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# POTENTIALITIES OF TEC TOPPING: A SIMPLIFIED VIEW OF PARAMETRIC EFFECTS

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## ABSTRACT

Reductions in the cost of thermionic-energy-conversion (TEC) modules yield direct decreases in cost of electricity (COE) from TEC-topped central-station power plants. Simplified COE, overall-efficiency charts presented here illustrate this trend. Additional capital-cost diminution will result from designing more compact furnaces with considerably increased heat-transfer rates allowable and desirable for high-temperature TEC and heat pipes. Such improvements can evolve because of the protection from hot corrosion and slag as well as the thermal-expansion compatibilities offered by silicon-carbide clads on TEC-heating surfaces. Greater efficiencies and far fewer modules are possible with "high-temperature, high-power-density TEC": This will decrease capital and fuel costs much more - and substantially increase electric-power outputs for fixed fuel inputs. In addition to more electricity, less pollution, and lower costs, TEC topping used directly in coal-combustion products will contribute to balance-of-payment gains and national energy independence.

## EXECUTIVE SUMMARY

High-temperature, high-power-density thermionic energy conversion (TEC) offers more power, lower costs, and less pollution from topping-cycle generation: High temperatures enable substantial Carnot gains, hence more power and less pollution from a given fuel input. And high power densities allow great reductions in numbers of converters for a given fuel input, hence much lower capital investments.

For a TEC-topped steam power plant the net overall efficiency with 0.15 bypass (K) is $\eta_{NOP} \approx 0.34 + 0.38\ \eta_{TEC}$ or with zero bypass $\eta_{NOP} \approx 0.34 + 0.45\ \eta_{TEC}$, where $\eta_{TEC}$ is TEC efficiency with optimized leads. The corresponding 30-year levelized cost of electricity in 1975 dollars is for $K = 0.15$ $COE_{75}^{30} \approx 4.9 + (17.6 + 0.064\ C_{TEC} + 0.5\ \eta_{TEC} + 17.9N)/(0.9 + \eta_{TEC})$ or for $K = 0$ $COE_{75}^{30} \approx 4.9 + (14.7 + 0.063\ C_{TEC} + 0.5\ \eta_{TEC} + 15.1N)/0.75 + \eta_{TEC})$, where $C_{TEC}$ is $\$/kW_t$ for the TEC system and N is $\$/10^6$ Btu for fuel. Thus, with a 0.15 bypass 10% $\eta_{TEC}$ yields

11% more electric power than steam alone; 20% $\eta_{TEC}$, 22% more power; 30% $\eta_{TEC}$, 34% more power; and 40% $\eta_{TEC}$, 45% more power. Also increasing $\eta_{TEC}$ with constant $C_{TEC}$ (\$100/$kW_t$ for example) and N (\$1/$10^6$ Btu and \$4/$10^6$ Btu) effects substantial changes in $COE^{30}_{75}$ relative to that for steam alone:

| N, \$/$10^6$ Btu | No TEC | | | 10% $\eta_{TEC}$ | 20% $\eta_{TEC}$ | 30% $\eta_{TEC}$ | 40% $\eta_{TEC}$ |
|---|---|---|---|---|---|---|---|
| 1 | 44.3 | $\frac{\text{mills}}{\text{kW·hr}}$ | $COE^{30}_{75}$ | ~6% more | ~3% less | ~10% less | ~16% less |
| 4 | 104 | | $COE^{30}_{75}$ | ~3% less | ~12% less | ~19% less | ~24% less |

Referred to $COE^{30}_{75}$ values for steam alone, 40% $\eta_{TEC}$ translates to ~7 mills/kW·hr less $COE^{30}_{75}$ with \$1/$10^6$ Btu and ~25 mills/kW·hr less with \$4/$10^6$ Btu: Higher fuel costs heighten the influence of $\eta_{TEC}$ on $COE^{30}_{75}$.

These numbers indicate parametric effects of TEC and fuel costs as well as TEC efficiency. But they fail to imply the great cost saving possible with fully matured high-temperature, high-power-density TEC: For negligible interelectrode losses and 10% back emission, using 1800 K, 30A/cm$^2$ TEC rather than 1600 K, 5A/cm$^2$ TEC produces the same power output 25-to-31% more efficiently with one-seventh the number of converters. Such gains are certainly worth striving to attain through TEC applied research and development.

Recent findings on hot-corrosion protection, slag resistance, and thermal-expansion compatibilities of silicon-carbide-clad heat receivers predict successful TEC service in high-temperature coal-combustion products. And new compact furnace designs with much greater heat-transfer rates optimized for TEC with emitter as well as collector heat pipes should allow further significant cost reductions.

Thus, high-temperature, high-power-density TEC topping not only offers more power, lower costs, and less pollution but also promises contributions toward balance-of-payment equity and national energy independence.

