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GAS TURBINE SYSTEMS DESIGNED FOR COAL WATER SLURRIES

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ABSTRACT

Numerous attempts have been made during the past two decades to develop advanced power generation systems which could burn coal or coal-derived fuels both economically and in an environmentally acceptable manner. Although much valuable technology has been derived from these programs, commercially viable power generation alternatives have not yet appeared. One prospective way to expedite the commercialization of advanced coal-fired power systems is to meld the latest gas turbine technology with the emerging technology for producing slurries of water and ultra clean coal. This paper describes a DOE-sponsored program to identify the most attractive gas turbine power system that can operate on slurry fuels. The approach is to use slurries produced from finely ground (<10 microns) coal powder from which most of the ash and sulfur has been removed. The gas turbines will incorporate a rich-burn, quick-quench combustor to minimize conversion of fuel-bound nitrogen to NOx, advanced single crystal alloys with improved hot corrosion resistance and strength, advanced metallic and ceramic coatings with improved erosion and corrosion resistance, and more effective hot section cooling. Two different power plant configurations are covered: a large (nominally 400 MW) combined cycle plant designed for base load applications; and a small (nominally 12 MW) simple-cycle plant designed for peaking, industrial, and cogeneration applications.

INTRODUCTION

Coal-burning gas turbines have been a dream for several decades. Numerous programs (surveyed in Ref. 1) have been conducted to develop advanced power generation systems which could burn coal or coal-derived fuels both economically and in an environmentally acceptable manner. Much valuable technology has been derived from these programs, but viable power generation alternatives have not appeared. Reasons for this include: continued technological difficulties, tightening environmental regulations, substantial economic risks, very high cost of new technology demonstrations, and considerable market uncertainties.

One prospective solution for expediting the commercialization of advanced coal-burning power systems is a compromise approach which melds the latest gas turbine technology identified during recent industrial and aircraft development programs with emerging technology for producing coal-derived fuels of intermediate quality. Two fuel production technologies, coal water slurries (CWS) and partially cleaned coal-derived gas look particularly promising. When combined with projected advances in gas turbine technology, the potential exists for leapfrogging, in the relatively near term, to an attractive coal-burning power system without overwhelming R&D and demonstration costs.

The United Technologies Research Center is currently under contract to the U. S. Department of Energy/Morgantown Energy Technology Center to study coal-burning gas turbine power systems. The overall objectives of the program are to: (a) conceptually define the best gas turbine and/or combined-cycle power system which could operate on partially-cleaned fuel to produce low-cost electricity while complying with applicable environmental regulations; and (b) define technical problem areas which need to be resolved before commercialization could be implemented.

The specific tasks that are to be performed in achieving these objectives include: (1) establish baseline system(s) for assessing the detailed technical and operating characteristics; (2) perform parametric analyses to define the sensitivity of cost of electricity to fuel quality, environmental regulations, component tradeoffs, and reliability; (3) identify, from the baseline system(s) and parametric analyses, the system(s) which has the greatest overall commercialization potential; and (4) describe a component R&D program that addresses the key technical issues and that could lead to commercialization.

This paper covers the CWS portion of the project and describes the CWS work completed to date. Included herein are a description of the baseline systems selected, the results of limited CWS testing, and discussion of technical problem areas.

BASELINE SYSTEM DESCRIPTIONS

Conceptual designs have been prepared for two different baseline CWS power systems: 1) a baseload, CWS-fired combined cycle (CWS/CC); and 2) a CWS-fired peaking gas turbine (CWS/GT). A comprehensive set of design and economic guidelines has been adopted for comparison purposes. Basically, the guidelines, detailed in Ref. 2, assume that there are no unusual or difficult problems relating to construction, water availability, or local environmental regulations. The economic guidelines are representative of standard utility practice as recommended by the Électric Power Research Institute (Ref. 3).

CWS/CC Baseload System

The baseload power plant is taken to be large enough (nominally 400 MW) that preparation of the CWS will be done on the utility site. The CWS preparation system design is based on the Integrated Carbons process for producing Purged Carbons, a low sulfur, low ash coal-derived product. The final CWS would be produced by blending Purged Carbons with water, a dispersant and, possibly, other additives such as a stabilizer or antifoaming agent. Further discussion of the CWS system is given in a subsequent section.

