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Economics of Mixed Potassium-Cesium Seeding of an MHD Combustion Plasma

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CONTENTS

	Page
Abstract	1
Introduction	1
Drawbacks of pure cesium seeding	3
Proposed solution	4
Results	8
Conclusions	11
References	12

ILLUSTRATIONS

1. MHD steam-turbine combined cycle power generation.................... 5
2. Effect of temperature on electrical conductivity of an MHD combustion plasma seeded with a potassium-cesium mixture........... 6
3. Effect of seeding level on electrical conductivity of an MHD combustion plasma seeded with a potassium-cesium mixture........... 7
4. Influence of mixed seeding on open-cycle MHD power cost (efficiency held constant).. 9
5. Influence of mixed seeding on open-cycle MHD power cost (duct length held constant).. 10

TABLES

1. Conductivities of plasmas seeded with potassium and cesium in the combustion of Upper Freeport seam hvbb coal with 105 pct stoichiometric air... 2
2. Conductivities of plasmas seeded with equal quantities of potassium or cesium, as a function of temperature................. 2

ECONOMICS OF MIXED POTASSIUM-CESIUM SEEDING OF AN MHD COMBUSTION PLASMA

by

P. D. Bergman[1] and D. Bienstock[2]

ABSTRACT

The high price of pollucite ore, its limited availability, and the need to provide stack removal of SO_2 present formidable obstacles to the use of pure cesium as a seeding material in MHD power generation. Cost estimates indicate that mixed potassium-cesium seeding is preferable to the use of either pure cesium or pure potassium. Cheaper electricity and higher open-cycle MHD operating efficiencies result from the use of mixed seed. Savings of $3,000,000 per year in power costs for a 1,000-MWE open-cycle MHD powerplant are envisioned if the mixed seeding technique is adopted.

INTRODUCTION

The proposed use of cesium-seeded combustion plasmas for open-cycle MHD power generation has attracted considerable interest. Way, Tsu, and Young have been the chief exponents of this approach (10-12).[3] Cesium has an ionization potential of 3.89 ev, compared with 4.34 ev for potassium. Thus, if identical combustion gases are seeded with an equal number of potassium and cesium atoms, respectively, the cesium-seeded combustion plasma will exhibit a greater electrical conductivity than will the potassium-seeded combustion plasma, by virtue of the greater availability of electrons.

In table 1, conductivity predictions are given for a combustion plasma produced by burning an Upper Freeport seam hvbb coal with 5 pct excess air and adding varying quantities of pure K_2O and pure Cs_2O seeds to the gas. It is evident that one-third the number of atoms of cesium as that of potassium is capable of providing approximately the same level of electrical conductivity. In table 2, the same number of atoms of potassium and cesium is used for seeding the coal combustion products at three different temperatures. The conductivity of the cesium-seeded combustion products is 80 to 90 pct greater than that of the corresponding potassium-seeded combustion products.

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[2]Research supervisor.
[3]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

The percentage conductivity increase for coal combustion products obtained by replacing potassium seeding with cesium seedings varies substantially with temperature, pressure, and the seeding levels considered.

TABLE 1. - Conductivities of plasmas seeded with potassium and cesium in the combustion of Upper Freeport seam hvbb coal with 105 pct stoichiometric air

(Temperature: 2,800° K; pressure: 8 atm)

Potassium		Cesium	
Seeding level, lb-mole K/ton coal	Conductivity, mho/m	Seeding level, lb-mole Cs/ton coal	Conductivity, mho/m
2.928	6.968	0.90	6.947
3.528	7.559	1.10	7.698
4.128	8.054	1.30	8.354

TABLE 2. - Conductivities of plasmas seeded with equal quantities of potassium or cesium, as a function of temperature

(Seeding level: 2 lb-mole K or Cs/ton coal; pressure: 4 atm)

	Temperature, ° K		
	2,400	2,500	2,600
Potassium......................	1.934	3.454	5.807
Cesium.........................	3.598	6.474	10.970

In general on an atomic basis, mole for mole, a cesium-seeded coal combustion plasma has a 50 to 100 pct higher conductivity than that of its potassium-seeded counterpart at customary MHD plasma seeding levels. On a weight basis, pound for pound, a cesium-seeded combustion plasma has a 5 to 30 pct higher conductivity than that of its potassium-seeded counterpart at the customary MHD plasma seeding levels. For a particular set of open-cycle MHD plant operating conditions, the enhanced electrical conductivity of cesium-seeded combustion products will lead to significantly shorter MHD channels and smaller superconducting magnets. These savings in material costs and improvements in equipment performance are then translated into lower capital investment costs and increased cycle efficiencies for central-station MHD power generation.

