TESTING OF A VERY HIGH-TEMPERATURE HEAT EXCHANGER FOR IFCC POWER SYSTEMS

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ABSTRACT

Laboratory and pilot-scale tests of a very high-temperature heat exchanger (HTHX) that could be used to produce pressurized air at up to 2000°F for an indirectly fired combined-cycle (IFCC) power plant were performed while three coal–biomass blends were fired. An IFCC using this type of heat exchanger has the potential to reach efficiencies of 45% when firing coal and over 50% when a duct burner is used to additionally heat the gas entering the turbine. Because of its high efficiency, an IFCC system is the most appropriate power concept for employing oxygen-enriched combustion in order to make carbon dioxide removal more economical.

In this paper, we summarize economic analyses of IFCC systems operated under an oxygen-blown near-zero-emission scenario. The calculations show that the cost of electricity is similar to that of an emissionless integrated gasification combined cycle, whereas the operation of an IFCC is much better understood since it is essentially the same as current pulverized coal (pc)-fired systems. In addition, we summarize the results from initial joining tests of MA956, an alumina-scale-forming oxide dispersion-strengthened alloy that is a candidate for construction of an HTHX.

INTRODUCTION AND BACKGROUND

The U.S. Department of Energy (DOE) projects that by 2015 worldwide use of electricity will approach 72 trillion mJ (20 trillion kWh), a 100% growth in only 20 years. This growth comes during a time of concern over global warming, thought by many policy makers to be caused primarily by increases in CO_2 emissions through the use of fossil fuels. Future government regulations resulting from negotiated global treaties may force electric utilities to reduce CO_2 emissions or buy CO_2 credits from nations producing less CO_2 per capita. Renewable energy

sources can also play a role supplying the electrical demand necessary to sustain a growing economy, but they cannot completely replace our reliance on fossil fuels in the foreseeable future. In thermal systems, biomass fuels can offset the demand for fossil fuels where sufficient biomass resources exist, but they are not abundant enough for 100% firing in a large baseload electrical generation plant. Therefore, in order to conserve valuable fossil fuel resources and reduce the impact of electrical generation on our global environment, more efficient electrical generation cycles employing biomass cofiring are necessary.

One type of advanced high-efficiency system is the indirectly fired combined-cycle (IFCC) using a slagging high-temperature pulverized coal (pc)-fired combustor and high-temperature heat exchangers (HTHXs) to produce clean air at up to 1100°C and 17 bar (2000°F and 250 psi) to turn an aeroderivative turbine, followed by a standard boiler and steam turbine to take advantage of the waste heat.[1–3] Approximately one-half of the power is produced using the more efficient aeroderivative turbine cycle as compared to a steam cycle, resulting in **a reduction of 50% in the cooling water required by the plant** and a more efficient overall method of producing electricity. To achieve the highest temperatures and **efficiencies of up to 55%**, a gas-fired duct burner can be used to additionally heat the gas entering the turbine. A process flow diagram of an IFCC is shown in Figure 1. The overall system design is like that of a natural gas combined-cycle (NGCC)-fired turbine system (along the top of the diagram), except that a pc-fired furnace is used to preheat the air entering the gas turbine (GT). Because of the very high temperatures, advanced oxide dispersion-strengthened (ODS) alloys must be used to construct the HTHX built into the walls of the furnace used to heat the process air going to the GT.[4] The similarity of designs makes it especially suitable as a pc-fired boiler retrofit technology. The HTHX and a GT could conceivably be retrofitted to smaller industrial boiler systems to produce electricity and heat for industrial or domestic use. The retrofit is equally applicable to district heating boilers, including those cofiring opportunity sources of biomass.