The combined-cycle power system is based on the detailed design presented in Ref. 4. A schematic diagram for this configuration is depicted in Fig. 1. This design uses a nominal 120-MW advanced industrial gas turbine termed the UT 200 (Fig. 2). This engine has a 12:1 pressure ratio, a firing temperature of 1160 C (2120 F) at the rotor inlet, and features large, external combustors on either side of the engine. The combustion zone of the external combustors has a residence time of approximately 0.2 sec., which is about an order of magnitude longer than that in conventional gas turbine combustors. The exhaust gas at 570 C (1060 F) is available for steam generation in the waste heat recovery steam generator. The steam cycle is basically a 16.5 MPa (2400 psia) reheat cycle with a nominal 538 C (1000 F) throttle and reheat temperature.

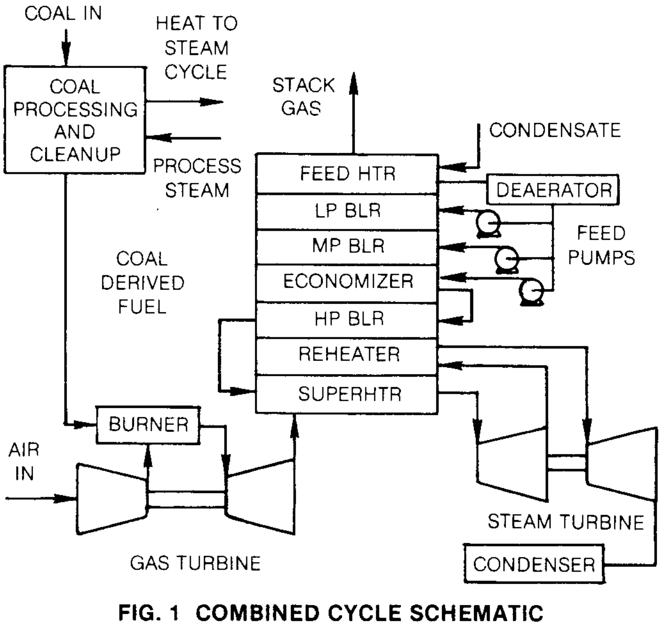

FIG. 1 COMBINED CYCLE SCHEMATIC

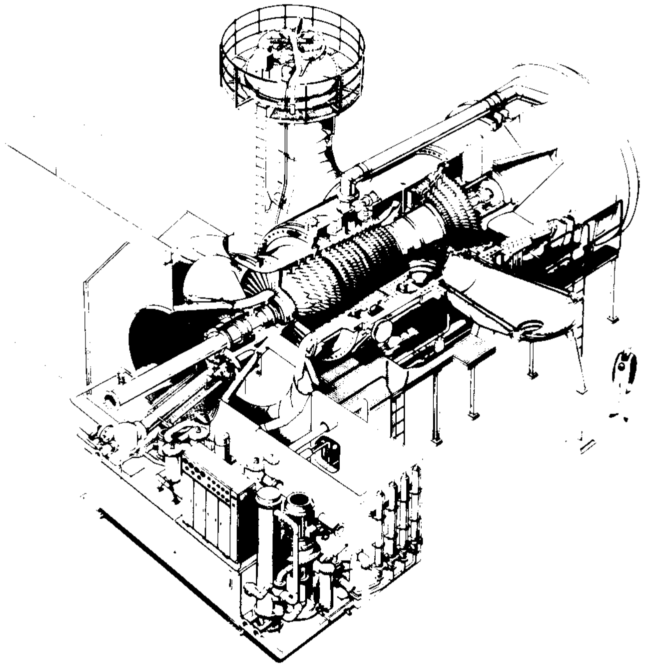

FIG. 2 UT200 GAS TURBINE

CWS/GT Peaking System

The peaking plant is taken to be relatively small, nominally 12 MW. In this case, the CWS will be prepared at a large, off-site, privately-owned facility and transported to the site in a ready-to-use condition. Otherwise, the CWS plant is the same as that for the baseload system.

Power would be generated by a simple-cycle gas turbine without heat recovery. The peaking gas turbine is based on an industrialized version of the PWA JT8-D aircraft engine, the most widely used aircraft engine in the world. The industrialized version, termed the FTX (see Fig. 3) would produce about 12 MW.

CWS SYSTEM

Because the technology for preparing and using CWS (especially for gas turbine applications) is in an embryonic state, it was not possible to obtain sufficient CWS information from published sources. Accordingly, a modest experimental program was initiated to prepare samples of Purged Carbons and to use these samples to make several CWS formulations.