All conductivity calculations reported here were performed with the Bureau of Mines Multiphase Equilibrium Program in combination with the STD Conductivity Algorithm (1, 5). It considers 51 gas phase species (neutral atoms, molecules, and ions) together with four liquid phases and one solid phase. The thermodynamic and physical constants employed in this program have been obtained from the most recent values given by the JANAF Thermochemical Tables.

DRAWBACKS OF PURE CESIUM SEEDING

There are three major obstacles to the practical application of pure cesium seeding for MHD power generation. The first is that to achieve the same levels of conductivity as a corresponding potassium-seeded mixture, one must spend approximately five times as much money for cesium seeding. This figure is based on a cost of 5 cents/lb K_2SO_4 and 50 cents/lb Cs_2O (6-7) in pollucite ore. Therefore, the seed recovery efficiency for cesium must be five times better than that for potassium, as one can only afford to lose one-fifth as much cesium seed as potassium seed. For example, in the case of potassium seeding, a seed-recovery efficiency of 98 pct has generally been deemed adequate for economic MHD power generation (8). If this 98 pct figure is recognized as valid, then a seed-recovery efficiency of 99.6 pct would be required for cesium seeding costs to be competitive with that of potassium seeding. Such high efficiencies consistently attainable are beyond the limits of present-day particulate collection technology for large powerplants, although they are achieved for incinerators with a lower flow rate. Also, at such high collection efficiencies, the costs of electrostatic precipitators become prohibitive (9). Furthermore, the possibility of cesium seed losses in the coal slag rejected from the MHD combustion chamber must be considered.

One of the most significant advantages of fossil-fuel MHD power generation is that it produces an effluent that is practically free of SO_2. The Bureau of Mines has shown that at customary potassium seeding levels, the MHD seed itself removes all the sulfur contained in a typical U.S. coal (2). For example, a seeding level of 1.5 g-mole K_2O/kg of coal is sufficient to remove the sulfur from coal containing 4 wt-pct sulfur. The bulk of U.S. coals have sulfur contents below 4 wt-pct. In fact, MHD energy conversion will render feasible the combustion of many high-sulfur Midwestern and Appalachian coals, which are presently not being burnt in existing coal-fired powerplants because of the inability to meet EPA emission standards.

In the Bureau of Mines process for sulfur removal and seed regeneration, the spent K_2SO_4 seed is collected and treated with a hot steam-hydrogen mixture to regenerate a sulfur-free seed and to evolve gaseous H_2S. Then H_2S is processed in a Claus unit to produce elemental sulfur. This scheme has two major advantages over other techniques for eliminating SO_2. First, the MHD seeding compound itself ties up all the sulfur in the system, rather than necessitating the introduction of a foreign scavenger into the system. Second, a solid potassium salt is treated rather than large volumes of combustion gas, thus substantially lowering plant investment costs.

It would be impossible to apply this process with pure cesium seeding because normal cesium seeding levels are too low to remove the sulfur from all but a very low sulfur coal (approximately 1 pct sulfur). Thus, it would be necessary to employ a flue-gas scrubbing process similar to those presently being developed for conventional powerplants. This additional expense for sulfur removal would obviate any economic gains from improvements in MHD plasma conductivity through the use of cesium.

The third drawback of pure cesium seeding is the inability to predict whether or not adequate quantities of cesium will be available to fuel the huge powerplants of the future. There are three major known deposits of pollucite ore: Bernic Lake, Manitoba, Canada; the Bikita district of Southern Rhodesia; and the Karibib area in the Territory of Southwest Africa. Some low-grade ore has been discovered in Maine and South Dakota (6). A 1,000-MWE (megawatt electrical) coal-fired open-cycle MHD powerplant operating with a seeding level of 0.70 lb-mole Cs_2O/ton coal and a seed recovery efficiency of 99 pct would annually require 3,450,000 lb of Cs_2O makeup seed. At Bernic Lake, the world's largest deposit has known reserves of 150 million lb of Cs_2O. Therefore, one large powerplant would consume in a single year approximately 2.3 pct of the Bernic Lake mine. If seed makeup requirements can be reduced by more efficient collection devices and if fresh deposits of cesium were discovered, the supply-demand picture would be considerably improved. At this preliminary stage, insufficient information is available to make any reliable predictions. In summation, these three problems, high cost of cesium, sulfur-removal capability, and limited reserves of pollucite, must be surmounted if pure cesium seeding is to be successfully applied to open-cycle MHD power generation.

PROPOSED SOLUTION

A potential solution to the dilemma just posed is to mix a small quantity of a cesium salt with a larger quantity of a potassium salt, and to employ the resulting potassium-cesium mixture as the MHD seed material. Qualitatively speaking, mixed seeding enjoys the following advantages: MHD plasma conductivities are higher than those corresponding to pure potassium seeding; low-cost sulfur removal can be achieved because enough seed is present to capture the sulfur from most U.S. coals; seed makeup costs are reasonable; existing cesium reserves are conserved because of the lesser amounts of cesium used.

