Energy, Vol. 2, pp. 171-177. Pergamon Press. Printed in Great Britain

THE COAL-URANIUM BREEDER: URANIUM FROM COAL

KIRK R. SMITH
Postgraduate Researcher, Energy and Resources Group and Biomedical and Environmental Health Sciences, 100 Building T-4, University of California, Berkeley, CA 94720, U.S.A.

(*Received* 21 *December* 1976)

Abstract—Evidence exists that much of the coal in the Western United States contains an appreciable amount of uranium. While not concentrated enough to be directly considered as a uranium resource, this uranium is enriched in the ash remaining after the coal is burned. Consequently, some coal ashes have concentrations of uranium which would classify them as intermediate-grade uranium ores (100–500 ppm). A combined facility, herein named a Coal-Uranium Breeder, which generated electricity or gas from coal and processed the ash to produce uranium could make available more nuclear energy than it consumed as fossil energy, depending on the reactor type and other variables. A considerable lessening of environmental impact is possible through the use of combined rather than separate coal plants and uranium mills. Potentially, a large fraction of U.S. uranium needs could be supplied at a reasonable cost and thus eliminate the apparent shortfall of sandstone uranium ores and delay the decision about the breeder reactor. More effort is needed to develop extraction techniques and to determine the uranium content of coals.

INTRODUCTION

One of the key issues involved in the current discussions about nuclear power, in general, and in determining the need for continued heavy emphasis on early development of the LMFBR,† in particular, is the uncertainty in the estimates of the amount of uranium that will be available at various prices. The argument for the LMFBR usually is stated in the following fashion:

All our low-cost uranium reserves will be committed to the presently planned LWRs‡ and HTGRs§ sometime near the end of this century. Although the LMFBR will cost more to build than conventional reactors, it uses so much less uranium that, if uranium prices rise beyond some point, the LMFBR will produce cheaper electricity. The exact price at which the breeder will begin to produce less expensive power depends on several factors such as the capital-cost differential between the LMFBR and the converter reactors, the extent and length of the learning curve for building reactors, safety, environmental control and safeguards costs for nuclear systems, enrichment costs, and the discount rate of public and private capital.[1] In any case, an early high cost of uranium argues more forcefully for an early large scale commitment to the breeder. In addition, we would be committing ourselves to large amounts of environmental damage if we mined low-concentration uranium ores such as Chattanooga shales.[2] The price rise in uranium depends on many factors among which are (a) The total electricity demand. (b) The fraction of that demand which is met by nuclear power. (c) The mix of reactor types. (d) The technology for finding, mining and milling uranium. (e) The amount of uranium in ores of various grades. (f) The costs of avoiding environmental damage.

Other studies have shown that only with unrealistically high assumptions about future electricity demand, the fraction that is nuclear power, and the price of uranium, can the LMFBR become economically competitive at the end of this century.[3] However, if, in fact, intermediate-grade uranium reserves are small, the uranium requirements of LWR and HTGR reactors will eventually necessitate mining the low-grade reserves contained in shale at high economic and environmental costs.[4] The published estimates of uranium resources show great uncertainty about the availability of intermediate-grade ores at \$30–100/lb of U_3O_8 (approx. 500–100 ppm, see Tables 3 and 4 of Ref. 4).

It is the purpose of this paper to discuss the use of a large potential source of intermediate-grade uranium. This uranium is contained in the very resource which is the chief competitor to nuclear power, namely, coal.

†LMFBR—Liquid Metal Fast Breeder Reactor.
‡LWR—Light Water Reactor.
§HTGR—High Temperature Gas-Cooled Reactor.

URANIUM AND COAL

Several investigators have found concentrations of uranium in many western and some eastern coals. More than twenty years ago, the extensive low-grade deposits were seen as a potential uranium resource.[5] However, later resource estimates have usually only included those few coals that have a high enough uranium concentration to be categorized as high-grade uranium ore.[4,6] Uranium in coal has also been viewed as a possible environmental pollutant, principally because of its potential release and that of its daughter products (e.g. radium) during combustion.[7] The bulk of these uranium-containing coal resources seems to lie in the lignite deposits of Northern Great Plains states, although other coals may also have significant amounts.[6] Unfortunately, there is no up-to-date and thorough tabulation of coal resources by uranium content. However, in a recent ERDA discussion of uranium resources,[4] there is brief mention of this resource in a footnote stating that, although lignites might contain 7 M short tons of U_3O_8, production would be limited because of the low concentrations. The total U.S. reserves and resources at less than \$30/lb U_3O_8, which does not include the uranium from lignite and would not be 100% recoverable, have been estimated as 3.7 M tons by ERDA.[8] Recent estimates derived by other methods, such as Lieberman's,[9] are much lower but are also confined principally to sandstone ores. If these lower estimates are correct and no other source of uranium is developed, the construction of LWRs will be limited severely within a decade.[9,10]

In spite of the relatively low initial concentration of uranium in most coals, there are characteristics of coal plants and uranium mills which could favor the use of a combined facility to produce both uranium and coal–gas or uranium and electricity.