## TEC TOPPING-CYCLE CONSIDERATIONS

Thermionic energy conversion (TEC) brings significant advantages to topping-cycle power generation: Substantially increased outputs and decreased costs of electricity are possible through carnot-efficiency gains inherent with TEC. But, its true potential remained veiled until recently (refs. 1 to 4) because of the apparently defensive avoidance of the high temperatures and great power densities attainable with TEC (refs. 5 to 18). These TEC characteristics are strengths not weaknesses. And to amplify that observation this paper further indicates the potentialities of "high-temperature, high-power-density thermionic energy conversion" (ref. 1).

Reference 4 adapts partially optimized results for TEC topping of a steam plant (ref. 3) to the cost-of-electricity (COE), overall-efficiency chart from reference 19. This adaptation allows the compatible comparison of "thirty-year leverlized costs in mid-1975 dollars" with "fuel cost assumed constant in fixed dollars" at $1/10$^6$ Btu for coal (fig. 1). The "partial optimization of steam-plant topping with $>$ 20 A/cm$^2$ TEC yields overall efficiencies near those for the most-efficacious advanced systems and COE's between the best and those for conventional steam plants. And as reference "3" concludes, 'we expect that further significant improvements can be made by optimizing the overall system design.' Such results should place TEC, STEAM among the best systems on figure" 1 (ref. 4).

In the present paper, corrected and reduced reference - 3 equations imply influences of TEC efficiency (10 to 40%) and cost (100 to 400 \$/kW$_t$) as well as fuel cost (1 to 4 \$/10$^6$ Btu) on overall efficiency and COE for TEC topping of central-station steam plants. In turn plots of TEC efficiency and power density reveal the striking performance gains possible with the hotter emitters at 30 A/cm$^2$ as opposed to 5 A/cm$^2$.

To develop a simplified view of these parametric affects the following sections discuss briefly some topping equations, TEC performance calculations, and trends caused by major variables.

## SOME RELATIONSHIPS FOR A TEC-TOPPED STEAM POWER PLANT

Reference 3 presents equations for the net overall plant efficiency ($\eta_{NOP}$) and total cost per thermal kilowatt ($C_{TPT}$) for TEC topping of a steam power plant:

$$\eta_{NOP} = (1 - h) \left\{ (1 - K)\eta_C \eta_{TEC} \eta_I + (1 - S)\left[K + (1 - K)(1 - \eta_{TEC})\right]\eta_S \eta_C - f \right\} \tag{1}$$

In this expression $\eta_C$ is combustion-system efficiency (0.90); $\eta_{TEC}$, TEC-system efficiency (calculated); $\eta_I$, inverter-system efficiency (0.94); $\eta_S$, steam-cycle efficiency (0.442); K, bypass-heat factor (0.15); S, steam-system electrical requirements (0.027); f, combustion-system electrical requirements (0.025); and h, balance-of-plant (BOP) electrical losses (0.015). The parenthetic values allow considerable reduction of (1):

$$\eta_{NOP} \approx 0.34 + 0.38\ \eta_{TEC} \text{ (desulfurization losses included, ~0.02)} \qquad (2)$$

Although (1) in reference 3 needs only a parenthesis after the second $\eta_{TEC}$, the $C_{TPT}$ equation there lacks $\eta_{TEC}$ as a multiplier of the inverter cost ($C_{INV}$) and fails to pass dimensional analysis ($C_{ST}1.2\ C_{CT}$ should be $C_{ST} + 1.2\ C_{CT}$). The authors of reference 3 substantiate the need for changes, yielding a corrected version of the $C_{TPT}$ equation:

$$C_{TPT} = C_F + C_H + 1.2\ (C_E + C_{BOP}) + (1 - K)(C_{TEC} + \eta_{TEC}C_{INV})\eta_C + K\eta_C C_{SH}$$

$$+ \left[K\eta_c + (1 - \eta_{TEC})\eta_c(1 - K)\right](C_{ST} + 1.2\ C_{CT}) \qquad (3)$$

In equation (3) the C's are dollars per thermal-kilowatt input for the furnace system ($C_F = 18.0$), high-temperature air heaters ($C_H = 20.6$), emission control ($C_E = 11.5$), site labor and other BOP ($C_{BOP} = 109.0$), TEC system ($C_{TEC}$ variable), inverters (exception: \$38.0/kW$_e$), finishing superheater ($C_{SH} = 12.2$), steam-turbine generator ($C_{ST} = 16.1$), and wet cooling towers ($C_{CT} = 11.6$). Again a reduction results:

$$C_{TPT} = 211.9 + 0.765\ C_{TEC} + 6.1\ \eta_{TEC} \qquad (\$/\text{kW}_t) \qquad (4)$$