To quantitatively evaluate the economic incentive for mixed seeding, a comparative study of power costs was made for a 2,000-MWT (megawatt thermal) open-cycle MHD powerplant burning a coal seeded with varying mixtures of potassium and cesium. A schematic diagram of the combined cycle powerplant under discussion is depicted in figure 1. Coal is burned under pressure to produce a high-temperature combustion gas. The combustion products are seeded with a non-sulfur-containing potassium and/or cesium compound, which renders them conductive. The ionized gas accelerates in a nozzle and flows through the MHD duct, in which dc electricity is directly extracted at the expense of the thermal energy of the gas. The combustion products flow through a diffuser, then through a waste-heat-recovery boiler where steam is generated, through a series of heat exchangers, through the seed recovery unit, and finally exits from the stack. A turbine-generator set is employed for additional power production in the steam-bottoming portion of the cycle.

The fuel used in this study was an Upper Freeport seam hvbb coal, the analysis of which was as follows, in weight-percent: Carbon, 73.92; hydrogen, 4.78; oxygen, 4.22; sulfur, 3.00; nitrogen, 1.28; chlorine, 0.15; ash, 13.44; and moisture, 3.20. The coal was burned with 95 pct of stoichiometric air, and the final 10 pct of the air was added in the steam plant so that nitric