Figure 1 is a schematic of a combined coal power plant and uranium mill. It is labeled a Coal–Uranium Breeder (CUB) because, in some circumstances, it would actually make available more fuel than it consumes. The use of a combined coal-gasification plant and uranium mill as a CUB is also feasible and most of the following discussion would apply to it as well. The inputs to the CUB are coal and water for cooling and processing. The outputs are U_3O_8 and electricity or gas, as well as various waste products and environmental emissions.

The uranium mill section of the CUB requires sulfuric acid, steam, hot water and electricity to process uranium ore. All of these are available from the coal plant. In fact, the ash, hot water

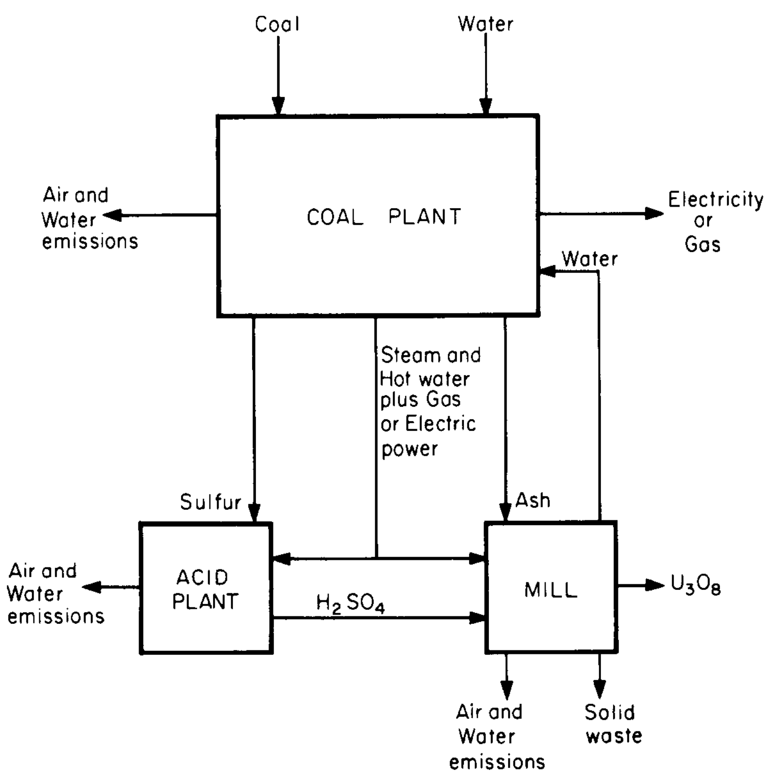

Fig. 1. Coal-Uranium Breeder (CUB).

and sulfur are often considered as waste products and their disposal results in a net cost to the coal plant. In a CUB they would create income.

Table 1 illustrates a possible mass balance for a CUB. The average annual U_3O_8 requirement for an LWR is about 131 short tons. This includes the requirement of the initial core and the annual refueling and is averaged over the lifetime of the plant.[4] Thus, one year of operation of this 1600-MWe CUB (or a 230 M ft^3/day gasification plant at 58% capacity and 66% thermal efficiency) would provide enough U_3O_8 to fuel a 1000-MWe LWR for one year. The annual fuel requirement for an HTGR is about 75 tons of U_3O_8.[4] Thus, a 1600-MWe or 230 Mft^3/day CUB would provide enough uranium for a 1750-MWe HTGR. This CUB in combination with an HTGR could be thought of as having a breeding ratio of 1.09 since it makes available 1.09 times more fuel than it consumes each year.

Table 1. Parameters of a Coal–Uranium Breeder designed to supply the uranium for a 1000-MWe LWR

Power Plant	Coal[c]
1600-MWe	7000 BTU/lb [3 880 kcal/kg]
58% capacity factor[a]	10% ash
37.5% thermal efficiency	0.7% sulfur
99.3% particulate capture[b]	25 ppm uranium
40% sulfur capture[b]	

Annual Flow (metric tons)
Coal 4,800,000 (25 ppm U)
Collected ash 477,000 (250 ppm U[d])
Sulfur captured 13,400
H_2SO_4 produced 39,000 (95% conversion)[e]
U_3O_8 produced 120 (85% recovery) (132 short tons)

[a] For comparison purposes the capacity factor is taken to be equal to the average capacity factor for the 40 year life of nuclear plants used in ERDA-1.[4]

[b] To meet 1975 EPA emission standards of 1.2 lb SO_2/million BTU input and 0.1 lb particulates/million BTU input.