Dividing (3) or (4) by (1) or (2) yields the total plant cost per electric kilowatt:

$$C_{TPE} = C_{TPT}/\eta_{NOP} \qquad (\$/\text{kW}_e) \qquad (5)$$

This equation in turn leads to one for capital cost of the plant:

$$C_{CPE} = C_{TPE} \times \frac{0.18 \text{ fixed charge} \times 10^3 \text{ mills/\$}}{0.65 \text{ capacity factor} \times 8760 \text{ hr/yr}} = 0.0316\ C_{TPE} \quad \frac{\text{mills}}{\text{kW}\cdot\text{hr}} \qquad (6)$$

Then a 2.004 EPRI factor produces 30-year levelized costs for operating and maintenance ($C^{30}_{OME}$, using 2.47 mills/kW·hr from ref. 3) and for fuel ($C_{FE}^{30}$) at N dollars per $10^6$ Btu:

$$C_{FE}^{30} = 2 \times \frac{N\$ \times 10^3 \text{ mills/\$} \times 3.41\times10^3 \text{ Btu/kW}\cdot\text{hr}_t}{10^6 \text{ Btu} \times \eta_{NOP}\text{kW}\cdot\text{hr}_e/\text{kW}\cdot\text{hr}_t} = 6.82\ N/\eta_{NOP} \qquad \left(\frac{\text{mills}}{\text{kW}\cdot\text{hr}}\right) \tag{7}$$

$$C_{OME}^{30} = 2\times2.47 = 4.94 \qquad \left(\frac{\text{mills}}{\text{kW}\cdot\text{hr}}\right) \tag{8}$$

And the 30-year levelized COE in mid-1975 dollars according to the ground rules governing figure 1 (refs. 19 and 4) is the summation of (6), (7), and (8):

$$COE_{75}^{30} = C_{CPE} + C_{FE}^{30} + C_{OME}^{30} \tag{9}$$

The reduced version of (9) is informative:

$$COE_{75}^{30} = 4.9 + (17.6 + 0.064\ C_{TEC} + 0.5\ \eta_{TEC} + 17.9\ N)/(0.9 + \eta_{TEC}) \qquad \left(\frac{\text{mills}}{\text{kW}\cdot\text{hr}}\right) \tag{10}$$

Reference 3 discusses increasing overall efficiency by reducing the bypass factor from 0.15 to zero, which produces the following effects.

$$\eta_{NOP} \approx 0.34 + 0.45\ \eta_{tec} \qquad \text{(desulfurization losses} \approx 0.02) \tag{2A}$$

$$C_{TPT} = 210.2 + 0.9\ C_{TEC} + 7.2\ \eta_{TEC} \qquad (\$/\text{kW}_t) \tag{4A}$$

$$COE_{75}^{30} = 4.9 + (14.7 + 0.063\ C_{TEC} + 0.5\ \eta_{TEC} + 15.1\ N)/(0.75 + \eta_{TEC}) \qquad \left(\frac{\text{mills}}{\text{kW}\cdot\text{hr}}\right) \tag{10A}$$

Here, subsequent calculations utilize the more conventional 0.15 bypass.

Equations (2), (10), (2A), and (10A) for the variables composing figure 1 emphasize the importance of TEC performance: $\eta_{NOP}$ varies directly with $\eta_{TEC}$. And the predominant $\eta_{TEC}$ effect on COE$^{30}_{75}$ derives from the denominator ($\propto \eta_{NOP}$) of the second term in (10) or (10A); the numerator $\eta_{TEC}$ effect is nearly negligible. Much stronger influences result from TEC power densities, which subsequent sections discuss. Those discussions cover results from converter-performance equations presented in the next section.

## TEC-PERFORMANCE EQUATIONS

The appropriate converter outputs are the current density,

$$J_O = J_{ES} - J_R \tag{11}$$

the electrode voltage,

$$V_O = \phi_E - \phi_C - V_D - V_A = \phi_E - V_B - V_A \tag{12}$$

the voltage at optimum-lead terminals,

$$V_{OL} = V_O - V_L \tag{13}$$

the electrode power density,

$$P_O = J_O V_O \tag{14}$$

and the effective power density with optimum leads attached to the converter,

$$P_{OL} = J_O V_{OL} \tag{15}$$

Here $\phi_E$ and $\phi_C$ are emitter and collector work functions, $V_D$ is the interelectrode voltage drop, $V_B = \phi_C + V_D$ is the barrier index or total internal loss, $V_A$ is the equivalent auxiliary input voltage (not used in the present calculations), and $V_L$ is the voltage loss required for optimum leads.

The current-density components correspond to emitter saturation,

$$J_{ES} = A(1 - R_E)\, T_E^2 \exp\,(-\phi_E/kT_E) \tag{16}$$

which has a collector-saturation counterpart,

$$J_{CS} = A(1 - R_C)\, T_C^2 \exp\,(-\phi_C/kT_C) \tag{17}$$

and to the reverse flow $J_R$, which includes reflections, backscattering, back emission, and other effects that diminish the output current density. In equations (16) and (17) A and K are Richardson and Boltzmann constants, $T_E$ and $T_C$ are emitter and collector temperatures, and $R_E$ and $R_C$ are emitter and collector reflection coefficients.