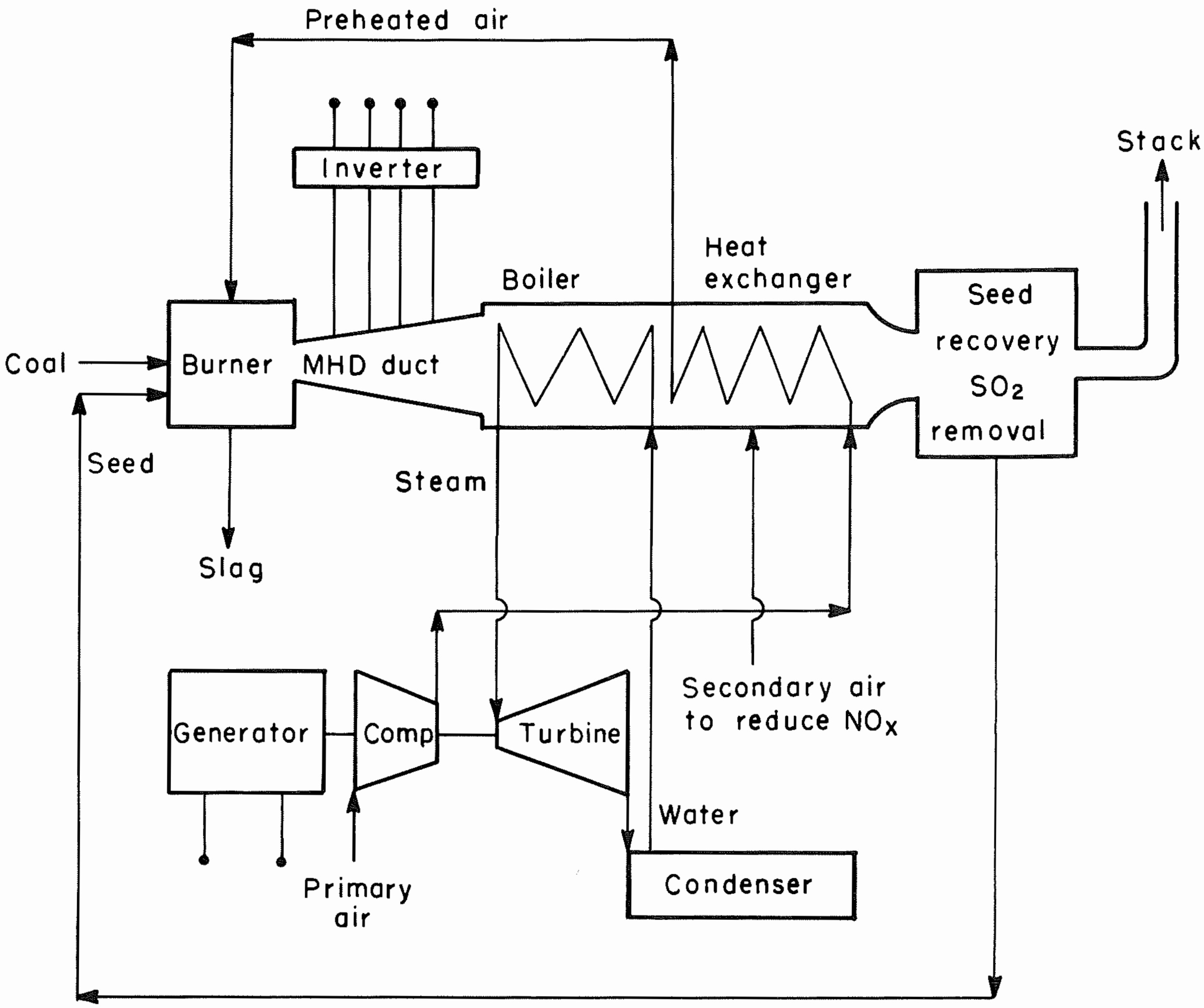

FIGURE 1. - MHD Steam-Turbine Combined Cycle Power Generation.

oxides could be reduced below EPA standards (2). A seeding level of 4 lb-mole atomic potassium + atomic cesium/ton coal was taken to provide enough alkali to remove the sulfur from the coal that contained 3 wt-pct sulfur. For all cases considered, this seeding level was maintained constant to assure the elimination of sulfur oxides from the combustion gas. Four types of seeding, given here in mole-pct, were considered: 100 potassium, 95 potassium-5 cesium, 85 potassium-15 cesium, and 75 potassium-25 cesium. Figures 2 and 3 show the effect on electrical conductivity of temperature, pressure, and seeding level for the above mixtures. These charts indicate the degree of improvement in MHD plasma conductivity that occurs as a consequence of mixed seeding.

The assumptions and approximations needed to carry out the required cycle analysis and cost estimates are partially described in reference 4.[4]

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[4]A Bureau of Mines Report of Investigations that provides complete technical and cost information is currently under preparation.

