1340°C (melting point > 1500°C). It was thought that partial melting of the ash might be possible in the turbine, which has a rotor inlet temperature of 1350°C. In the gas turbine combustor trials, the UCC was fed to the combustor by a pneumatic transport system, and fired with air preheated to 450°C (maximum). The initial design of the UCC delivery system resulted in occasional instabilities in fuel delivery, which had a detrimental impact on overall combustion efficiency.

Table VII. Chemical Composition of UCC

Element	Content, ppm		
	Parent Coal	UCC (laboratory)	UCC (GT trial)
Si	24,800	35	78-129
Al	12,300	8	43-63
Ti	733	477	398-486
Fe	3,383	34	127-184
Ca	437	22	11-61
Mg	431	5	5-7
Na	919	58	160-227
K	464	9	0.2
P	86	3	4.5-6.0
Mn	13	0	0.5-0.7
V	29	12	8.1
Total ash	8.3%	0.15%	0.28%
Ash particle size	–	< 5μm	<4 μm
Ash fusion (IDT)	>1500°C	>1500°C	>1500

Assessment of the turbine after firing with six tons of UCC from the pilot plant revealed no major practical problems; stable and efficient combustion were achieved. Initial tests showed no erosion of the turbine blades, though there was the possibility of some particle adherence. One concern was the substantially higher maximum temperature measured at the combustor wall when burning UCC, compared to kerosene, which ranged from 150 to 400°C, depending on the UCC equivalent fuel/air ratio.

The success of the initial trials has led to efforts to optimize NO_x control when firing this fuel. In addition, component lifetime trials are planned with the adapted 501G turbine. These will involve tests with considerable quantities of UCC at high pressure (10 atm), and at temperatures corresponding to the rotor inlet temperature of the turbine. A key objective of these trials is to establish the role of the sodium and titanium compounds present in UCC after processing, since these do not exist in petroleum products, so that there is little experience available. While limited quantities of ash remain in the UCC, ash fusion temperature (>1500°C) may be an issue, since the combustion temperature in modern gas turbines approaches this level.

Plans are to follow the lifetime trials with pilot-scale demonstration in 2008, at a capacity of 6-15 MW. This facility would run for some 18 months, and consume around 20,000 tons of UCC. If the commercial demonstration is successful, it is expected that the fuel could become available on a commercial scale within 4-5 years.

Abstracted from: K. Clark, et al., "Ultra-Clean Coal as a Gas Turbine Fuel," Report on the Collaborative Study to Evaluate the Production and Utilization of UCC as a Direct-Fired Fuel in Gas Turbine Combined-Cycle power Plants, CSIRO web site: http://www.csiro.au, and D. Appleyard, "Turbines That Burn Coal," Modern Power Systems, 24 (11), 27-30 (2004).

The European Fossil Energy Coalition

The Fossil Energy Coalition (FENCO) has been formed to represent European countries that aim to reinsert funding for fossil energy into the European Commissions R&D (Framework) programs, and is particularly focused on the European Commission and the European Parliament. Based on projections that the total coal use worldwide will increase in absolute terms for several decades to come, FENCO favors a balanced portfolio of energy supply options to ensure that European industry can gain a share of the global market. By coordination of the fossil energy programs of the European Member States, a critical mass initiative could be established in Europe that could compete with the U.S. and Japan (where there is perceived to be significant government support). The main drivers behind the FENCO initiative are Germany and the U.K, and it is intended that the German and U.K. national programs for development of fossil-based technologies will form the core of FENCO.

The German Program (COORETEC) addresses the improvement of many technologies, including CO_2 capture and storage (CSS). COORETEC coordinates three major R&D programs address the development of conventional power technologies in Germany: AG Turbo; MARCKO II; and COST 522/5. The U.K. national program is Carbon Abatement Technologies (CAT). Successful development and deployment of CSS offers the promise of nearly zero emissions of power technology based on fossil fuels. It is expected that the development of capture-ready technologies will provide the route from efficiency-improvement programs (such as AD700), to the development of CCS technologies. As a result, the technical scope of FENCO embraces both efficiency, improvement, and CCS.

It is planned that the work proposed by FENCO will be established as an ERA network, that can be funded through the Framework 6 program for the coordinating efforts;

the R&D efforts will continue to be funded or managed through national public programs.

The nickel-based alloy development program in Phase II of the AD 700 Program that was co-funded under FP5 has been coordinated since the start of Phase II with the MARCKO Project in Germany. This means that information on development on different nickel based alloys is exchanged between the two groups.

Abstracted from: *S. Kjaer, J. Bugge, Elsam Engineering, Denmark; and C. Stolzenberger, VGB, Germany, "Europeans Still Aiming for 700°C Steam," Modern Power Systems, Vol. 24(11), pp. 19-25 (2004). Used by permission of Wilmington Publishing, Sidcup, Kent.*

