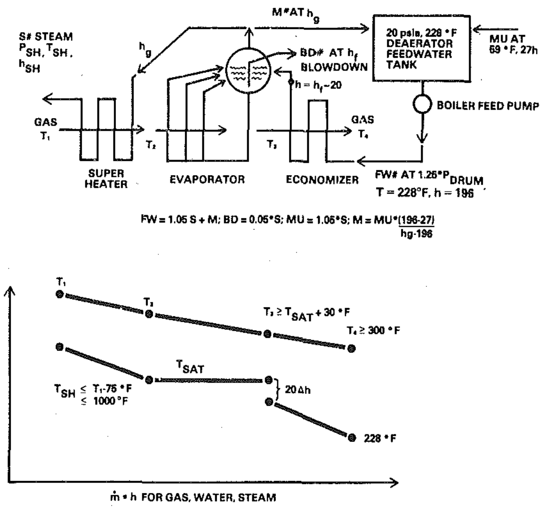

Fig. 6 Heat recovery steam generator—schematic and temperature profiles

Fuel:	Distillate, 3 dollars per million Btu, 19663 Btu per pound higher heating valve (45728 kJ/kg), 18550 Btu per pound lower heating valve (43139 kJ/kg).
Combustor:	99 percent combustion efficiency, 3 percent pressure drop, combustor pressure is 14.5525 times the pressure ratio, injection steam 50°F (27.8°C) or more above saturation at combustor pressure.
Turbine:	2200°F (1204°C) total temperature at first stage, stage inlet at 1.0 Mach number, three stages, air cooled, exhaust pressure loss 5 in. water (1244 N/m^2) plus 15 in. water (3733 N/m^2) if HRSG and plus 8 in. water (1990 N/m^2) if regenerator in exhaust.
Regenerator:	Air side pressure loss 2.2 percent, gas side pressure loss 2.0 percent, effectiveness related to air side 81 percent.
Turbine Cooling:	Cooling air schedule varied with pressure ratio and steam injection rate.

APPENDIX II

Criteria for Exhaust Plume Visibility Limit

When any exhaust stream contains water vapor, its mixture with ambient air may create a white opaque condensate plume. Although the condensate is water (it is commonly called steam) its appearance can be mistaken for smoke. Virtually every stack discharge will exhibit such a visible plume on a cold winter morning. A suitable criterion would limit plume visibility to being no more frequent than for alternative power plant stacks. Since most coal-burning plants will require flue gas scrubbers, that was the exhaust chosen as the standard for comparison. Flue gas scrubbing saturates the flue gas with water vapor at 125°F (52°C). The gas is reheated to 175°F (79°C) prior to exhausting from the stack. A psychrometric diagram shows that similar plume visibility potential will exist for any atmospheric discharge meeting the following criterion:

$$\text{Minimum discharge temperature } {}^\circ\text{F} = (50 + 1277*\mathit{Humidity})/(1 - \mathit{Humidity}).$$

Humidity is the weight fraction of water vapor in the stack gas. If the stack temperature exceeds this criterion, then its visible exhaust plume on cold days will start after the coal-fired stack plume has already been visible and will disappear before that plume disappears.

Table 5 Heat recovery steam generator parameters

Type Plant	Makeup	Steam Produced	Comments
STIG Cycle	635 gpm	330 P, 952 °F, 1499h	Injected Steam
Combined STIG	757 gpm	1450 P, 1000 °F, 1494h 183 P, 574 °F, 1309h	Out of HRSG Injected Steam
Combined Cycle	7 gpm	1450 P, 1000 °F, 1494h	2.5 in. Condenser

The criterion defines the stack temperature for exact parity with a coal-fired power plant with flue gas scrubbing on the basis of the appearance, duration, and disappearance of a visible white condensate in the exhaust plume.