Purged Carbons Process

A simplified flow diagram for the Purged Carbons process is given in Fig. 4. The heart of the Purged Carbons process is an acid leach which uses both hydrochloric and hydrofluoric acid. These acids are extremely reactive to most minerals, but they are not reactive to hydrocarbons in coal. After contact with the acid, virtually all of the ash is dissolved, leaving a material which contains only combustible hydrocarbons and sulfur. The acid is regenerated and recycled back to the leach step. The sulfur that is present as iron pyrite is removed by gravity separation.

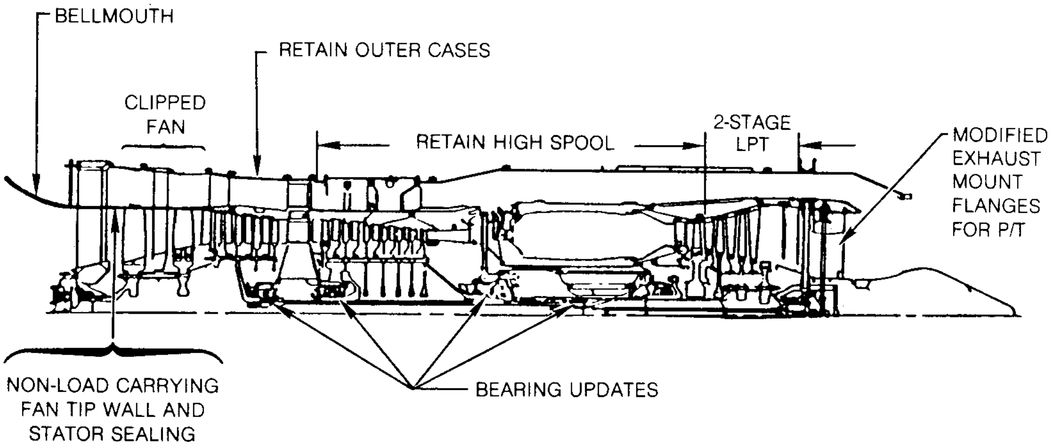

FIG. 3 FTX INDUSTRIAL ENGINE

The Purged Carbons process also makes grinding much easier since coal treated with acid is left much more friable. With improved grinders and jet impaction millers, the friable coal can be reduced to particle sizes below 5 microns using less energy than with conventional grinding techniques.

Purged Carbons Samples

The Purged Carbons samples were produced from a low ash, eastern coal obtained from the mines of the Westmoreland Coal Company in Boone County, West Virginia. The feed coal is a blend of coal from the Cedar Grove (85%) and upper Stockton-Lewiston (15%) seams. The analyses of the feed coal and resulting Purged Carbons is given in Table 1. This analysis of Purged Carbons corresponds to the estimated composition from a commercial process and differs slightly from the bench scale samples.

The ash content was reduced from 5.76% to 0.29% while the sulfur was reduced from 0.75% to 0.64%. The volatile matter was reduced slightly from 33.8% to 30.5%. The composition of the ash is given in Table 2. All the metal oxides are reduced substantially, including the alkali metals. The total alkali concentration is estimated to be 52 parts per million of Purged Carbons.

CWS Preparation

Two Purged Carbons samples were used by the Inmont subsidiary of United Technologies to develop CWS's with high solid loading (by weight of coal) suitable for use in gas turbines. One sample had a top size of 10 microns and an average size of 3.8 microns. The second sample had a top size of 3 microns and an average size of 1.9 microns. A cursory screening and evaluation of dispersants was conducted based on the following criteria: viscosity of the CWS, solubility of the dispersant in water, the tendency to foam, commercial availability, and price.