A Brief History of 20Cr-25Ni Steel as Used in the UK

There has been considerable, recent interest in 20Cr-25Ni steels for application as tubing in advanced steam generator designs, and as thin foils for the construction of recuperators used with small gas turbines and diesel engines. This interest is based on the ability to develop a combination of high creep strength and excellent oxidation resistance at elevated temperatures in an alloy that has cost advantages over the competing Ni-based alloys. In fact, the 20Cr-25Ni austenitic steel is not a new alloy: it has been used commercially in the UK as nuclear fuel cladding in the Advanced Gas-cooled (nuclear) Reactors (AGRs) since 1962. Optimisation and property evaluation work which led to its selection was underway in various nuclear-research centers in the UK from about 1956. The alloy is still used extensively in the UK nuclear industry as fuel cladding, and as braces within the fuel stringers. In the former case, it is used in the form of thin-walled (~ 0.38 mm/15 mil thick) tubing of approximately 15 mm (~0.6 in) diameter and 1 m (38 in) in length, which also has a surface helical network of ribs (0.25 mm/0.01 in height) to aid heat transfer to the circulating coolant of CO_2/1%CO at 41 bar (600 psi) pressure. This tubing contains hollow pellets of enriched UO_2 fuel, and is sealed with welded end caps of the same alloy at top and bottom. This constitutes a single fuel pin, of which there are around 90,000 in a typical AGR. The total length of 20Cr-25Ni tubing in such a reactor is then about 90 km (56 miles). Electrical output from a typical reactor will be approximately 600 MW, and AGRs, although considered old technology, still produce roughly 15% of the UK's total electrical requirement.

Normal operating temperatures of the fuel cladding are in the range 550-850°C (1022-1562°F) and exposure periods can extend to 6 years. Some postulated fault situations can result in the cladding experiencing temperatures of 1300°C (2372°F), however, for brief periods (up to 1 hour). An important primary function of the fuel cladding is to provide a structural framework, and to confine the enriched UO_2 pellets and radioactive products within it. Oxidation of the cladding and its chemical compatibility with the coolant, together with its mechanical properties under both normal and fault conditions, have been important research issues for decades. Very little, if any, of the early research and development work was published in the open literature at the time, however, although papers did appear, typically some 10 years after the event.

Current alloys are double vacuum melted, with close control of trace elements to avoid the formation and release into the circuit (via spalled oxide) of highly-active radio-nuclides. A typical notional composition is (mass %): 20Cr, 25Ni, 0.015C, <0.004N, 0.6Nb, 0.5Mn, 0.6Si, 0.02S, 0.01P, <50ppm Co, all other trace elements in the ppm range, balance Fe.

Structure and Creep of the Basic Alloy

Present practice in the UK nuclear industry is to use the alloy in the fully-recrystallised, weak condition after annealing in hydrogen for 1 hour at 930°C (1706°F). The structure is entirely austenitic, with a dispersion of submicron NbC particles having spacings of around 1 mm (reported in the conference: Creep Strength in Steel and High Temperature Alloys, The Metals Society, London, 1974). Other papers on 20Cr-25Ni creep and structure at this conference addressed the precipitation process; the influence of the Nb:C ratio; and also the effects of cold work. The mechanical behavior has been studied extensively, with emphasis on biaxial creep of internally-pressurised, ribbed tubes, and the annealing of void-like creep fracture damage during stress-free periods at high temperature. The regeneration of creep ductility that ensues has been allowed for in lifing codes.

Mechanistic studies have indicated creep-strengthening by NbC precipitation directly onto dislocation networks, as well as drastic reduction in creep ductility by particle-denuded zones at grain boundaries, through a strain-mismatch process. A theoretical treatment was developed to describe the strengthening process in these thermo-mechanically treated variants of the alloys.

Creep of TiN-Strengthened 20Cr-25Ni Steels

In the late 1960s, this writer initiated development of high-strength versions of the steels, based on the formation of a dispersion of TiN particles produced by internal nitridation. At about the same time, parallel, independent work using the same approach on 18Cr/12Ni steels was also being undertaken in the US by Allegheny Ludlum.

Internal nitridation of AGR cladding was undertaken in the UK after tube manufacture and rib machining of relatively weak alloys, containing around 1.5 mass% Ti. The annealing was performed at 1150°C (2102°F) in a 1-atmosphere mixture of $95\%N_2/5\%H_2$, at which temperature Ti was selectively nitrided in preference to Cr. Excess nitrogen was then removed from the alloy by a further anneal at the same temperature, but in pure H_2. This treatment produced through-thickness penetration of the nitridation front, and a corresponding dispersion of TiN particles which, through most of the section, were of sub-micron, cruciform shape.

Creep data on these strengthened 20Cr-25Ni/TiN alloys were available in the open literature from 1972, and summarised the optimization work with regard to Ti, Si and Zr additions. Very large increases in creep strength were obtained, typically a factor 10^4 reduction in creep rate, compared with the standard 20Cr-25Ni/Nb steel. Later, mechanistic studies related these improvements to the existence of threshold stresses which were needed for dislocations to by-pass the cruciform TiN particles.

Oxidation of the Standard and TiN-Strengthened Alloys

The main findings of the early development work on the standard 20Cr-25Ni/Nb steel, with emphasis on its high-temperature oxidation properties, were presented at the conference: Corrosion of Steels in CO_2, Br. Nuclear Energy Soc., Eds. D.R. Holmes et al., London, (1974), which showed how the 20Cr-25Ni/Nb steel had the best oxidation behaviour in high-pressure CO_2/5vol%CO, of a number of other possible candidate steels for fuel cladding. These included: 18Cr8Ni/Nb, 19Cr14Ni/Nb, 20Cr-25Ni/low-C, 20Cr-25Ni/Ti, 20Cr30Ni/3Mo/Nb, 20Cr30Ni/Mo and 20Cr30Ni/Nb. Data were also provided on the effect of thermal cycling frequency on the standard 20Cr-25Ni/Nb. The benefit of Si additions on the oxidation of type 321 steel was found to be significant at around 0.5-0.7 mass%, and this was used as the optimal range for the 20Cr-25Ni/Nb. Later work on this actual alloy and its TiN-strengthened variant by the UK nuclear industry confirmed this choice, and established that a reasonably continuous silica layer was formed underneath the protective surface chromia layer at this alloy composition. It was considered feasible that control of the oxidation reaction was by cation transport through this silica layer. At Si contents in excess of around 1 mass%, chromia growth rates were found to increase and this was associated with the formation of discreet particles and intergranular intrusions of silica, rather than a continuous layer. Chromia growth rates in the optimized alloy, over a wide range of temperatures, were collated in studies which addressed breakaway oxidation resulting from Cr depletion in the alloy, due to its selective oxidation, as well as the development of predictive procedures.