APPENDIX III

Heat Recovery Steam Generator (HRSG)

Figure 6 shows a schematic of the heat recovery steam generator and the temperature profiles that limit heat recovery from the gas turbine exhaust gas. An additional constraint requires that the injection steam be at least 50°F (27.8°C) superheated relative to a saturation pressure equal to compressor discharge pressure. Only 99 percent of the gas turbine exhaust is accounted as flow through the HRSG to allow for bypass stack leakage. The bypass would be used during startup and to limit excess steam production. Unlike typical power boilers the HRSG units for STIG cycles operate with 100 percent makeup (MU). The deaerator is serviced by saturated steam (M) to produce feedwater (FW) at 228°F (109°C). A large 5 percent blowdown (BD) was assigned to limit drum water solids concentrations. The economizer heats the feedwater to within 20 Btu per pound (46.5 kJ/kg) of the drum saturated water enthalpy. The temperature pinch point limits are 75°F (41.7°C) at the superheater outlet, 30°F (16.7°C) leaving the evaporator section, and a 300°F (149°C) lower limit on stack gas temperature. From the drum to the gas turbine the pressure losses would be 5.8 percent in the superheater, 5 percent in the connecting steam line, and 35 percent in the high recovery control throttle at the gas turbine. The gas turbine combustor pressure was 14.5525 times the pressure ratio, and the resulting steam drum pressure would be 1.5 times the combustor pressure. A sodium zeolite water treatment would be used for the low pressure HRSGs. High pressure power boilers for the STIG combined cycle would require the more expensive complete demineralizer water treatment. Table 5 shows the parameters of the HRSGs for the selected gas turbine cycles of this study.

DISCUSSION

J. L. Jones, C. N. Chang, and J. Hamill[1]

This paper has been reviewed with great interest because of past work by IPT in the development of the Cheng Dual-Fluid Cycle (DFC) engine. The DFC engine was, in fact, discussed in detail with the General Electric Company in 1976. Only limited recognition of the benefits of steam injection in a gas turbine engine is given in this paper. Full benefit of the Dual-Fluid Cycle was not presented because of the argument on plume visibility. IPT's staff asserts that plume visibility should not be a real constraint on the DFC engine (called STIG in this paper). The Cheng Dual-Fluid Cycle engine maximizes waste heat recovery by critically metering steam-to-air ratio uniquely for a given set of gas turbine cycle parameters.

We would like to point out that the plume visibility limitation analysis cited in Messrs. Brown and Cohn's paper contains certain assumptions which made them conclude that the combined cycle offers better efficiency and cost benefits so long as utilities operate the combined cycle more than 1000 hr annually—a conclusion with which we disagree.

With reference to the paper, we wish to present our views.

1 Considering the plume visibility criterion presented in Ap-

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[1] International Power Techonlogy, Inc., 506 Oakmead Parkway, Sunnyvale, Calif. 94086.

pendix II, it is clear that, for zero humidity, the minimum discharge temperature goes to 50°F, whereas 125°F was indicated in Fig. 2. When we plot the visible plume limit criteria (according to the equation presented in Appendix II and assuming humidity defined as wgt. steam/wgt. exhaust gas), using the same Fig. 2, we find it approaches the stack temperature at a steam-to-air ratio of about 0.165, which is near the peak efficiency condition identified in the authors' calculations. The visible plume region, thus, is barely a constraint on the STIG system defined by the authors.

If one accepts the authors' definition of humidity as wgt. steam/wgt stack gas, then the visible plume limit for the sample case extends to a steam-to-air ratio of 0.175 and no constraint is imposed on the DFC (STIG) system.

2 From a physical and thermodynamic point of view, plumes should not appear for a given moisture content if the exhaust temperature is above the equilibrium dew point. In reality, the plume appears when the exhaust gas mixture is cooled down faster than the diffusion rate of the steam. That is the reason why the plume generally appears a short distance away from the top of the exhaust stack and then disappears again further away from the stack. Hence, the plume visibility problem is more or less an engineering design problem of the stack rather than a limitation in physical principle.