Many electric utilities that use coal for power generation are considering the use of renewable fuels such as waste products or energy crop-derived biomass fuels as a potential economic option for reducing greenhouse gas emissions. Calculations by the National Renewable Energy Laboratory[5] show that cofiring 15% and 5% by heat input of urban waste biomass with Illinois No. 6 coal reduces greenhouse gas emissions by 22% and 7%, respectively, on a CO_2-equivalent basis per unit of electricity produced. Therefore, biomass cofiring in coal-fired plants has the potential to significantly reduce greenhouse gas emissions, with relatively minor impacts on operation.[6]

In addition to reducing net emissions of carbon dioxide by cofiring the IFCC with biomass and coal, these systems are especially suitable for firing with recycled flue gas supplemented with oxygen as the fuel oxidizer. The recycled flue gas can be used to keep the gas flow rate and flame temperature similar to that of the air-blown combustion. However, with oxy-firing, much higher heat-transfer rates to the HTHX are possible at similar gas temperatures because the flue gas is composed almost solely of carbon dioxide and water vapor, which are both very strong infrared radiation emitters. Specifically, the O_2-blown heat recovery rate could be 50% greater

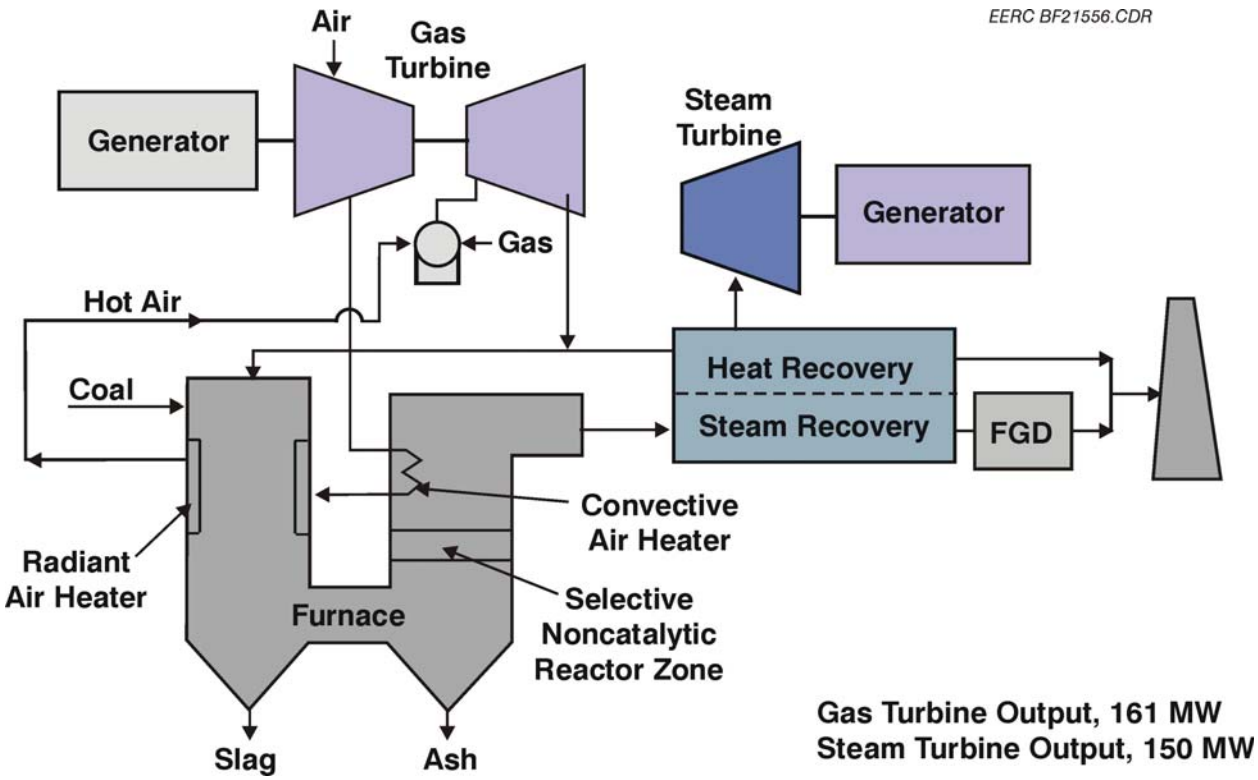

Figure 1. Process flow diagram of an IFCC.

than the air-blown heat recovery rate at a given furnace temperature.[7] Also, by reducing the amount of flue gas recirculation (FGR), the Energy & Environmental Research Center (EERC) demonstrated that flue gas flow rates could be substantially reduced relative to air-blown operation, conceivably **reducing the size of the furnace and downstream pollution control devices**. Also, after particulate cleanup and SO_2 scrubbing, the final flue gas consists almost entirely of carbon dioxide and water vapor. Therefore, it would be possible to **condense most of the water for reuse in the plant** and harvest the remaining carbon dioxide for industrial use or geological sequestration so that the **plant could operate essentially emission-free**.