An underlying concept in modelling scale spallation is that of a critical strain energy criterion in which the stored energy within the oxide layer, which increases progressively during cooling, becomes sufficient to produce oxide/metal decohesion. Based on thermobalance measurements of the critical temperature drop to initiate spallation, several studies have shown that the spallation process occurs by wedge cracking rather than buckling, and can be defined by an effective interfacial fracture energy of 6 $J.m^{-2}$. Finite element methods have been used to show that a significant fraction of this value represents energy dissipation by substrate creep during cooling. It means that weaker alloys are more resistant to spallation than stronger alloys.

Because of the thin-walled sections used in AGR fuel cladding, particular attention has been paid to the consequences of oxide spallation, both in terms of the mass of material released (a radioactive dust burden in the reactor circuit), and its consequences on section loss through pit formation.

Carbon Deposition and Carburization

The oxygen potential of the AGR environment is dominated by the CO_2/CO ratio but, under normal circumstances, the carbon potential is determined by the dissociation of trace hydrocarbons, such as ethene. Carbon activities greater than unity are readily obtained and deposition of filamentous carbon on heat transfer surfaces is a continuing issue. Not surprisingly, much effort has been spent on trying to understand mechanisms but it is only recently, through TEM examination, has this been achieved. It was found that the carbon filaments are catalysed by 10 nm Ni particles which are formed in the early stages of oxidation of the alloy. This is so because the oxygen activity is sufficient to oxidize Fe and Cr, but not Ni. The initially-formed spinel oxides are porous, and allow access of the hydrocarbon-bearing gas to these catalytic particles. A fine surface grain size, or pre-oxidation to form a silica or chromia surface layer, are good things. The deposition process can also be inhibited by poisoning of the catalytic particles by S, in the form of additions of around 100 vppb of COS.

From: Hugh E. Evans, Department of Metallurgy and Materials, School of Engineering, The University of Birmingham, Birmingham, UK.

Program Awards for the Development of Multi-Megawatt Fuel Cell Systems

The US Department of Energy's new Fuel Cell Coal-Based Systems program is intended to develop the fuel cell technology required for central power stations that will produce affordable, efficient, environmentally-friendly electricity from coal. The new program leverages knowledge gained in DOE's Solid State Energy Conversion Alliance (SECA) on solid-oxide fuel cell (SOFC) technology. Key system requirements to be achieved include:

- At least 50 percent overall efficiency in converting the energy contained in coal to grid electrical power.
- Capture of 90 percent or more of the system's carbon dioxide emissions.
- Cost of $400 per kilowatt, exclusive of the coal gasification unit and carbon dioxide separation subsystems.

Projects will be managed by the Office of Fossil Energy's National Energy Technology Laboratory, and will be conducted in three phases: Phase I involves design, cost analysis, fabrication, and testing of large-scale fuel cell stacks fueled by coal synthesis gas. Central to the Phase I effort will be the resolution of technical barriers with respect to the manufacture and performance of larger-sized fuel cells._ _Phases II and III will focus on the fabrication of aggregate fuel cell systems and will culminate in proof-of-concept systems to be field tested for a minimum of 25,000 hours. These systems will be sited at existing or planned coal gasification units, potentially at DOE's FutureGen facility.

The first two projects selected are:
Solid Oxide Fuel Cell Coal Based Power Systems which will develop an integrated, gasification fuel cell system that merges General Electric's SECA-based SOFC, a gas turbine, and coal gasification technologies. The system design incorporates a fuel cell/turbine hybrid as the main power generation unit. The project team involves General Electric Hybrid Power Generation Systems in partneship with GE Energy, GE Global Research, the Pacific Northwest National Laboratory, and the University of South Carolina. The value of this DOE Phase I award is $7.5 million, which has a duration of 36 months.

Coal Gas Fueled Solid Oxide Fuel Cell/Gas Turbine Hybrid Power System with CO_2 Separation which will develop large-scale fuel cell systems based on a Siemens Westinghouse Power Corporation in-house gas turbine and SECA-modified tubular SOFC technology. ConocoPhillips will provide gasifier expertise, while the baseline design will incorporate an ion transport membrane oxygen separation unit from Air Products and Chemicals Inc. The value of this DOE Phase I award is $7.5 million, and the duration is 36 months.