TABLE 1

PURGED CARBONS ANALYSIS

LOW-ASH EASTERN COAL

Dry Basis, % by wt.	Feed Coal	Purged Carbons
Ash	5.76	0.29
Total Sulfur	0.75	0.64
Pyritic Sulfur	0.15	0.02
Volatile Matter	33.8	30.5
Halogens (ppm)	1,840	1,230

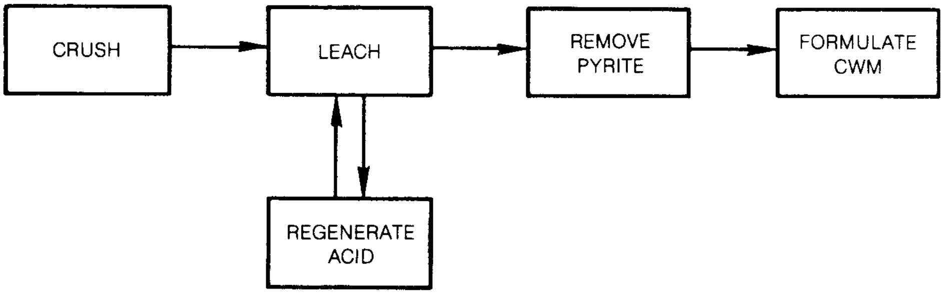

FIG. 4 PURGED CARBONS PROCESS FLOW SHEET

TABLE 2

PURGED CARBONS ASH ANALYSIS

LOW-ASH EASTERN COAL

Oxides, ppm	Feed Coal	Purged Carbons
SiO_2	32,060	295
Al_2O_3	17,840	718
TiO_2	947	714
Fe_2O_3	3,896	257
CaO	842	455
MgO	345	78
Na_2O	353	56
K_2O	900	13
P_2O_5	63	15

The initial screening identified several effective dispersants, but most of these were eliminated because they contained high alkali and sulfur concentrations. One dispersant, PLURONIC® F682F block-copolymer surfactant* showed promise and was subjected to further testing. That dispersant is a nonionic poly (oxypro-pylene) glycol polymer. PLURONIC® F68LF, although a low foamer in the PLURONIC®series, had foam buildup during CWS preparation. After preparation, this slurry would settle to 60% of its original volume because of defoaming. This problem, however, can be controlled by addition of 1% (by weight of dispersant) of n-butanol.

CWS Properties

Rheological trends of CWS systems with PLURONIC® F68LF have been established. Solids levels as high as 68% by weight of coal (with 10 micron top size) were achieved with 1.8% dispersant (based on coal weight). A plot of viscosity in Fig. 5 shows a very small viscosity increase between 50% and 65% solids. Between 65% and 68% the rise in viscosity is exponential. Each of the CWS systems between 50 and 68% were dilatant (shear thickening). The degree of shear thickening rises with increasing solid loading, as illustrated in Fig. 6.

The variation in viscosity with dispersant level is shown in Fig. 7. Considering the cost of dispersant and the viscosity trends in the figures, a CWS with 65% solid loading and 1.2% dispersant level looks practical.

TECHNICAL PROBLEM AREAS

It was obvious from the beginning of this program that there were numerous technical problem areas that, if not solved, could prevent commercialization of CWS systems. Some of these key problem areas are listed in Table 3. The technical problems fall into four general areas dealing with the fuel, the combustor, the turbine, and the environment. The column on the right in Table 3 is labeled solution. The items in this column are not always a solution, but in some cases they represent an approach to take in arriving at a solution.