In this paper, we summarize a portion of the results from tests of IFCC subsystems while cofiring coal and biomass. The bulk of the work was funded by the Xcel Energy Renewable Development Fund. Some support for the materials development was also provided by the DOE Advanced Research Materials Program. We describe economic analyses of IFCC systems operated under an oxygen-blown near-zero-emission scenario. In addition, we summarize the results from transient liquid-phase bonding tests of MA956, an alumina-scale-forming ODS alloy that is a candidate for construction of an HTHX.

RESULTS AND DISCUSSION

ECONOMIC ANALYSIS OF O_2-BLOWN IFCC

A brief study was performed to identify the performance and the first-order economics of an IFCC compared to typical pc-fired plants, integrated gasification combined cycles (IGCCs), and NGCCs. Since the pilot-scale testing of coal–biomass cofiring showed no significant influence of biomass cofiring on the operation of the combustor and since the cost of biomass is only slightly less than that of coal, it was assumed that costs for cofiring would be essentially the same as for just firing coal, so no separate calculations were included for cofiring. Two main IFCC firing scenarios were investigated: coal-fired with air and coal-fired with O_2. Because IFCC systems have a high potential for operation as zero-emission power plants, special focus was placed on firing with O_2 and including CO_2 recovery. Two main IFCC energy cycles were investigated: 1) advanced aeroderivative GT with coal-fired HTHX with 2100°F exit and NG-boost fuel and 2) commercially available aeroderivative GT using only a coal-fired HTHX with 2100°F exit, i.e., all-coal IFCC.

When a fuel was fired in an IFCC with O_2, it was assumed that flue gas, consisting primarily of CO_2 and H_2O, would be recycled to replace a portion of the N_2 normally found in the primary and secondary air used in a pc burner. Recycling would be done in order to keep the flame temperature from becoming too high. In all cases it was assumed that the amount of O_2 supplied would be 20% greater than that required to completely burn the fuels, but that the amount of recycled flue gas would be less than the amount of N_2 excluded so that the total concentration of O_2 in the flue gas, before fuel combustion, would be approximately 50%. By using a reduced flue gas recycle rate relative to the N_2 replaced, the overall size of the furnace and pollution control devices can be reduced. All systems used an advanced cryogenic air separation unit (ASU) to supply 98% O_2 for combustion. Also, the exhaust for each, consisting essentially of only H_2O and CO_2, was cooled, the H_2O removed, and the CO_2 compressed to 140 bar (2000 psia) for pipeline recovery so that the plant would operate with essentially zero emissions.

Comparison to NGCC

The effect of fuel cost on the NGCC and IFCC plants is shown in Figure 2. At NG prices above \$4.74/10^6 kJ (\$5.00/MMBtu), the IFCC plants are more attractive than the NGCC plants with CO_2 recovery.

Comparison to pc-Fired and IGCC

The levelized cost of electricity (LCOE) is widely used to compare alternative power systems. The Electric Power Research Institute (EPRI) developed the most widely used methodology for determining LCOE.[8] This procedure was the basis of the LCOE presented by Parsons.[9] These values are used to compare the 10-year LCOE of pc-fired plants, IGCC, and natural gas-supplemented and all coal-fired O_2-blown IFCCs with CO_2 recovery. The fuel costs were estimated by applying the different system heat rates and prorating the value for the coal and gas fractions. The fuel costs are based on the 2002 fuel costs of \$0.99/10^6 kJ (\$1.04/MMBtu) for coal