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DOE Unveils Plans for Gas Turbines to Operate on Coal-derived Syngas and Hydrogen

The US Department of Energy (DOE) has issued its plans for the development of gas turbines for efficient operation on coal-derived syngas and hydrogen, in the form of a request for proposals from industry. The program envisions that funding of up to $100m will be available, spread over 10 years; interested parties were to submit proposals by the end of May, 2005, and awards are expected by the end of September, 2005. The plan features five main topics, which are as follows:

1. Hydrogen Turbines for FutureGen

These are large-frame, H_2-fuelled machines (nominally 300 MW in combined-cycle duty) that are to be available for commercial offering in 2015. These machines are intended to have the capability of integration with coal-based, integrated, gas turbine combined-cycle (IGCC) power plants that are ready for CO_2 sequestration, and to have the fuel flexibility for operation on 100% H_2 and conventional coal-derived synthesis gas. To the extent possible, components from existing state-of-the-art machines will be used (rotors, compressors and ancillary sub-systems), although some component redesign will be necessary to optimize combustion, and to maximize work extraction with hydrogen-based fuels. Advanced subsystems, components or technologies could be tested and validated at the DOE's FutureGen project, during the planned 2012-2015 operation and test phase.

Performance goals for hydrogen turnibes include:
1) by 2010: a 2 to 3 percentage point increase in combined-cycle efficiency when compared large-frame CCGT machines fueled with coal-derived syngas;

2) by 2015: a 3 to 5 percentage point increase in com-

bined-cycle efficiency when compared large-frame CCGT machines fueled with coal-derived syngas (that is, efficiency equivalent to the 45 to 50% [HHV] of current F- or G-frame machines fueled with natural gas);

3) NO_x emissions < 3 ppm (at 15% oxygen); and

4) cost less than $1000/kW.

The DOE recognizes that significant technical challenges exist due to, for instance, the conflicting requirements for NO_x prevention, NO_x control, and higher efficiency, and that conflicts also exist between efficiency and capital cost. The approaches taken to manage the trade-offs required are expected to be a major discriminating feature among the programs proposed.

This program segment will be implemented in three phases: in Phase I a conceptual design and R&D implementation plan will be developed, covering concept to commercial deployment; this is expected to require a period of 1 to 3 years. Phase II will be the detailed design and validation test program, lasting 2 to 4 years; and Phase III will address system fabrication and testing, over 2 to 4 years.

2. Turbines and Combustors for Oxy-Fuel Rankine Cycle Systems

These are intended to use nearly pure oxygen as the oxidant, along with gasification-based coal-derived gaseous fuels. When natural gas is used as fuel (and while capturing the CO_2), these systems (combined with current steam turbines) are expected to have the potential to reach nominal efficiencies in the 30% range. With anticipated advances in gasification, oxygen separation, and steam turbine technology (in the 2015 time frame), efficiencies in the 50-60 % (HHV) range are anticipated when fueled with coal.

Major sub-tasks required to address the issues associated with these systems are:

a) Evaluation of coal-based, oxy-fuel systems, and development and testing of oxy-fuel combustors that can operate in zero-emissions, coal-based systems. Effort is needed to evaluate, through systems studies, a suite of coal-based, oxy-fuel systems options, and then to use state points (temperature, pressure, species and mass flow) selected from these studies to design, fabricate and test an appropriately-sized oxy-fuel combustor or combustor module. Where appropriate, these considerations should include advances in turbine technology, oxygen separation technology, gasification technology, and other sub-systems that could enhance performance.

- Combustor design, and the logical testing and development of this component must take into account future turbine integration. Further, the systems evaluated should consider alternate locations for CO_2 extraction (low pressure vs. high pressure) that could minimize the penalty for CO_2 pressurization.

- System configurations that produce excess H_2 for export also are to be evaluated. System configurations that capture carbon and produce electricity or H_2, and could be readily deployed, retrofitted into existing fossil fueled power plants, or take advantage of existing commercial/industrial infrastructure, also are of interest.

- Combustors developed under this program are to include the capability to use fuels with a range of carbon-to-hydrogen ratios, and to demonstrate the ability to vary that ratio on a load-following or varying hydrogen export basis.

- Combustor testing is to be based on appropriate fuels, including actual coal-derived synthesis gas; simulated coal-derived synthesis gas; high-H_2 fuels; and CO. The option exists to test the combustor at the DOE's FutureGen project. Actual testing would occur in the 2012-2015 time frame.

b) Development of turbine technology for oxy-fuel Rankine cycle, coal-based power systems that is intended to enable large (300-600 MW) advanced, coal-based power systems to achieve overall plant efficiencies in the 50-60 % (HHV) range (depending on fuel: coal or natural gas). Such machines should be ready for commercial offering by 2015. Such efficiencies are expected to require turbine working fluids temperatures in the range of 1650 to 1760°C (3000 to 3200°F), and turbine designs incorporating high-pressure, intermediate-pressure, and low-pressure stages.

- The working fluids will comprise mostly H_2O and CO_2 as a result of the direct combustion of O_2 and gaseous fossil fuels. Depending on the coal-based gasification process, gas stream cleanup, and the combustion process, the potential exists for the presence in the working fluid of small amounts of O_2, compounds of nitrogen, sulfur, and trace contaminants.

- The final turbine exhaust gas should be conducive to the separation and capture of CO_2 in a way that promotes high overall system efficiencies, and minimizes the penalty of CO_2 compression. Options for working fluid reheat are to be considered.

- The anticipated approach will evaluate the effects of various CO_2/H_2O compositions on the blade aerodynamic design, and will address the materials issues faced by the hot gas-path components.

- Synergies are to be sought among existing materials development efforts and existing materials and manufacturing technologies. It is envisioned that the low-temperature condition (approximately 730-815°C/1350–1500°F) in the application of oxy-fuel turbine technology will be similar to the high-temperature condition in ultra-supercritical steam turbines, so that attempts are to be made to leverage possible synergies in the materials development efforts for ultra-supercritical steam turbines.