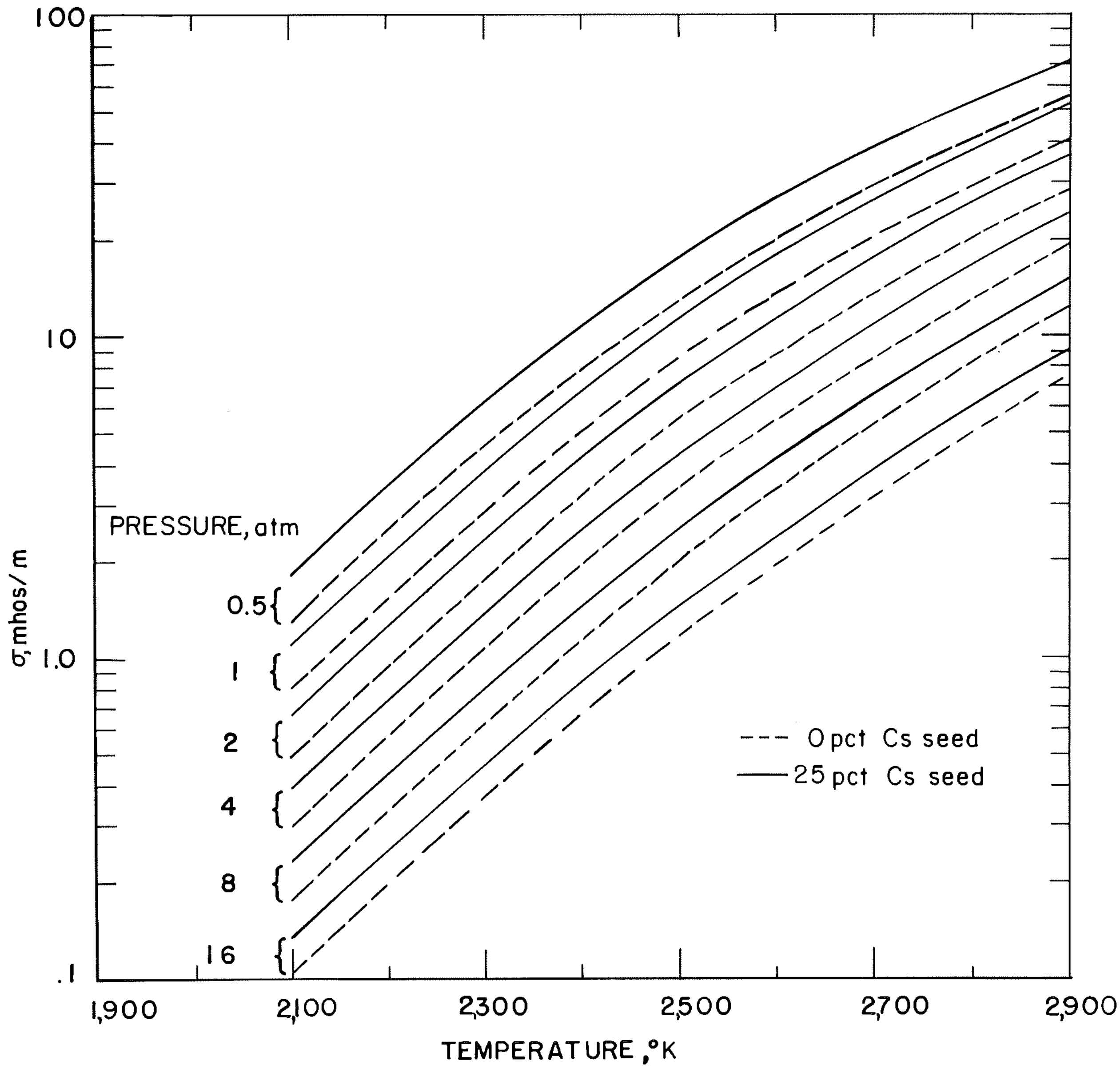

FIGURE 2. - Effect of Temperature on Electrical Conductivity of an MHD Combustion Plasma Seeded With a Potassium-Cesium Mixture. Upper Freeport seam hvbb coal burned with 5 pct deficient air seeded with 4 lb-mole potassium + cesium/ton of coal.

This paper assessed the economic and technical feasibility of linking coal-gasification with MHD power production and attempted to provide realistic cost estimates for future MHD powerplants. These figures have served as a basis for computing the power prices quoted in this study. Only relative cost comparisons are involved in this work, therefore these base-cost figures are not a critical consideration.