An important theoretic detail relates to a common inconsistency in the treatment of back emission (refs. 1, 20 and 21): In generalized TEC terminology back emission subtracts from the emitter current in obtaining the net output current. This usual definition of back emission requires it to be only that part of the collector emission that reaches the emitter and thereby diminishes the output current according in a net-flow balance at the converter boundaries. Thus, back emission is not the saturated collector emission given by equation (17), regardless of $R_C$ modification, because the emission barrier is incorrect: This observation derives from the fact that, in the generally cited TEC power-producing mode, the emitter electron barrier (motive maximum) is a few tenths of a volt (the interelectrode voltage drop) above its collector counterpart. So during steady-state operation the preponderance of collector saturated emission cannot clear the emitter sheath, even in the absence of other deflecting encounters. Therefore, most of the collector saturated emission must return to its source nullifying to a large extent its effect on the diminution of the net output current.

Unless the interelectrode loss is much closer to zero than to its currently common value of about a half volt, only a small fraction of the collector emission, the true back emission $J_{BE}$, will reach the emitter:

$$J_{BE} = A(1 - R_{BE})\, T_C^2 \exp\,(-V_B/kT_C) \tag{18}$$

In this equation the effective back-emission reflection coefficient $R_{BE}$ comprises $R_C$ and similar coefficients for all interelectrode mechanisms that return collector-emitted electrons to their source - except those for noncollisional repulsion by the emitter sheath. Thus, using equation (18) without $R_{BE}$ produces a conservative estimate of the converter output current. Such an approximation seems reasonable for low cesium concentrations, reduced enhanced-mode pressures, and small interelectrode gaps. Of course, with zero interelectrode losses assumed (ref. 6 for FY 81) as well as negligible interelectrode-reflection effects, equations (17) and (18) become identical.

A simplified, yet reasonable estimate of TEC efficiency with optimum-lead losses ($\eta_{OL}$) embodies the previously discussed inputs (ref. 1 based on refs. 22 and 23) and serves as $\eta_{TEC}$:

$$\eta_{OL} =$$

$$\frac{(J_{ES} - J_{BE})\left\{\phi_E - \phi_C - V_D - V_A - 2\left[2.45\times10^{-8}\ \eta_{EC}(T_E^2 - T_C^2)/(2 - \eta_{EC})\right]^{1/2}\right\}}{J_{ES}(\phi_E + 2kT_E) - J_{BE}(\phi_E + 2kT_C) + 5.7\ 10^{-12}\left[0.05 + 7.5\times10^{-5}(T_E - 1000)\right](T_E^4 - T_C^4)} \tag{19}$$

Here the last term of the denominator approximates nonelectronic thermal transport while the factor following the first 2 in the numerator represents the optimum-lead loss $V_L$. Deleting $2V_L$ from equation (19) transforms that expression into one for the TEC electrode efficiency $\eta_{EC}$ used here to compute the optimum-lead loss. Of course, the electrode efficiency is the true converter evaluation analogous to other power-generator performance ratings. But because of relatively high TEC current densities and low voltages the optimum-lead efficiency seems more pragmatic. A discussion of results from (19) as well as (15), (10), and (2) follows.

## SOME PARAMETRIC TEC-TOPPING EFFECTS

Figure-1 ground rules apply identically to figure 2, which is another $COE_{75}^{30}$, $\eta_{NOP}$ chart. In fact four representative points from figure 1 for coal-fed systems using $\$1/10^6$-Btu fuel appear on figure 2. With this orienting backdrop, topping results from equations (2) and (10) offer additional perspective on $COE_{75}^{30}$, $\eta_{NOP}$ trends for variations of $C_{TEC}$ and $\eta_{TEC}$. Incidentally the steam-plant basis for equations (2) and (10) at 34% $\eta_{NOP}$ and 44.3-mills/kW·hr $COE_{75}^{30}$ differs slightly from its figure-1 counterpart.