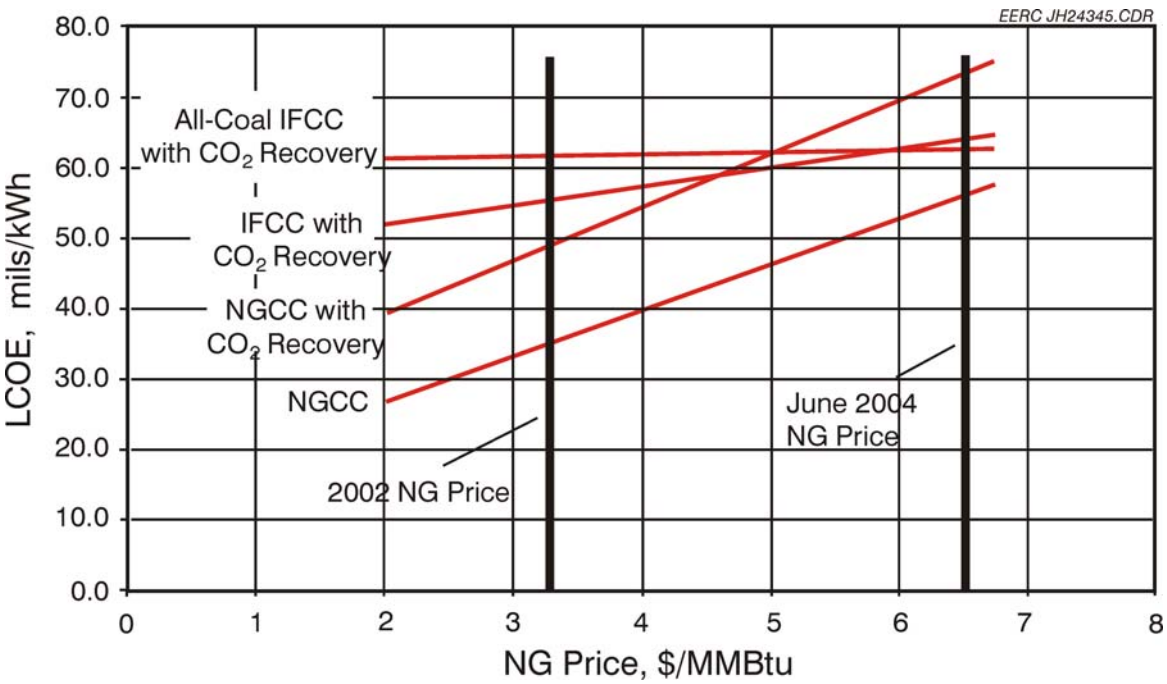

Figure 2. The effect of NG price on LCOE.

and \$3.08/10^6 kJ (\$3.25/MMBtu) for NG.[9] Costs for consumables and fixed and variable operating and maintenance (O&M) were assumed the same for the IFCC plants as for the O_2-blown pc plant. The results shown in Figure 3 indicate that the LCOE for an oxygen-blown IFCC with CO_2 recovery (near-zero emissions), whether fired only on coal or with some supplemental natural gas firing, is approximately 25% less than for a pc-fired plant in which the CO_2 is captured and comparable to the LCOE for an IGCC system. The advantage of the IFCC over an IGCC is that its operation is essentially the same as that of a pc-fired system and, therefore, more likely to be adopted by the existing utility industry.

Effect of a Carbon Tax

An alternative to CO_2 recovery would be to pay a carbon tax. The tax increases the COE by increasing the cost of the fuel. For example, a carbon tax of \$83/metric ton (\$75/ton) C emitted (3.32 metric ton [3.67 ton] CO_2) would increase the price of coal by the fraction of coal which is carbon multiplied by \$83/metric ton (\$75/ton). For the coal used by Parsons, that would be 0.58 metric ton carbon/metric ton as-received coal, which would increase the coal cost by \$48/metric ton (\$43/ton) from the assumed price of \$28/metric ton (\$25/ton).[9] If the baseline pc plant were to have a carbon tax, it would raise the LCOE as shown in Figure 4. The figure also shows that it would take a carbon tax somewhat under \$55/metric ton (\$50/ton) carbon to raise the LCOE of the baseline pc to a level higher than the LCOE for the IFCC with CO_2 recovery and to a value around \$83/metric ton (\$75/ton) carbon to be higher than the all-coal IFCC with CO_2. Given the propensity of the utility industry to use trade-off credits rather than invest in new technology, the introduction of CO_2 recovery technology becomes dependent on the carbon tax rate, with a value of approximately \$55/metric ton (\$50/ton) carbon being the threshold and