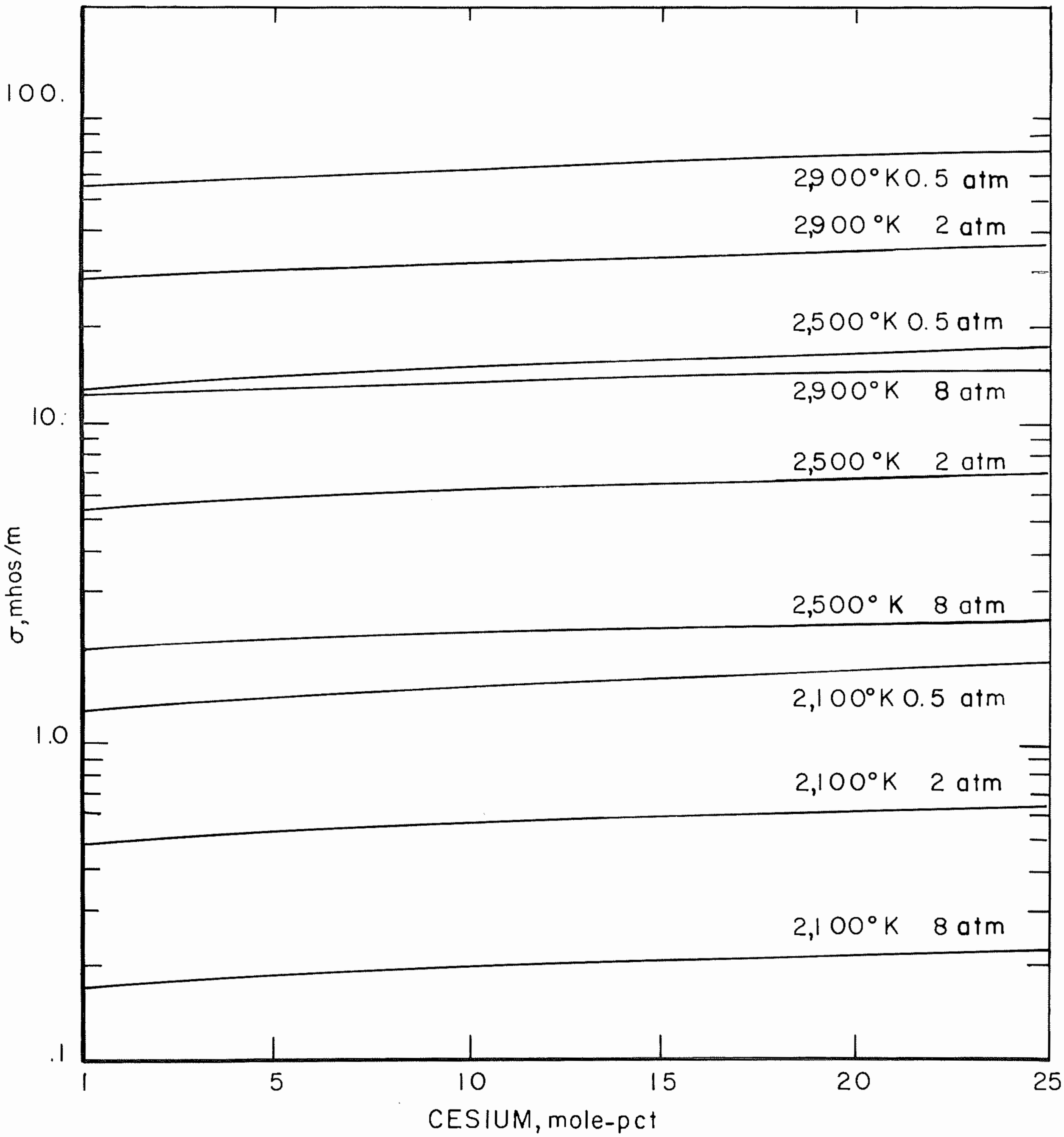

FIGURE 3. - Effect of Seeding Level on Electrical Conductivity of an MHD Combustion Plasma Seeded With a Potassium-Cesium Mixture. Upper Freeport seam hvbb coal burned with 5 pct deficient air and seeded with 4 lb-mole potassium + cesium/ton of coal.

Another obvious approach to improving system performance is by raising existing potassium seeding levels rather than resorting to the use of cesium. Increased seed levels increase the potassium available for ionization but decrease the combustion temperature. Conductivity is an exponential function of temperature, so these two effects tend to cancel each other and a seed level is reached at which the conductivity of the combustion gas is a maximum. This optimal potassium seeding level is approximately 4 lb-mole potassium/ton coal for the system under consideration. It was found that further introduction of potassium salts (KOH or K_2SO_4) into the combustion plasma leads to either no gains or minor decreases in cycle efficiency. Thus, the addition of extra potassium seed is purely superfluous, and if heavy enough additions are made, it may actually prove to be detrimental. Higher potassium seeding levels are not a viable alternative to mixed potassium-cesium seeding.

RESULTS

Mixed seeding can lower the price of electricity in two ways: First, by reducing the cost of the MHD channel and superconducting magnet; second, by improving the efficiency of the combined power cycle. These two approaches to cutting power costs were examined separately. In the first case, the cycle efficiency was held constant at 50.4 pct by adjusting the power output from the MHD topping cycle, and the length of the MHD generator was allowed to freely vary as the seed composition changed. In the second case, the length of the MHD channel was held fixed at 60 ft, and the cycle efficiency was permitted to vary as the seed composition changed. By examining these two contrasting modes of operation, it was possible to gain a reasonable appreciation of the savings to be realized with mixed seeding.

The results of this analysis are plotted in figures 4 and 5. Shown on these graphs are the percentage change in overall power costs as a function of mixed seed composition. The efficiency of seed recovery serves as a third system parameter. Positive percentages represent savings ensuing from mixed seeding; negative percentages represent losses. It is immediately apparent that greater savings result from permitting the cycle efficiency to fluctuate than by allowing the length of the duct to change. Savings of 2 to 4 pct can be expected from the variable efficiency system, and savings of 1 to 2 pct can be expected from the system having a variable duct length. It should be realized that this conclusion is to a certain degree contingent on the relationships assumed for scaling the MHD generator and the superconducting magnet. Magnet costs were increased 8 pct/m of length; MHD channel costs were assumed proportional to the 0.6 power of the duct volume.

For both cases, at seed recovery efficiencies above 98 pct, cost reductions can be anticipated. As the seed recovery efficiency drops, the heavy expense of cesium makeup becomes the dominant economic factor, overwhelming improvements in cycle efficiency and duct-magnet costs. As the mixture composition shifts towards increase in cesium the high cost of makeup cesium, coupled with a slower rise in plasma conductivity, become the pivotal factors. As seed losses drop below 2 pct, the prospects for incorporating larger amounts of cesium into the seeding mixture improve correspondingly.

The kind of savings projected here should be viewed in the proper perspective. A savings of 1 to 2 pct in power costs is equivalent to the cost of the seed recovery step itself; a savings of 3 to 4 pct is equivalent to the cost of sulfur elimination in the power cycles considered. Each percentage