The exhaust gas dew point limit as a criteria for plume visibility, when added to Fig. 2, is clearly well below the exhaust gas temperature over the range of steam-to-air ratios of interest.

3 Using the engine operating conditions defined in the paper, we have calculated the efficiency and power output for the Cheng Dual-Fluid Cycle engine. A special computational program, developed by IPT for the DFC engine, was used. This program was devised to locate the maximum efficiency peaks and identify the critical combinations of fuel, air and steam for these peaks according to IPT's patent on the Cheng-DFC engine (U.S. Patent No. 4,128,994). This calculation uses the same component losses as those employed by G.E. in 1976 and in this paper (see Table 1). For the DFC engine at 2200°F turbine inlet temperature and compression ratio 16:1 with 2.5 percent loss to blade cooling air, the thermal efficiency is 44.5 percent (HHV) or 47.5 percent (LHV) and the throughput is 291 KW/PPS air flow. For comparison to combined efficiency, see Fig. 4. The stack temperature is 251.5°F which is 98°F above the dew point temperature. This temperature differential is much higher than normally encountered during wet scrubber exhaust stack operation where reheating the exhaust gas by 35°F (T) is sufficient to eliminate the visible plume.

Table 1 Input conditions

Inlet pressure loss	4″H_2O
Compressor efficiency	88 percent
Pressure drop across combustor	3 percent
Combustion efficiency	99 percent
Turbine efficiency	90 percent
Turbine back pressure loss	20″H_2O
ΔT pinch	30°F
ΔT upper	75°F
Cooling air lost to the cycle	2.5 percent

4 In reality, when a Cheng DFC engine is operating at 2200°F at a higher pressure ratio, say 20:1, the thermal efficiency will be over 50 percent (LHV) and with a reduced steam-to-air ratio; hence, the exhaust will be further away from the visible plume conditions.

The Cheng Dual-Fluid Cycle (STIG) engine has better thermal efficiency and lower unit capital cost ($/kW) than was cited by the authors. These improved characteristics would result from a correct interpretation of the plume problem, and the use of the optimum waste heat boiler pressure, plus the recognition of the increased power output that is used for cost normalization.

For example, the boiler pressure at 330 psig cited by the authors in the STIG system at a compressor pressure ratio of 16:1 has an over pressure of about 90 to 110 psig. This not only reduced the recoverable waste heat but also critically reduces the thermodynamic potential of the steam due to the resultant throttling requirement.

Actually, the real problem with exhaust gas plumes is not visibility due to water content, but the presence of pollutants, normally NO_x and SO_2. The injection of steam into the combustor of the DFC engine provides for the effective suppression of NO_x production to well within acceptable limits. In addition, IPT is developing a practical and effective method for the clean-up of sulfur compounds from the exhaust gas of plants burning coal-derived synfuel or other higher sulfur content fuels, to avoid the occurrence of acid rain or other pollution problems.

Authors' Closure

The discussers contend that the benefits of steam injection have been understated, and that plumes do not become visible unless the discharge gas is at its dew point. In their discussion they attribute no humidity to the ambient air and account no water vapor products from the combustion of fuel. Their simplified use of injected steam as the only source of humidity in the exhaust leads to the erroneous assertion that a simple cycle gas turbine exhaust can be cooled to 50°F without condensation and their own replot of Fig. 2 with a less restrictive plume parity criteria limit. The ambient air as defined in Appendix I has 0.0064 pounds of water vapor per pound of mixture, and combustion of distillate oil adds 1.39 pounds of water vapor per pound of fuel burned. The fuel flow and other data evaluated are detailed in reference [6]. The visible plume limit criterion of Fig. 2 is correct as presented.