This program segment also will be implemented in three phases: Phase I will involve the development of a conceptual design and R&D implementation plan, covering concept to commercial deployment; this is expected to require a period of 1 to 3 years. Phase II will be the detailed design and validation test program, lasting 2 to 4 years; and Phase III will address system fabrication and testing, over 2 to 4 years. These periods of performance are intended to be consistent with the goal of enabling a U.S. commercial offering in a 2015 time frame.

3. MW-Scale Turbines for Hydrogen Utilization

The major goals of this effort are:

1) Large turbine power systems (1 to 100 MWe) that can efficiently burn H_2 with reduced NO_x emissions (< 3 ppm), while maintaining or extending simple-cycle efficiencies;

2) Combustion systems that can be retrofitted into existing MW-scale turbines, and use H_2 to augment existing fuels and combustion systems to yield NO_x emissions < 3 ppm; and

3) MW-scale turbines that operate under reducing conditions, for integration into coal-based co-production systems.

Three major initiatives are suggested:
a) Development of highly-efficient, zero-emissions, hydrogen combustion technology for turbines that can be installed or retrofitted into existing turbines that can use H_2 as a fuel, maintain or extend current levels of efficiency, reduce NO_x emissions to less than 3 ppm (at 15% O_2), and eliminate emissions of CO_2. It is envisioned that turbines developed through this subtopic area will be applicable to electrical power generation in the less than 100 MWe size range, and for mechanical power applications. Further, these machines are expected to be reliable and available to use traditional fuels and applications.

Since a major intent of this program is to allow near-term technology (e.g., prevention of NO_x formation) to be accelerated and deployed as soon as possible, independent of efficiency improvement efforts, NO_x emissions prevention or control approaches may be pursued as efforts parallel to the efficiency improvement approach.

This effort is viewed as requiring a three-phased approach, with the overall goal of providing a commercial offering in the 2010-2011 time frame. Phase I (over 12 and 18 months) would be the development of a conceptual design and R&D implementation plan: from concept to commercial deployment; Phase II (24 and 36 months) is the detailed design and validation test program; and Phase III involves system fabrication and testing (12 and 24 months).

b) Development of H_2 combustion systems to allow fuel augmentation for reducing NO_x formation in MW-scale combustion turbines, with the intention that the technology developed can be implemented in new machines, and retro-fitted into existing turbines. Note that it is expected that the utilization of hydrogen in a fuel-augmentation application will provide solutions to technical issues associated with the management and implementation of a hydrogen infrastructure.

The envisioned effort involves three Phases, consistent with the goal of providing a commercial offering in the 2010-2011 time frame: Phase I (12 and 18 months), conceptual design and R&D implementation plan: concept to commercial deployment; Phase II (12 and 24 months) detailed design and validation test program; and Phase III (18 and 24 months) system fabrication and testing.

c) Turbines for use in power and H_2 co-production in industrial applications where they are expected to operate in a co-production mode (co-products: electricity, hydrogen or synthesis gases) under a range of reducing conditions, and to require significant modifications to achieve higher efficiencies and reduced emissions. The goal of this effort is to produce a comprehensive assessment and evaluation of the opportunities and issues associated with the coal-based production of electricity and hydrogen in industrial applications.

The coal-based gasification systems of interest are in the 50-100 MWe (equivalent) size range, show high efficiency, ultra-low emissions of critical pollutants (< 3 ppm NO_x), and offer reduced costs while generating co products.

The effort in this segment, which is expected to occupy 18 and 24 months, is intended to identify and involve multiple turbine suppliers that have potential products applicable to these systems, can identify the technical issues associated with the required modifications for these applications, and propose an R&D plan (including budget estimate and schedule) to produce these turbines.

4. Novel Concepts for the Compression of Large Volumes of CO_2

Zero-emission power plants that are designed to capture CO_2 have a significant energy penalty due to the requirements of separating and compressing the gas. This penalty can range from 8 to 12 percentage points, depending on the exhaust state (temperature, pressure, and purity) of the CO_2 prior to compression. Final pressures for the compressed CO_2 would typically be on the order of 103 bar (1,500 psia) in a supercritical state for pipeline transportation. Typically, flow rates are on the order of 273,000 to 318,00 kg/h (600,000 to 700,000 lb_m/h) (based on a 400 MWe IGCC).

Novel concepts are sought for more efficient and lower-cost options for the compression of large volumes of CO_2. Applications must provide a clear technical explanation detailing the cost and efficiency benefits for the proposed approach, as well as an option for the development of a test plan for testing of the technology at full- or module-scale at the DOE's FutureGen project in the 2012-2015 time frame.

The effort will involve three Phases: Phase I (12 and 18 months) conceptual design and R&D implementation plan: concept to commercial deployment; Phase II (18 and 24 months) detailed design and validation test program; and Phase III (12 and 24 months) system fabrication and testing.