On figure 2 reducing $C_{TEC}$ from 400 to 100 $\$/kW_t$ decreases $COE_{75}^{30}$ by ~19 mills/kW·hr at a 10% $\eta_{TEC}$ ($\eta_{NOP}$ = 37.8%) and by ~15 mills/kW·hr at a 40% $\eta_{TEC}$ ($\eta_{NOP}$ = 49.2%). Increasing $\eta_{TEC}$ from 10% to 40% drops $COE_{75}^{30}$ by ~14 mills/kW·hr at a 400-$\$/kW_t$ $C_{TEC}$ and by ~10 mills/kW·hr at a 100-$\$/kW_t$ $C_{TEC}$. In accord with equation (2) a 10% $\eta_{TEC}$ yields ~11% more electric power than the basic steam capability; 20% $\eta_{TEC}$, ~22% more power; 30% $\eta_{TEC}$, ~34% more power; and 40% $\eta_{TEC}$, ~45% more power. And for a 100-$\$/kW_t$ $C_{TEC}$ equation (10) indicates that a 10% $\eta_{TEC}$ produces ~6% greater $COE_{75}^{30}$ than that for steam alone; 20% $\eta_{TEC}$, ~3% less $COE_{75}^{30}$ than steam; 30% $\eta_{TEC}$, ~10% less $COE_{75}^{30}$ and 40% $\eta_{TEC}$, ~16% less $COE_{75}^{30}$.

Because many feel that such a comparison at $\$2/10^6$ Btu is more realistic than at $\$1/10^6$ Btu, figure 3 is particularly meaningful. All figure-2 ground rules, except fuel cost, remain unchanged for figure 3. Note the higher range and steepening trends for the $COE_{75}^{30}$, $\eta_{NOP}$ relationships in figure 3 compared with those of figure 2: Now $COE_{75}^{30}$'s run from ~46 to ~85 mills/kW·hr (a span of ~39) instead of ~32 to ~66 (~34) in figure 2.

As equation (10) shows the $COE_{75}^{30}$ alterations over the $C_{TEC}$ range persist when only fuel cost changes: On figure 2 (3, 4, or 5) reducing $C_{TEC}$ from 400 to 100 $\$/kW_t$ decreases $COE_{75}^{30}$ by ~19 mills/kW hr at 10% $\eta_{TEC}$

and by ~15 mills/kW·hr at 40% $\eta_{TEC}$ But as figure 3 reveals, increasing $\eta_{TEC}$ from 10% to 40% drops $COE^{30}_{75}$ by ~18 mills/kW·hr at a 400-\$/kW$_t$ $C_{TEC}$ and by ~14 mills/kW·hr at a 100-\$/kW$_t$ $C_{TEC}$. Of course the power-output gains for TEC topping remain unchanged in the transition to figure 3 (or 4 or 5) from 2. However the equation (10) basic-steam $COE^{30}_{75}$ rises from 44.3 to 64.2 mills/kW·hr. And for a 100-\$/kW$_t$ $C_{TEC}$ equation (10) indicates that a 10% $\eta_{TEC}$ produces ~1% greater $COE^{30}_{75}$ than that for steam alone; 20% $\eta_{TEC}$, ~5% less $COE^{30}_{75}$ than steam; 30% $\eta_{TEC}$, ~15% less $COE^{30}_{75}$. 40% $\eta_{TEC}$, ~21% less.

Reference 4 mentions an effect of a \$3/10$^6$-Btu fuel cost compared with that of the \$1/10$^6$-Btu value used for figure 1. Here figure 4 treats the implications of this fuel-cost change more fully. Again, the $COE^{30}_{75}$, $\eta_{NOP}$ relations exhibit an even higher range and still steeper trends. And for a 100-\$/kW$_t$ $C_{TEC}$ equation (10) indicates that a 10% $\eta_{TEC}$ produces ~2% less $COE^{30}_{75}$ than that for steam alone; 20% $\eta_{TEC}$, ~10% less $COE^{30}_{75}$ than steam; 30% $\eta_{TEC}$, ~17% less; and 40% $\eta_{TEC}$, ~23% less.

Reference 18, "using solvent-refined liquified-coal (sic) at a levelized cost of \$4.66GJ (4.92/10$^6$ Btu), "indicates 1978 trends toward high fuel expenditures, which are even more pronounced today. So comparison of figure 5 results with those of figure 2 is especially significant in implying effects of sharply increasing fuel costs. To compare figures 2 and 5 the second paragraph of this section appears again here with figure 5 numbers in parentheses:

> On figure 2 (5) reducing $C_{TEC}$ from 400 to 100\$/kW$_t$ decreases $COE^{30}_{75}$ by ~19 (19) mills/kW·hr at a 10% $\eta_{TEC}$ ($\eta_{NOP}$ = 37.8 (37.8)%) and by ~15 (15) mills/kW·hr at a 40% $\eta_{TEC}$ ($\eta_{NOP}$ = 49.2 (49.2)%). Increasing $\eta_{TEC}$ from 10% to 40% drops $COE^{30}_{75}$ by ~14 (27) mills/kW·hr at a 400-\$/kW$_t$ $C_{TEC}$ and by ~10 (22) mills/kW·hr at a 100-\$/kW$_5$ $C_{TEC}$. In accord with equation (2) a 10% $\eta_{TEC}$ yields 11 (11)% more electric power than the basic steam capability; 20% $\eta_{TEC}$, 22 (22)% more power; 30% $\eta_{TEC}$, ~34 (34)% more power; and 40% $\eta_{TEC}$, ~45 (45)% more power. And for a 100-\$/kW$_t$ $C_{TEC}$ equation (10) indicates that a 10% $\eta_{TEC}$ produces 6% greater (3% less) $COE^{30}_{75}$ than that for steam alone;

> 20% $\eta_{TEC}$, ~3 (12)% less $COE^{30}_{75}$ than steam; 30% $\eta_{TEC}$, ~10 (19)% less $COE^{30}_{75}$; and 40% $\eta_{TEC}$, ~16 (24)% less $COE^{30}_{75}$.