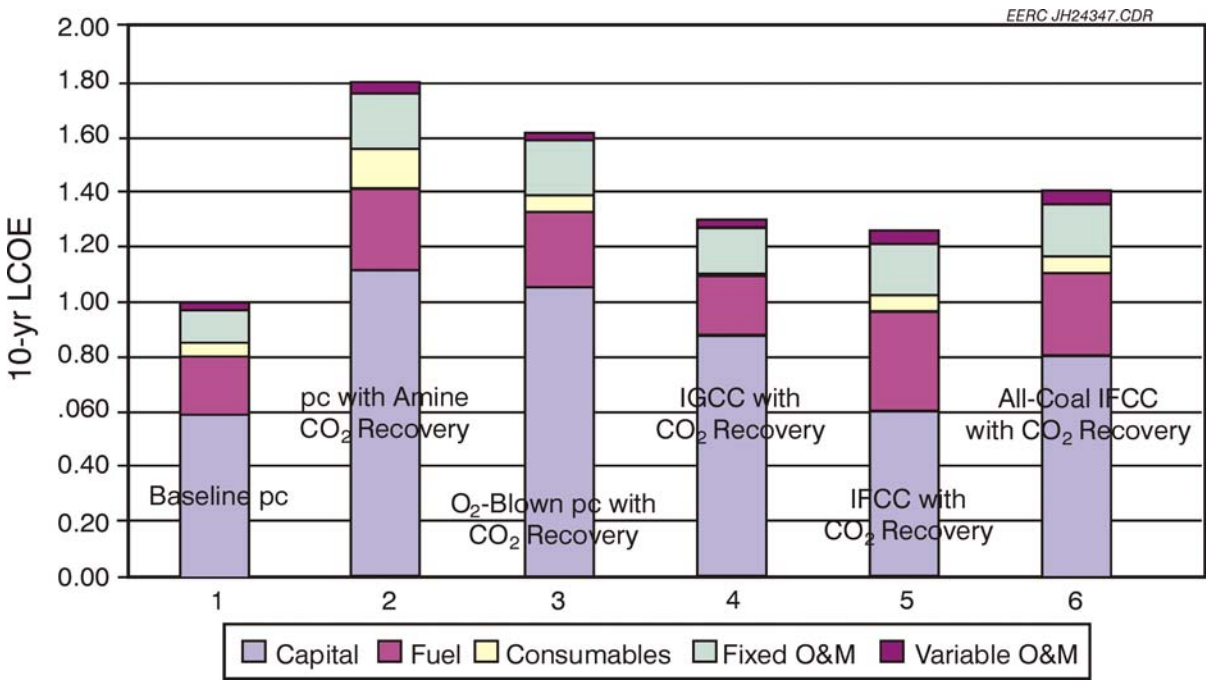

Figure 3. Normalized LCOE for coal-fired plants.