5. Advanced Brayton Cycles for Highly-Efficient, Zero-Emission Systems

This 18 to 24 months effort involves the development of concept(s) or approach(s) that will take the state-of-the-art Brayton cycle (in a combined-cycle application) from the current 58-60% efficiency (LHV) to 65-67 equivalent efficiency, or higher. The machine(s) proposed must consider the need for integration into advanced, coal-based and natural gas-based, zero-emission systems, with the ability to attain 60% efficiency (HHV) and 75% efficiency (LHV), respectively, prior to carbon separation and capture. The systems proposed must consider options for zero CO_2 emissions, and show how this would affect the turbine design and operation, and overall system performance. The continual development of other subsystems (gasifier; air separation unit; membrane separation; fuel cells) should be taken into account, since these will affect the performance of these advance systems when integrated with and advanced Brayton Cycle. Further, the concept(s) should show how the machine would be optimized at the initial design stage for individual fossil fuels (coal synthesis gas; H_2 derived from coal; and natural gas), or made fuel flexible. Careful consideration should be given to the required trade-off between NO_x prevention in the turbine combustor, and NO_x control from the system, and all associated penalties. These trade-offs should be managed to produce advanced, clean, and low-cost systems with high efficiencies. It is expected that these machines, and associated variations, will be fully integrated (depending on the application).

The baseline goal for NO_x emissions is less than 3 ppm (at 15% O_2). Favorable consideration will be given to Brayton cycles and systems that can efficiently surpass this limit, while maintaining reasonable values of other constraints. Approaches that are expected to bring about these advances may include, but are not limited to, the following:

- increasing the turbine rotor inlet temperature to 1700°C (3100°F), or higher;
- increasing pressure ratio to 35, or higher;
- augmentation of the working fluid;
- pressure-gain combustion;
- inter-stage reheat;
- inter-cooling;
- recuperation;
- air separation integration; and/or
- CO_2 compression integration.

It is anticipated that the efforts in this area will involve systems studies which will occupy 18-24 months, and identify research and development requirements for proposed, advanced Brayton cycles; identify state points (mass flow; composition; temperature; and pressure) at key stages in the advanced Brayton cycle; and assess technology issues to determine the feasibility, R&D requirements, cost, and input on developmental feasibility. A R&D Implementation Plan is a required deliverable to be submitted to DOE for approval within six months of project award. This plan will outline the project plan from concept to commercial deployment, and document alternative concepts and configurations to be examined; proposed testing and validation test plans, trade-off analyses and evaluation methods, criteria for decision making processes, project milestones, go/no go decision points, task interdependencies, critical path for product development, and other relevant project activities. Also required is a budget estimate for completing Phase II and III work.

Extracted from: DOE Solicitation "Enabling Turbine Technologies for High-Hydrogen Fuels," DE-PS26-05NT42380, issued March 31, 2005.

Meeting Announcements

October 5-7th, 2005: A conference on Power Plant Emissions Reduction: Technologies & Strategies, will be held at the SAIC Executive Conference Center, Washington, D.C. A pre-conference workshop (October 5th) will survey the costs, benefits, and performance of emissions reduction technology. The conference sessions will be concerned with: assessing the near-term situation for coal-fired environmental regulation; carbon emission regulation and strategies; assessing the costs and benefits of implementing technical solutions; the financial outlook for coal plant retrofits; and playing in the emission allowance markets. Information is available from: mail@infocastinc.com; or www.infocastinc.com/coalsus.html.

October 20-22nd, 2005: The 6th International Symposium and Exhibition on Gas Cleaning at High Temperatures will be held at the Cusmos Square International Education and Trading Center, Osaka, Japan. The conference scope covers recent developments and new trends related to gas cleaning, particle removal, and ash behavior control for high efficiency coal and fossil fuel power generation systems, as well as biomass and solid waste combustion or gasification systems, and mobile sources such as diesel cars. Specific topic areas include: sources, formation mechanics, properties, and measurement as particulate, and gaseous components; influence of particle properties, gas composition, and operating conditions on particle collection processes, particle structure, and regeneration of filter media; materials, structure, properties, and testing of filter media; operating experience in the process industries or advance power generation; gas cleaning and separation for fuel cells and other advanced power generation systems; and impact of new trends or policies in advanced power generation or industrial processes on hot gas cleaning technology. The official language of the conference will be English and details can be found at the conference website: "http://www.tuat.ac.jp/~jcht-6." http://www.tuat.ac.jp/~jcht-6.

October 26-27th, 2005: The Thermal Spray Society's Combustion Turbine Coatings Symposium 2005 will be held in Houston, Texas. The symposium will focus on all aspects of surface engineering technologies for industrial turbines: failure analysis & fracture mechanisms of coatings; applications / case studies; equipment / processes; thermal spray processes; air/slurry processes; diffusion and (EB)-PVD coatings; thermal barrier coatings; wear & erosion resistant coatings used for life extension and performance enhancement; nondestructive test methods for determining the condition of service run thermal barrier coatings, MCrAlY and diffusion aluminide coatings; and materials analysis & characterization. For more information, contact Mitch Dorfman, Sulzer Metco, fax: 011 41 52 262 01 66.

November 8-10th, 2005: The 4th in a series of Stainless Steel World Conference and Expos will be held in the MECC Congress Center, in Maastricht, The Netherlands. Papers are sought in all areas of application of stainless steels (including nickel base and titanium based alloys) in the areas of power generation, chemical and petrochemical industry applications, use of clad materials, fabrication of welding, high strength steels, and nanotechnology, use in the water industry, cost effectiveness of stainless steels, design rules, corrosion fatigue, and standardization. Abstracts of about 300-400 words should be submitted by email before February 25, 2005, to the Stainless Steel World Conference Coordinator: Ms. Marion "mailto:Barth@ssw2005@kci-world.com." Barth@ssw2005@kci-world.com.