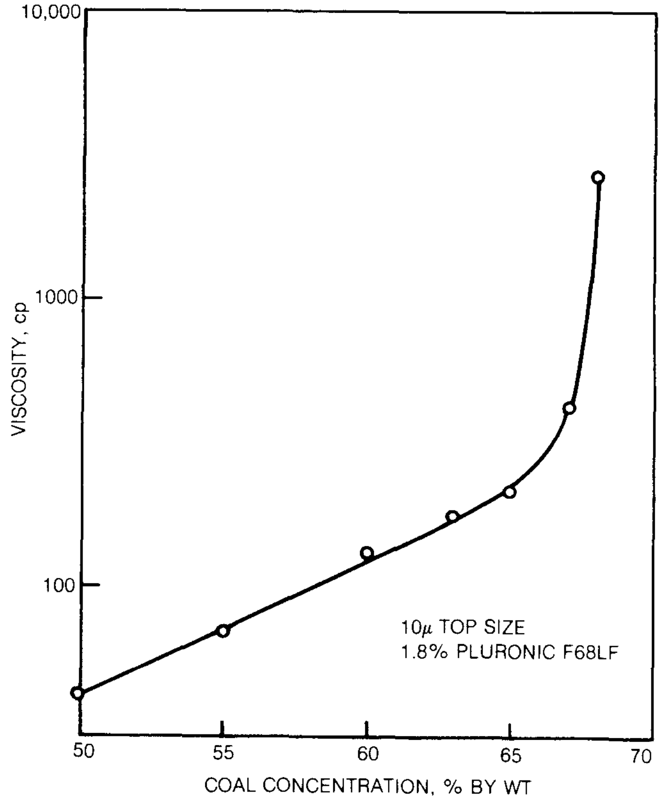

FIG. 5 CWS VISCOSITY VS COAL CONCENTRATION

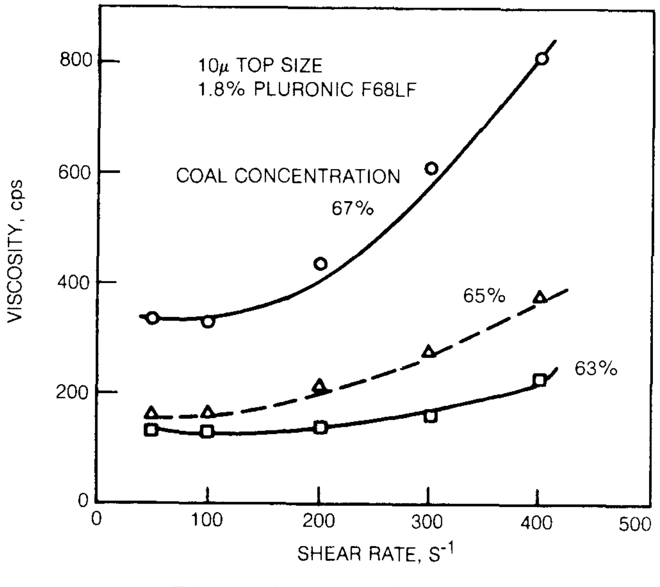

FIG. 6 VISCOSITY VS SHEAR RATE

There is not sufficient space to cover all these problem areas, but a few examples will be discussed. The first problem, fuel impurities, will be handled by both fuel and exhaust gas treatment. The beneficiation provided by the Purged Carbons process will remove most of the impurities. The sulfur level is low enough that further sulfur removal might not be necessary. Should environmental regulations require further removal, flue

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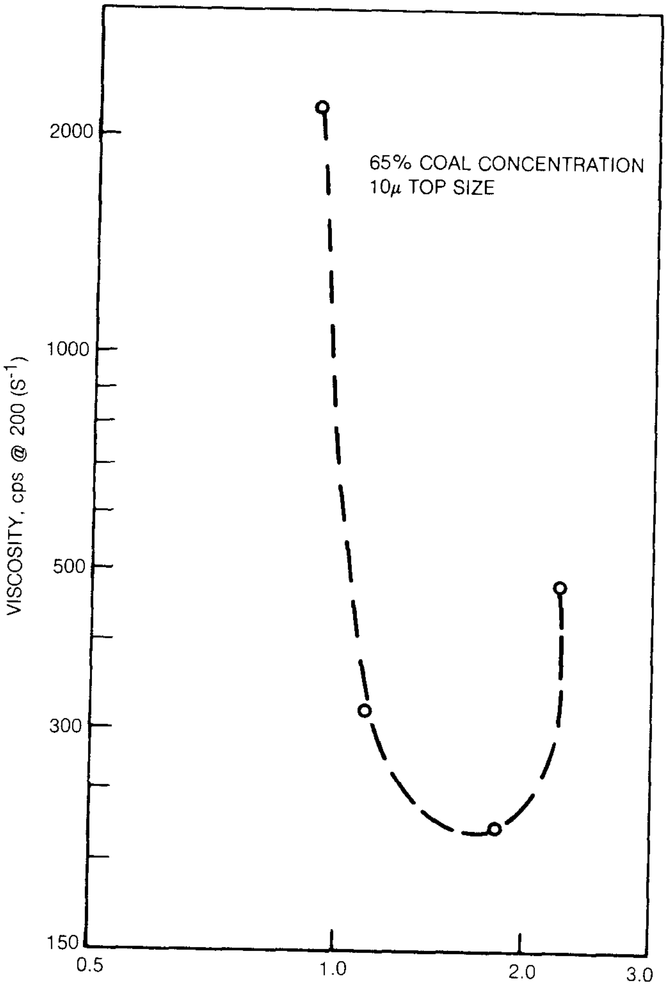

FIG. 7 PLURONIC F68LF CONCENTRATION, % BY WT OF COAL

gas desulfurization would be necessary. The ash level, however, is high enough to require particulate cleanup from the flue gases. There are a number of commercially available methods to do this.