For steam alone the $COE^{30}_{75}$ is 44.3 mills/kW·hr on figure 2 for \$1/$10^6$ Btu and 104 mills/kW·hr on figure 5 for \$4/$10^6$ Btu. So the last quoted set of "40% $\eta_{TEC}$, ~16 (24)% less $COE^{30}_{75}$" also means "40% $\eta_{TEC}$, 7 (25) mills/kW·hr less $COE^{30}_{75}$." As the dotted "steam-COE" lines emphasize, higher fuel costs heighten the influence of $\eta_{TEC}$ on $COE^{30}_{75}$.

## TEC-PERFORMANCE INFLUENCES

The importance of converter-performance improvements in TEC topping of power plants (TOPP) stands out in figures 1 to 5. However, figures 6 and 7 emphasize a far more important characteristic of the results for TEC with 10% back emission and negligible interelectrode losses: Changing from low emitter temperatures and low power densities to allowable high-temperature, high-power-density TEC not only significantly increases converter efficiency but also greatly reduces the number of TEC modules, hence the cost, required for a given thermal input or a desired power output.

Reference 1 indicated this effect in 1977 for space nuclear electric power utilizing TEC with 925 K collectors. Those results parallel or analogize TEC-TOPP implications:

> These underlined values also reveal the significant output and efficiency gains for TEC operation at 1800 K and 30 A/cm$^2$ as compared with 1650 K and 5 A/cm$^2$ (refs. 5 to 8): <u>The 28.5% increase in optimum-lead efficiency</u> means lighter radiators and either more output power or smaller nuclear reactors and lighter shield-dependent weights for NEP. <u>The 10.8% higher optimum-lead voltage</u> requires less power conditioning capability and results in lower transmission-line losses for a given quantity of output power. <u>The 560% gain in effective output power density</u> allows many fewer converters and associated current-collecting bus bars for a given output-power level. <u>And of course the higher emitter temperature</u> (coupled with greater efficiency) enables the use of substantially fewer and/or smaller emitter heat pipes. This reduction in turn should produce significant decreases in shielding-related as well as reactor weights. The higher emitter temperature can also make possible considerably increased collector temperatures if parametric studies indicate the need for lower radiator weights (the $T^4$ influence).

"Less power conditioning ... fewer converters and associated current-collecting bus bars ... fewer and/or smaller, emitter heat pipes" all relate directly to the TEC-TOPP application.

Similarly, in a comparison of figures 6 and 7 results, using 1800 K, 30 $A/cm^2$ TEC rather than 1600 K, 5 $A/cm^2$ TEC (1) for a given power output requires about one-seventh the number of converters and yields 25-to-31%-more efficiency, (2) for a given thermal input produces 25-to-31%-more power output with less than one-fifth the number of converters. In fact figures 6 and 7 indicate that using 1600 K, 30 $A/cm^2$ TEC rather than 1600 K, 5 $A/cm^2$ TEC generates ~12% more output power within ~79% fewer converters for a given thermal input. These potentially great cost savings are in no way implied by equations (3) and (10) or figures 2 to 5.

But are the advantages of high-temperature, high-power-density TEC attainable? The DOE TEC program aims at approaching converter capabilities represented by figures 6 and 7. Figure 15 of reference 4 shows the definite progress in that direction. For the fully matured TEC technology, figures 6 and 7 reveal that the higher efficiencies at 30 $A/cm^2$ are available for emitter temperatures down to 1300 K. Furthermore reference 3 predicts much lower costs for converter modules with the higher power densities in TEC TOPP even with emitters at 1500 K. However TEC service at much higher temperatures in coal-combustion products appears feasible: References 24 to 28 support this observation with gratifying findings on silicon-carbide protection against hot corrosion and slag as well as workable thermal-expansion compatibilities. And TEC with suitable silicon-carbide cladding appears substantially more economical than with lower-temperature super alloy protection (private communication with F. N. Huffman, Thermo Electron Corporation).