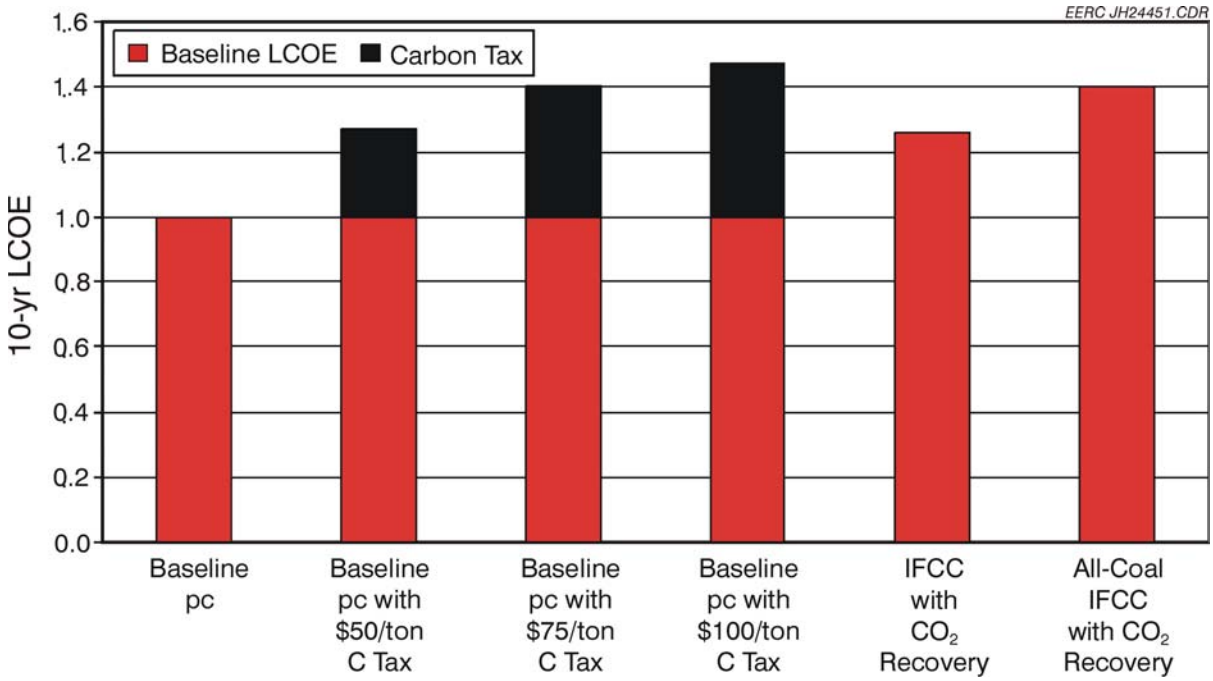

Figure 4. Effect of carbon tax.

$44/metric ton ($40/ton) if 20% biomass cofiring is used. If rules for CO_2 similar to the best available control technology for other pollutants are implemented, then CO_2 recovery will be required, and the IFCC would be an attractive alternative power system.

TLP BONDING OF MA956

MA956 is an iron–chromium–aluminum ODS alloy made by Special Metals. Because it forms an adherent alumina scale, laboratory testing has shown that it is highly resistant to corrosion by the products of coal combustion. However, because of the dispersion of small oxide particles within its structure, it can not be welded because this would lead to segregation of the dispersed oxide. Therefore, the EERC investigated transient liquid phase (TLP) bonding of the alloy. In these tests, one TLP metal foil type provided by Oak Ridge National Laboratory (ORNL) was used to join pieces of MA956 under three different processing conditions. Both the TLP metal type and processing conditions remain proprietary and so cannot be described here, but the three conditions will be labeled as A, B, and C for the purposes of this report. The three TLP-bonded samples were cross-sectioned and examined by scanning electron microscopy (SEM).

An SEM micrograph of Joint A is shown in Figure 5. The TLP metal migrated approximately 150 µm into the ODS alloy but left relatively large areas of highly concentrated TLP metal within the ODS alloy. Minor porosity was detected at the joint interface. A yttrium/aluminum-rich particle phase was formed at the interface, with a concentration of 45/25 wt%, respectively, that contained small amounts of chromium and iron. Oxygen content was very low and, in many