The contention that dew point temperature is the sole criterion for plume visibility is not correct. Condensation plumes result from the mixing of two gases such as exhaust gas and ambient air. Figure 7 shows the psychrometry of that mixing with dashed lines showing visible plumes for both the STIG cycle and the Flue Gas Desulfurization-Coal Stack when the ambient air is at 20°F. When the ambient warms and reaches the plume criteria parity line, both stack plumes would become invisible simultaneously. The stack condition endorsed by the discussers of 251.5°F with 154°F dew point falls in the "worse than FGD zone" and would result in exhaust plumes being visible more frequently and for longer duration than the plants constrained to be on the plume criteria parity line. Plume visibility is more than

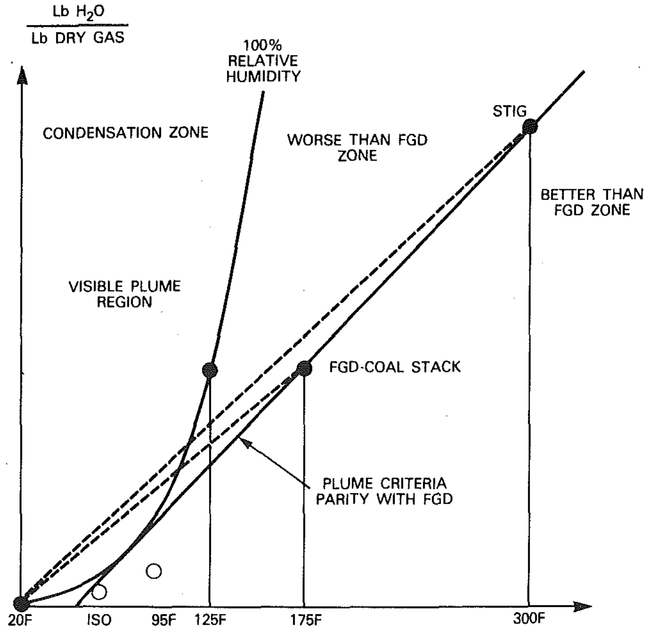

Fig. 7 Psychometry of visible plume formation and plume parity criteria

a stack design problem and dew point temperature of the exhaust is not an appropriate plume visibility criteria.

The performance presented by the discussers for the CDFC engine was evidently made without realistically accounting for the air chargeable for turbine cooling. Both the higher specific work and the higher efficiency claimed by the discussers appear to correlate with their assumption of 2.5 percent "lost" cooling air. It is unfortunate that the discussers compare their analytic results to the authors' performance estimates for the STIG and for combined cycle plants that are based on realistic values for chargeable cooling air flow. The air coolant schedule used conforms to reference [4] evaluations as a function of firing temperature, pressure ratio, and water vapor content of the expansion gases.

R. J. Boyle [7] examines the effects of inclusion and exclusion of cooling air on steam injection gas turbine cycles. The results with cooling air corroborate the findings of the authors' study, but even with uncooled turbines Boyle does not project the extremes of specific work and efficiency claimed for the CDFC cycle by the discussers.

A serious concern with steam injection is the margin to combustion instability in the gas turbine. The total steam pressure drop of 50 percent provides for the use of a high recovery control valve that precludes pressure feedback between the combustor and the boiler, and steam pipe and superheater pressure drops. Omission of these pressure drops would improve the STIG performance, but at the expense of being unrealistic for a viable design.

The STIG cycle chosen for cost and performance evaluation was close to optimum efficiency despite the limitation added by the plume criteria. For all of the cycles evaluated the performance and costs were derived in a manner identical to reference [4]. The evaluations were made as fairly as possible by adhering to reasonable constraints for component performance that could be expected with a moderate development effort.

Additional References

6 Brown, D. H., "Steam Injected Gas Turbine Study: An Economic and Thermodynamic Appraisal," EPRI AF-1186 TPS 77-737, Sept. 1979.

7 Boyle, R. J., "Effect of Steam Addition on Cycle Performance of Simple and Recuperated Gas Turbines," NASA Technical paper 1440, Apr. 1979.