In addition to the preceding potentialities high-temperature, high-power-density TEC should encourage designs of more compact furnaces with significantly greater heat-transfer rates. In turn high-temperature-emitter heat pipes can collect outputs from optimum-cost furnaces and transform them to TEC-input thermal-power densities. Such increased degrees of design freedom should facilitate overall-plant optimization, which could yield even lower relative costs. This capability is important because curves for $C_{TEC} = 0$ fall essentially on the dashed lines representing figure-1 points.

Thus high-temperature, high-power-density TEC promises greater efficiencies, far fewer topping modules, and improved overall-plant optimization - decreasing capital and fuel costs as well as increasing power outputs. And with lower costs, more electricity, and less pollution, TEC topping in coal-combustion products will also contribute to balance-of-payment gains and national energy independence.

The potentialities of TEC topping alone warrant the applied-research and development efforts required for their attainment.

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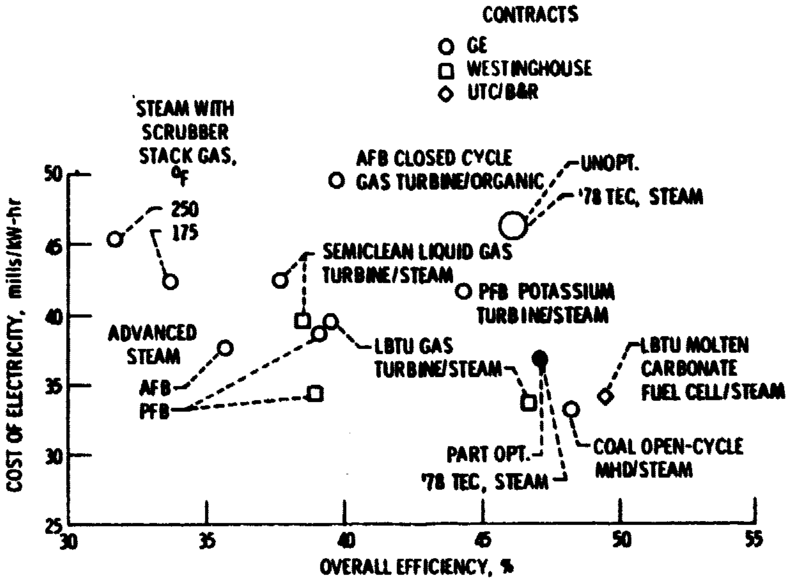

Figure 1. - ECAS Phase 2 results using 30-year levelized cost in mid-1975 dollars. Fuel cost assumed constant in fixed dollars.

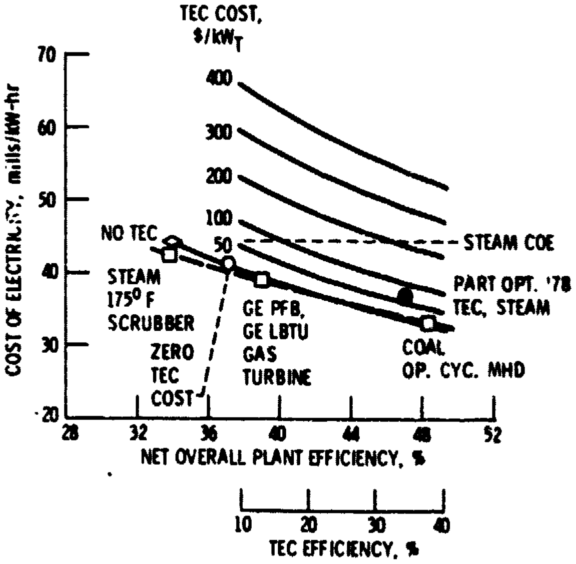

Figure 2. - ECAS Phase 2 results for central-station steam-plant topping, using 30-year levelized cost in mid-1975 dollars and $1/10^6-Btu fuel cost.

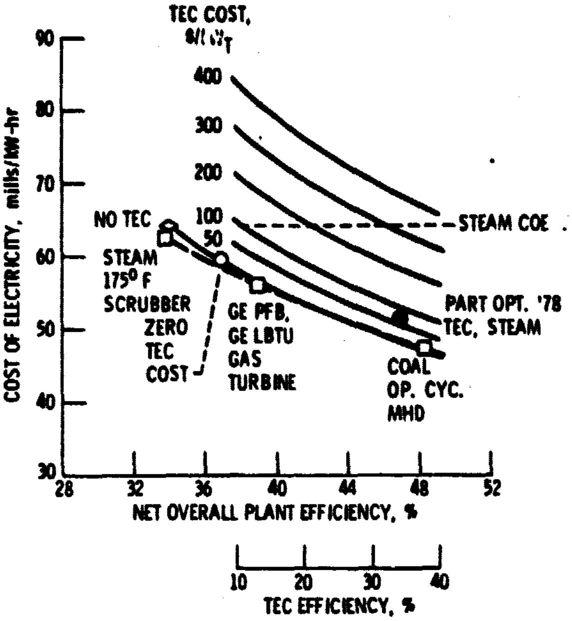

Figure 3. - ECAS Phase 2 results for central-station steam-plant topping, using 30-year levelized cost in mid-1975 dollars and $2/10^6-Btu fuel cost.