TABLE 3

KEY PROBLEMS

	Problem	Solution
Fuel	Impurities	Fuel and exhaust treatment
	Handling	Rheological testing
Combustor	Fuel Injection	?
	Char burnup	Long residence time
	NO_x	Rich burn, quick quench
	Corrosion	Materials, cooling,
	Pattern factor	Good mixing
Turbine	Erosion	Materials, cooling, small particles
	Corrosion	Materials, cooling
	Deposition	Periodic cleaning
Environmental	SO_x	?
	Particulates	?

The combustor problem is particularly challenging. The char burnup can be accommodated by allowing long residence time. This is difficult to do within the confines of a typical industrial gas turbine combustor; an off-board combustor might be necessary. To minimize NOx production from fuel-bound nitrogen, a rich-burn, quick-quench (RBQQ) design would be used. This concept uses a rich burn first stage to convert fuel nitrogen to nitrogen gas, followed by a quick quench and lean burnout stage (see Fig. 8). This concept was first conceived and reduced to practice by Pratt & Whitney under contract to the Environmental Protection Agency. It is now the basis of widespread investigation by the industrial gas turbine industry for future fuels.

Perhaps the most critical problems are turbine corrosion and the associated erosion and deposition caused by coal ash. The most cost-effective solution, in the long run, will be a materials solution. Current

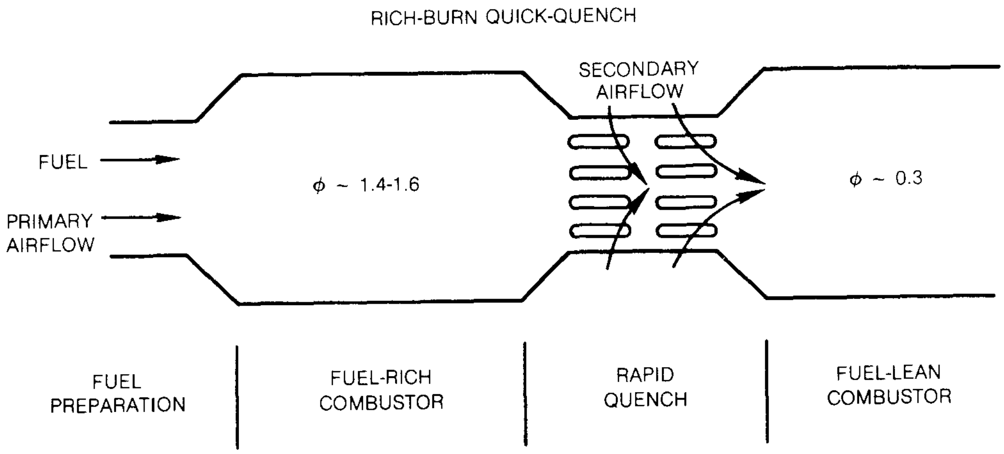

FIG. 8 ELEMENTS OF RICH/LEAN STAGED COMBUSTOR

industrial gas turbines generally use platinum or rhodium aluminide diffusion coatings on a cobalt or nickel base cast alloy. To achieve suitable engine life with these combinations, the alkali content in the fuel is generally limited to one ppm. The alkali content in the CWS solids (refer to Table 2) is roughly a factor of 70 higher.

There have been substantial material improvements derived from recent aerospace research. In particular, directionally solidified and single crystal alloys have been developed which are among the strongest and most corrosion resistant materials to be used in aviation gas turbines. The relative strength and hot corrosion resistance of these alloys are compared to conventional alloys in Fig. 9.