November 14-16th, 2005: An international conference and exhibition on Continuous Casting of Non-Ferrous Metals will be held at the Edwin-Scharff-Haus, in Neu-Ulm, Germany. The main sessions are: process and technology of continuous casting: remarks about actual design, materials, and technology; DC casting of aluminum alloys: state of the art, and new challenges; state of the art modeling of aluminum and copper continuous casting processes; and melt treatment of copper and aluminum, the complex step before casting. For further information, see the conference web site at: www.dgm.de/concast.

November 21-22nd, 2005: The 2005 Clean Coal and Power Conference will be held at the Renaissance Mayflower Hotel, Washington, D.C. The program will focus on the significance of coal as a viable energy source for use in meeting the growing global demand for energy, as well as its role in the potential solutions to the associated political, environmental, economic, and social issues. Sessions will address: economic stability; energy security; transition to a sustainable energy future; new coal power technologies leading to zero-emission coal; existing power plants: improving performance with new technology; and challenges and opportunities in sequestration R&D. For more information, contact: Faith Cline, Office of Clean Coal_, U.S. Dept. of Energy, Washington, DC 20585; 'phone: (202) 586-7920; e-mail: faith.cline@hq.doe.gov; conference web site: http://www.fossil.energy.gov/news/events/cleancoal/.

November 30th-December 2nd, 2005: An International Symposium on High Temperature Oxidation and Corrosion (ISHOC05) will be held at the Nara-Ken new public hall, Nara City, Japan. The technical sessions will address the following areas: fundamentals of oxidation and corrosion; mechanical and chemical aspects of scale adhesions; protective coatings/surface treatments; erosions/metal dusting; waste incinerators/recycling systems; power plants/energy conversions systems; oxidation and corrosion in materials processing; and life predictions/databases/software. For further information see the symposium website at "http://homepage3.nifty.com/ishoc05/," http://homepage3.nifty.com/ishoc05/, or contact the symposium secretary at: isaoseaki, @isaos@mmm.muroran-it.ac.jb.

December 4-5, 2005: The 2005 Power-Gen International conference will be held at the Sands Expo, Las Vegas, Nevada. The topic areas discussed will include: market trends and strategies; environmental issues; power plant technology; renewable energy; distributed generation/onsite power; fuels; and operation and maintenance. For information, e-mail: pgiconference@pennwell.com.

January 23-24, 2006: The 3rd Discussion Meeting on the Development of Innovative Iron-Aluminum Alloys will be held at the TREFF Hansa Hotel, Mettmann-Düsseldorf. The topics will include: novel, light-weight steels; alloys for high-temperature applications; constitution, phase transformations, defects; fundamental aspects and properties; mechanical properties and microstructures; processing and joining; coatings; and environmental resistance. Further information is available from: Joachim Konrad, Max-Planck-Instut für Eisenforschung GmbH, Düsseldorf, Germany; e-mail: konrad@mpie.de; website: ww.mpie.de.

March 12-17th, 2006: The annual NACE Corrosion Conference will be held at the San Diego Convention Center, San Diego, California.

March 12-16th, 2006: The TMS Annual Meeting & Exhibition will be held at the Henry B. Gonzalez Convention Center in San Antonio, Texas. Three symposia are of particular interest:

(1) Materials in Clean Power Systems: Applications, Corrosion, and Protection. Proposed session topics include: Structural materials for applications in SOFCs, MCFCs, PEMFCs, and others; Hydrogen Production; Clean coal power plants and hydrogen generation; Gas filtration/cleanup and separation; Hydrogen delivery and embrittlement; Fundamental understanding on corrosion in power generation systems; and Protective coatings and newly developed materials. The main organizer is: Zhenguo Gary Yang of the Pacific Northwest National Laboratory, 'phone: (509) 375-3756; e-mail: zgary.yang@pnl.gov

(2) Advanced Materials for Energy Conversion III. Sessions will include: Thermoelectronics; Fuel Cells; Storage of Hydrogen and its Isotopes; Batteries; Supercapacitors; Superconductors; Magnets and Magnetic Refrigeration; Membrane Materials; Thermal Energy Storage Materials, Photovoltaics; and other related topics. The main organizer is: Dhanesh Chandra of the University of Nevada; 'phone: (775) 784-4960; e-mail: dchandra@unr.edu

(3) Effects of Water Vapor on High-Temperature Oxidation and Mechanical Behavior of Metallic and Ceramic Materials. This symposium is intended as a forum for investigators studying effects of water vapor on high-temperature oxidation and mechanical properties, in order to understand underlying mechanisms and predict material performance under a variety of conditions (low to high water-vapor concentrations/pressures, temperature cycling, influence of other reactive species, etc.). Papers describing work with metals/alloys as well as ceramics will be included.

The main organizer is: Bruce Pint, of the Oak Ridge National Laboratory; 'phone: (865)576-2897; e-mail: pintba@ornl.gov

March 28-30th, 2006: The 8th Annual Electric Power Conference is scheduled to be held in New Orleans. The Powder River Basin Coal Users' Group, and the Combined Cycle Users' Group will co-locate their annual meetings with the conference. The sessions will address: power industry trends-near term; fuel strategies; generating fleet optimization value, availability, performance, profitability; plant optimization; power plant safety and security; coal power plants-upgrades and new capacity; gas turbine-based power plants; combined-cycles and combustion turbines; nuclear power; plant operations and maintenance; power plant heat exchangers and cooling systems; turbines, generators and auxiliaries; power generation facilities design; performance testing and test codes; environmental regulatory trends, strategies and technology; fuels, combustion, and emission issues; energy strategies and technologies for 2005; alternative energy; renewable and advanced energy systems; distributed generation, CHP, and recycling energy; and selling and marketing to the power industry. For details, contact Kim Arellano, Conference Director, at (832) 242-1969, extn. 313, or kima@tradefairgroup.com.The conference has a web site: www.electricpowerexpo.com/conf_cfp.asp.