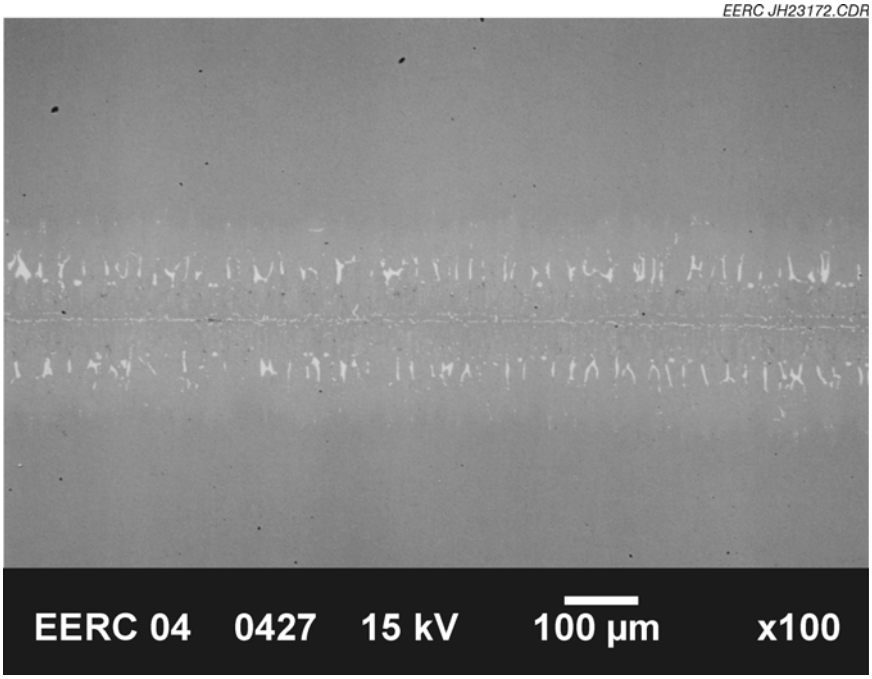

Figure 5. SEM micrograph of Joint A. The light area is the TLP metal diffusion.

instances, not detected, so the particles are not oxides. The particle diameter was approximately 4 µm. The yttrium/aluminum particles were also detected away from the interface but always adjacent to an area of TLP metal. This relationship is not fully understood and is being researched. The large TLP metal concentrations were centered at about 70 µm from the interface. It is difficult to tell during SEM examination, but the metal appears to be traveling between ODS alloy grains. The metal contains elevated levels of aluminum and titanium, with small amounts of iron and chromium. The titanium concentration was triple that of the base alloy, which implies that the surrounding alloy was slightly deficient in aluminum and titanium.

TLP Joint B is shown in Figure 6. Porosity at the interface is minor. Migration of TLP metal from the interface was detected to a distance of approximately 350 µm, or roughly twice that of Joint A. Concentrations of TLP metal can still be observed; however, they are smaller and thinner and at the outer limits of the metal migration. The TLP metal concentration at the joint interface is much less than that found in Joint A. The same yttrium/aluminum-rich phase was observed adjacent to areas rich in TLP metal. The particle size of this phase was about half that of the previous sample. A new TLP metal phase was detected which has titanium levels eight times that of the base alloy. The phase appears as small, 2 µm and less, particles dispersed in the TLP-affected zone of the alloy. This is a curious, unexpected phase that is also being investigated.

Joint C is shown in Figure 7. Migration of the TLP metal is approximately the same as that of Joint B, but the dispersion is even greater. The porosity at the interface was low but higher than that of the two previous joints. The yttrium/aluminum-rich phase was still present, but the particle size was found to be approximately 1–2 µm. The titanium-rich phase was found in the

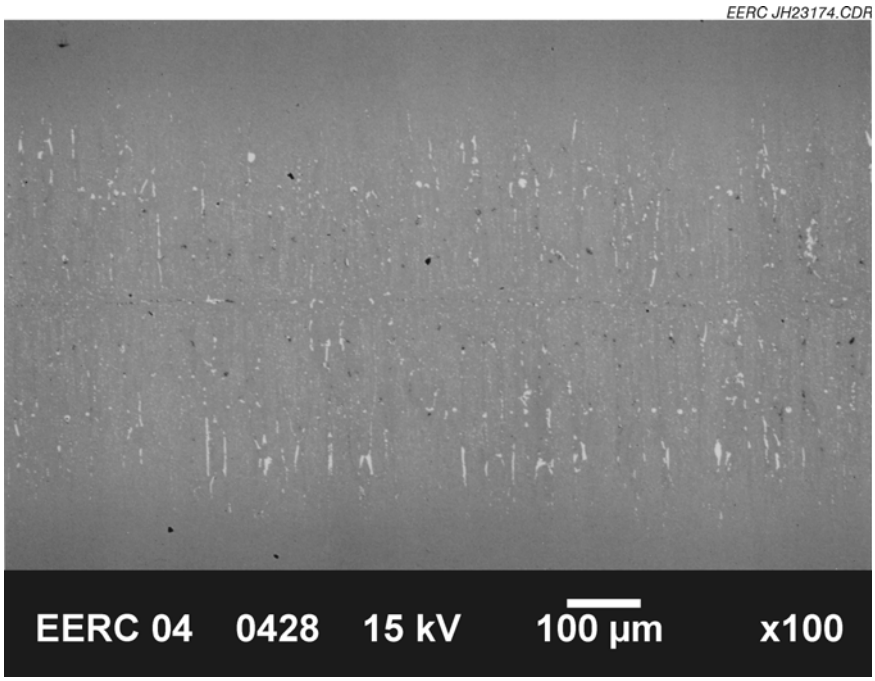

Figure 6. SEM micrograph of Joint B.