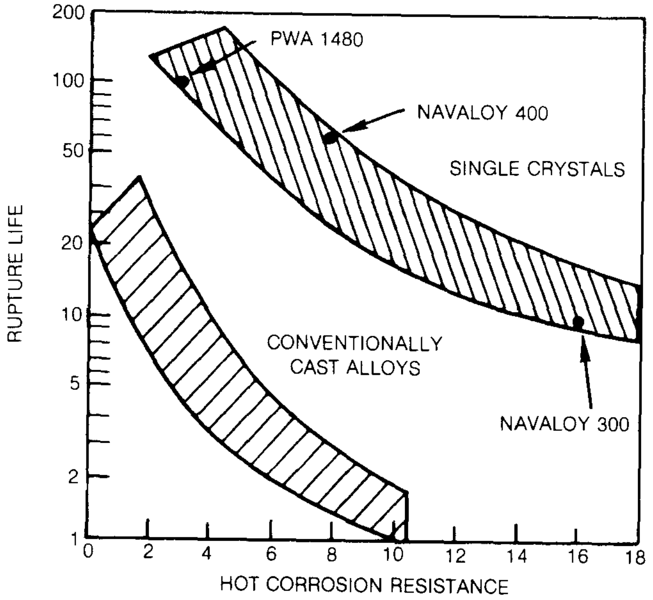

FIG. 9 SINGLE CRYSTALS PROVIDE SIGNIFICANT IMPROVEMENTS IN HOT CORROSION/ STRENGTH

Corresponding improvements have been made to protective coatings. Coatings have long been used to protect base metals. It is important to realize that the mechanical properties of the coating can play an important role in determining the life and use temperature of the component. The relative life as a function of environmental effects and mechanical property comparisons for aluminide and MCrALY overlay coatings are shown in Fig. 10. The hatched areas are due to differences related to the base alloys.

Considering the improvements in base metals and coatings, it seems that the tolerance of gas turbine materials to alkali metals has been improved by about a factor of 10. Assuming that the amount of alkali deposited on the turbine blades is directly proportional to the alkali content in the fuel (this is a major assumption which needs experimental verification for CWS), then the fuel alkali limit could be increased to 10 ppm. This means that the gap between what the turbine can take and what is in the fuel has been reduced from a factor of 70 to a factor of seven. This is still an uncomfortable gap. Further materials improvements such as ceramic coatings combined with more complete coal beneficiation should close the gap.

CONCLUDING REMARKS

The material presented herein constitutes a progress report for an ongoing study of the use of CWS fuel in gas turbine power plants. Because of the embryonic nature of the technology and the status of the study, no conclusions have been reached. Indeed, it might seem that more questions have arisen than have been answered so far. Nevertheless, progress has been made and the general understanding of the problems of burning coal in this type of system has improved.

A number of problem areas have been identified for coal-burning gas turbines, but the major problem is corrosion caused by alkali metals in the coal ash. Improvements in base materials and coatings derived from aircraft engine programs have greatly extended the tolerance of gas turbines to alkali metals and narrowed the gap between what the turbine can take and what will be in the fuel. Future improvements in materials and coal beneficiation will, hopefully, close the gap completely.

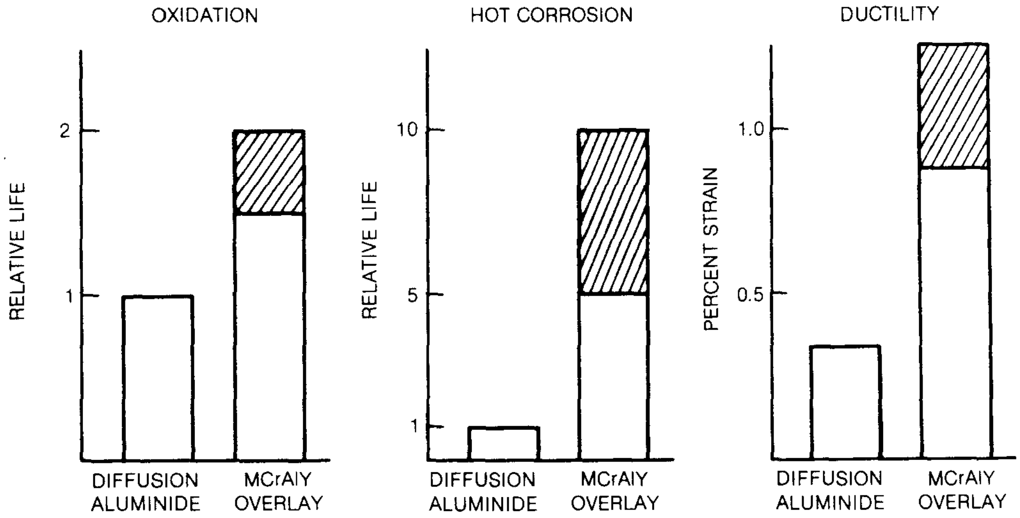

FIG. 10 PROPERTIES OF TURBINE AIRFOIL COATINGS

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