May 8-11th, 2006: The 51st Annual Technical Congress & Exposition on Gas Turbines will be held at the Barcelona

International Convention Center, Barcelona, Spain.

May 15-19, 2006: The 28th International Exhibition-Congress on Chemical Engineering, Environmental Protection, and Biotechnology, will be held in Frankfurt-am-Main, Germany. The lecture series includes: materials for process components; plant equipment: components, piping, reactors; plant controls: systems, field devices, concepts; new materials for fuel cell technology; and natural and synthesis gas for power generation and transportation fuels. Details are available from: DECHEMA e.V, e-mail: achema@dechema.de; web site: http://www.achema.de.

May 21-25th, 2006: The 31st International Technical Conference on Coal Utilization & Fuel Systems will be held at the Sheraton Sand Key, Clearwater, Florida. The theme will be: "Coal Technology: What's Next?" Panel sessions will discuss this topic, as well as: global climate change issues; hydrogen from coal; oxy-fuel technology; gasification: the technology of choice; CO_2 management; the environmental role of high efficiency power generation; the new big idea; how is Europe addressing CO_2 and global warming; and a FutureGen update. Technical sessions will focus on: advanced power cycles for electric utility applications at new and existing power plants (including FutureGen; the clean coal power plant initiative; gas turbines for advanced power plants; advanced power systems; and advanced materials); environmental & health aspects (including CO_2 capture, storage and sequestration); domestic & worldwide coal resources quality issues; transportation issues (including co_2 transportation pipelines); the utility perspective (including upgrading existing plants, and issues regarding utilization of Powder River Basin Coal). For details, contact the Coal Technology Association, 601 Suffield Drive, Gaithersburg, Maryland, 20878; Attention: Barbara A. Sakkestad, 'phone: (301) 294-6080; e-mail: BarbaraSak@aol.com; or Web site: www.coaltechnologies.com.

June 5-9th, 2006: The 23rd World Gas Conference will be held at Amsterdam RAI Exhibition and Congress Center, Amsterdam, The Netherlands. The main sessions are entitled: Gas-to power: the driver for market growth? Gas for sustainability: hype or reality? Regulation and LNG: agents of change? and Gas goes global: sellers' or buyers' market? For details, see the conference website at "http://www.wgc2006.ml" www.wgc2006.ml.

Call for Papers

June 21-23, 2006: The seventh InternationalEPRI Conference on Welding and Repair Technology for Power Plants will be held at the Sawgrass Marriott Resort and Spa, Ponte Vedra Beach, Florida.The scope of the conference will address the repair of nuclear, fossil, heat recovery steam generator (HRSG), and steam turbine power plant components. Topics for discussion include repair methods; performance; prior service effects; repair qualifications; materials properties; advanced repair technology; and case histories. Emerging and advanced welding technologies for new fabrication and repair also will be addressed. Abstracts (due December 9th, 2005) should be sent to: Shane Findlan at sfindlan@epri.com; Kent Coleman at kcoleman@epri.com, or David Gandy at davgandy@epri.com.

October 11-13, 2005: The Third CAME-GT Conference on Gas Turbine Technology will take place in Brussells, Belgium. The new EU Framework Research and Technology Development Program will be starting in late 2006/early 2007, and this conference will have all the latest information about the Work Program. A call for papers will be issued shortly. Updates can be obtained from: judy.henson@power.alstom.com.

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A Word from Our Sponsor...

The newsletter is back after a hiatus resulting from a number of factors beyond our immediate control. The intent is to continue publication at a frequency of three (or possibly four) issues per year, depending on the availability of funding. We also intend to continue the practice of featuring the six most recent issues, as well as the running index, on the Fossil Energy Program web site (http://www.ornl.gov/sci/fossil/, under "Publications"), and of mailing hard copies to readers in North America.

Mark your calendars for the 20th Annual Conference on Fossil Energy Materials, the annual reporting of research carried out under the US Department of Energy's Office of Fossil Energy, Advanced Research Materials Program, which is planned for April 24-26th, 2006, in either Knoxville or Oak Ridge, Tennessee.

Materials & Components

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Prepared for the U.S. Department of Energy, Office of Fossil Energy Advanced Research Materials Program. Edited by .Ð Ian G. Wright, telephone (865)574-4451, and Dr. R.R. Judkins, Director, Fossil Energy Program, Oak Ridge National Laboratory, Bldg. 4508, P.O. Box 2008, Oak Ridge, TN 37831-6084, telephone (865)574-4572.

Materials & Components Newsletter is available free of charge to qualified individuals worldwide who are involved in present or potential materials/components activities related to the development of fossil energy systems. Requests to be placed on the distribution list should be addressed to: Ian G. Wright, Oak Ridge National Laboratory, Bldg. 4500-S, P.O. Box 2008, Oak Ridge, TN 37831-6156, telephone (865)574-4451, fax: (865)241-0215, e-mail: wrightig@ornl.gov.

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