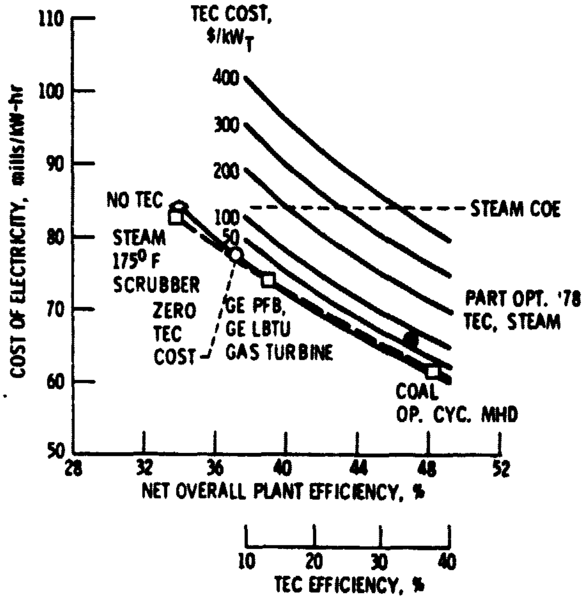

Figure 4. - ECAS Phase 2 results for central-station steam-plant topping, using 30-year, levelized cost in mid-1975 dollars and $3/10^6-Btu fuel cost.

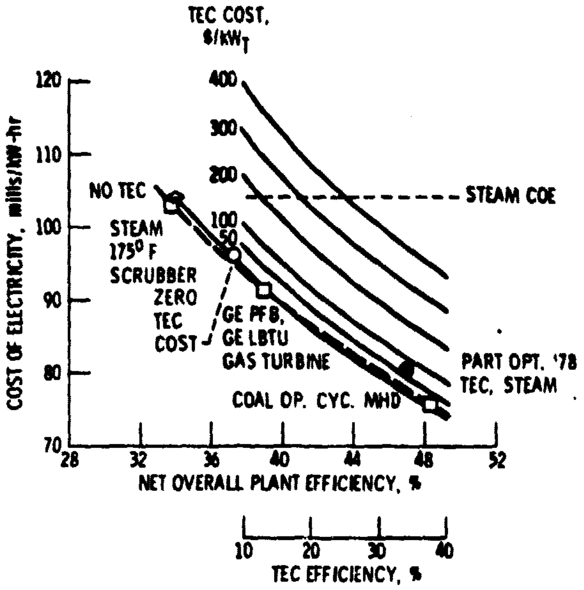

Figure 5. - ECAS Phase 2 results for central-station stream-plant topping, using 30-year levelized cost in mid-1975 dollars and $4/10$^6$-Btu fuel cost.

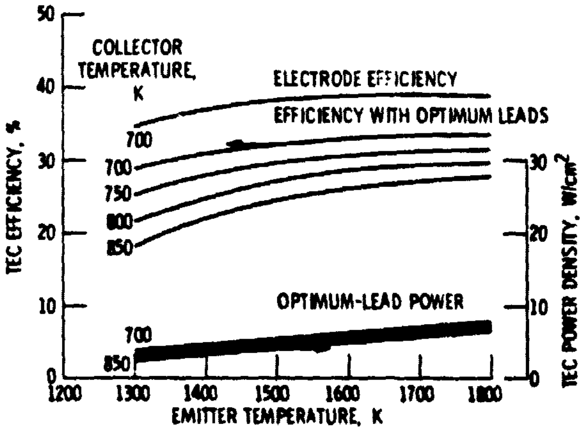

Figure 6. - TEC performance at 5 A/cm$^2$ with 10% back emission and negligible interelectrode losses.

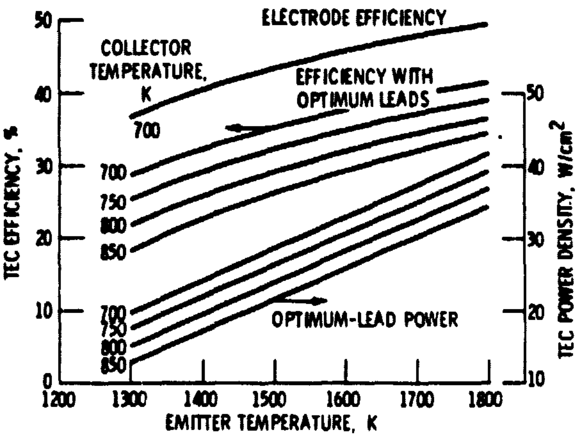

Figure 7. - TEC performance at 30 A/cm$^2$ with 10% back emission and negligible interelectrode losses.