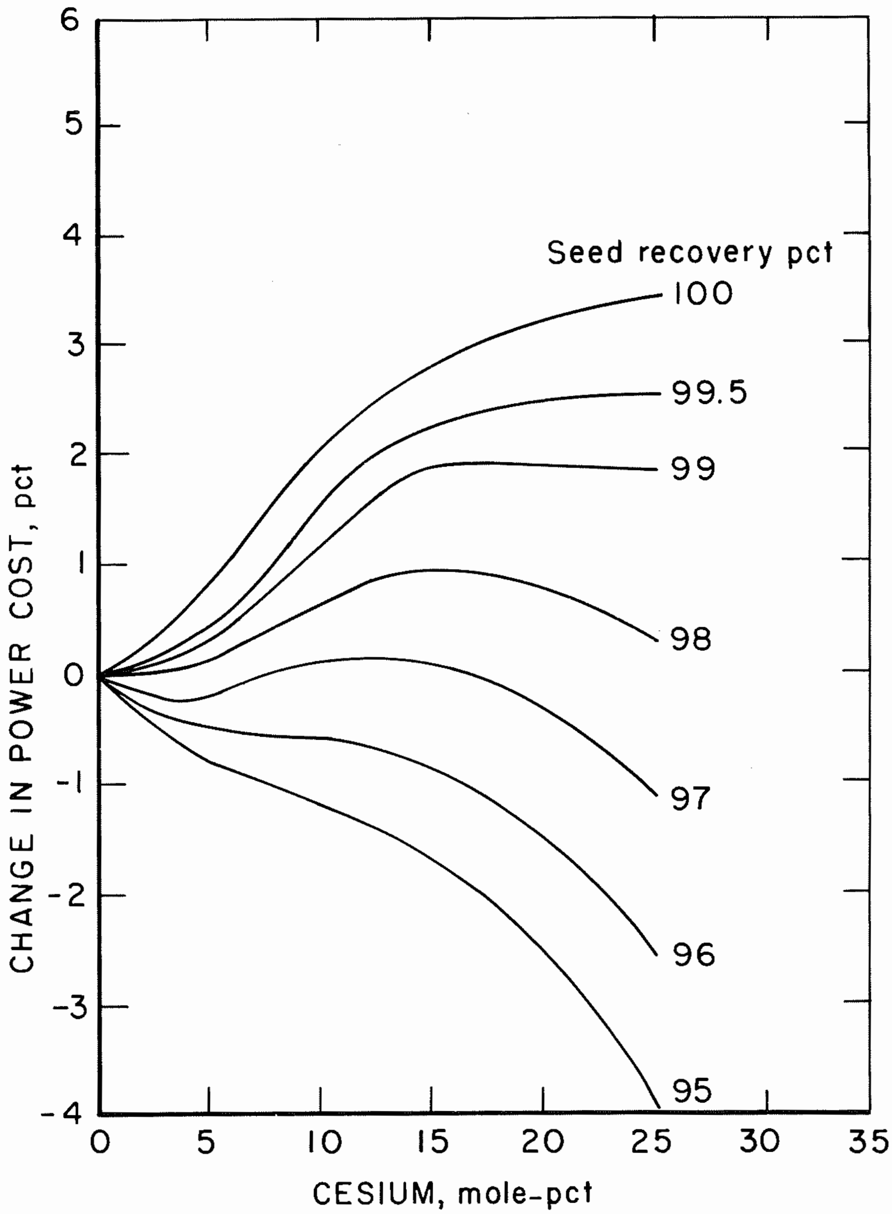

FIGURE 4. - Influence of Mixed Seeding on Open-Cycle MHD Power Cost (Efficiency Held Constant). Price of power, 11 mills/kwhr (99 pct potassium recovered); price of coal that contains 3 wt-pct sulfur, \$4/ton; seeding level, 4 lb-mole potassium + cesium/ton of coal; price of K_2SO_4, 5 cents/lb; price of Cs_2O (as pollucite), 50 cents/lb; cycle efficiency, 50.4 pct.

point reduction in the price of electricity for a 1,000-MWE plant leads to a savings of \$770,000 per year in powerplant operating costs. A 1,000-MWE coal-fired open-cycle MHD powerplant operating with a mixed seeding level of 0.30 lb-mole Cs_2O + 1.70 lb-mole K_2O/ton of coal (15 mole-pct cesium-85 mole-pct potassium) and a seed recovery efficiency of 99 pct would require 1,480,000 lb of Cs_2O makeup seed annually. If a pollucite ore that contains 25 pct Cs_2O was employed, this would be equivalent to 3,000 tons of makeup pollucite per year.

As a result of this study, a coal-burning combustion experiment employing a 15 pct cesium-85 pct potassium mixed seed is presently in progress, using the Bureau of Mines MHD high-temperature furnace. The purpose of this test is to explore the combustion behavior and the recovery chemistry of mixed potassium-cesium seed and to compare it with previous research performed with pure potassium seeding (3). Data on cesium losses to the slag, the affinity of cesium for sulfur, the extractability of spent cesium seed from fly ash, and the elimination of sulfur from the spent seed mixture, will be acquired. This experiment will provide important information on the characteristics and problems associated with using mixed seeding at MHD operating conditions.