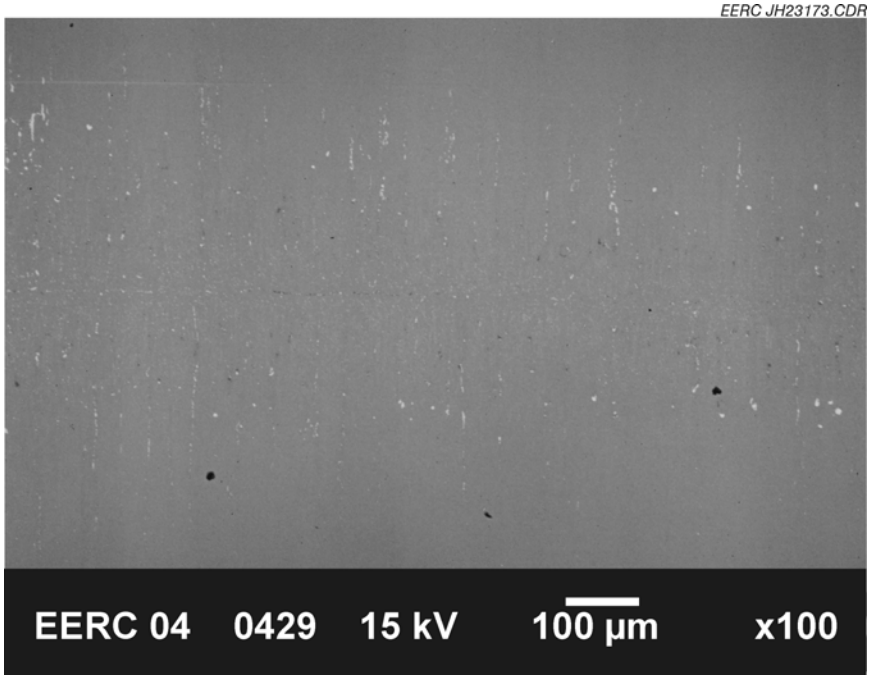

Figure 7. SEM micrograph of Joint C.

sample, with titanium concentrations now reaching 75 wt%, but the particle size is roughly the same as for Joint B. The TLP metal-rich areas of this sample have iron and titanium concentrations which are roughly double that of Joint B.

CONCLUSIONS

Even with the limited number of configurations analyzed, it is apparent that the IFCC with CO_2 recovery offers better performance and lower COE than pc plants with CO_2 recovery. This is also true with the lower-performing all-coal IFCC. The IFCC also has competitive COEs to IGCC plants, but with an operation essentially the same as a pc-fired plant, it would more likely be adopted by utilities than the IGCC. At NG prices above \$4.70/10^6 kJ (\$5.00/MMBtu), the IFCC systems are attractive alternatives to NGCC systems with CO_2 recovery while maintaining the standard operations of a pc plant. A near-zero-emission IFCC is also cheaper to operate than a modern pc system if a carbon tax of more than \$55/metric ton (\$50/ton) C is imposed. If 20% biomass cofiring is employed, the breakeven point compared to a coal-fired pc plant would be \$44/metric ton (\$40/ton) of carbon.

In general, TLP metal migration and dispersion improved with joining temperature. At the higher temperatures, an unexpected secondary titanium-enriched phase was formed and is being investigated. Porosity was very low but increased slightly with temperature. Residual TLP metal in the joint was enriched in aluminum, titanium, iron, and a little chromium. The migration of

the metal appears to be between the grain boundaries. Overall, these TLP results appear promising, but ultimately it is the strength of the joints that is of utmost importance. Therefore, portions of each of the joints have been sent to ORNL for tensile strength testing.

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