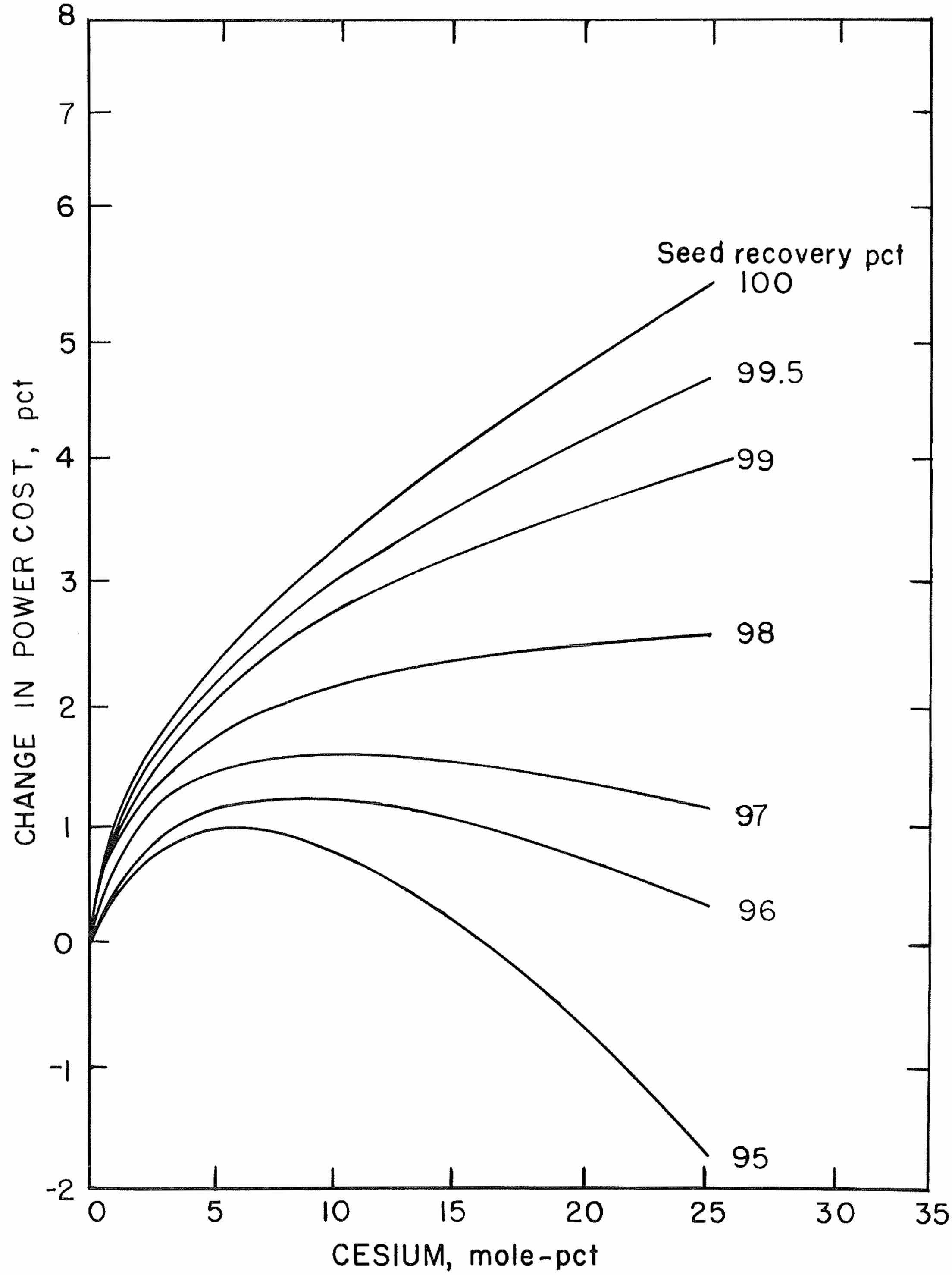

FIGURE 5. - Influence of Mixed Seeding on Open-Cycle MHD Power Cost (Duct Length Held Constant). Price of power, 11 mills/kwhr (99 pct potassium recovered); price of coal that contains 3 wt-pct sulfur, \$4/ton; seeding level, 4 lb-mole potassium + cesium/ton of coal; price of K_2SO_4, 5 cents/lb; price of Cs_2O, 50 cents/lb; MHD duct length, 60 ft.

CONCLUSIONS

Mixed potassium-cesium seeding of MHD combustion plasmas is a promising concept worth pursuing. A definite economic incentive exists for mixed seeding. Cost savings as high as $3,000,000 a year in power costs for a 1,000-MWE open-cycle MHD powerplant are foreseeable. The disadvantages of pure cesium seeding, such as exorbitant seed makeup costs, inadequate sulfur removal, and limited availability of cesium, can be surmounted. Mixed seeding in an open-cycle central-station MHD powerplant would lead to cheaper electricity and higher cycle-operating efficiencies.

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