[c] Typical values for lignite.[11] An Argonne study [12] indicates that the *average* uranium content of *all* U.S. coals burned may soon be ten times the 1970 average of 3 ppm.

[d] Almost all the uranium ends up in the slag or fly ash.[13]

[e] If all this was used in the uranium mill it would provide 164 lb/ton ore or about 35% more than would be required for shale.[14] This extra acid may be necessary for extracting the uranium from the slag. The acid requirements will vary depending on the amount of acid-consuming minerals in the ash.[15]

The exact materials balance and breeding ratio would depend greatly on the characteristics of the coal, on its ash, uranium and Btu contents. In addition, the recovery percentage depends on the uranium concentration in the final ash, which depends both on the original uranium concentration and the ash content. Recovery diminishes as the ash content increases because the uranium is less concentrated in the final ash. The breeding ratio could be much higher, depending on the type of reactor, the type of coal, and the recovery technology (see Fig. 2).

Processes have been developed to extract uranium from lignite both with[16] and without[17] roasting but have generally been designed for the relatively high-grade but scarce uraniferous lignite ores.[18] An attractive potential removal scheme might be designed by taking advantage of the characteristics that (probably) trapped uranium in the coal naturally. Coal will extract uranium from solution[19] and the coal, thus further enriched in uranium, could be burned to ash which would be further concentrated. In addition, there is at least some evidence that coal could actually be improved in this process because some of the sulfur will exchange with the uranium being extracted.[20]

There is some government-sponsored work being conducted on various methods of removing uranium from coal[21] and, although there does not appear to be good published references, much work is going on in several countries which is cloaked in industrial secrecy.

The estimate of the total amount of uranium which might become available from CUBs is very sensitive to the assumptions about coal use, average uranium content and recovery percentage. Table 2 illustrates the range of possibilities for the percentage of uranium requirements which could be met by CUBs. The scenarios of energy production have been taken from the ERDA National Energy Plan.[22]

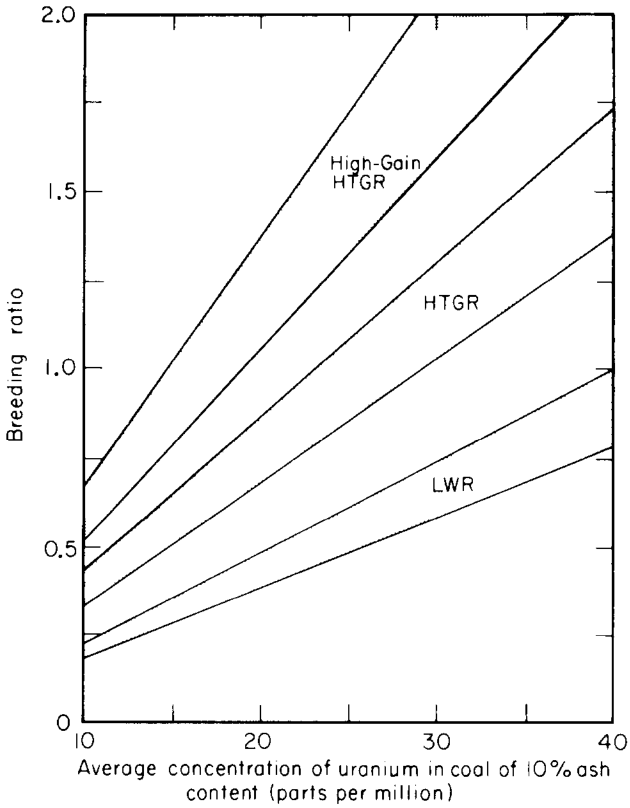

Fig. 2. Breeding Ratios for Coal-Uranium Breeder in combination with various nuclear reactors. Uranium requirements for reactor are from ERDA.[4] The lower line for each type of reactor corresponds to coal of 9000 Btu/lb. The upper line is coal of 7000 Btu/lb.

Table 2. Possible uranium production from Coal-Uranium Breeders

Year 2000 Scenarios from ERDA[22]	Numbers of 1 GWe Plants[a] HTGR	LWR	Coal[b] Million Short Tons	Total Uranium Requirements[c] Short Tons U_3O_8	Potential Percentage from CUBs[d]
# III Intensive Electrification	90	807	1381	112,470	15%
# IV Limited Nuclear	9	215	2112	28,840	92%
# V Combination of all technologies	90	412	1790	60,720	37%

[a] LMFBR's counted as LWR's. 58% capacity factor assumed.[4]

[b] Coal exports have been subtracted from these totals.

[c] 131 tons U_3O_8/year - LWR; 75 tons U_3O_8/year - HTGR[4]

[d] 50% of total coal assumed to be western with an average of 25 ppm uranium which is 85% recoverable.

Figure 3 illustrates how the total uranium availability depends on the average uranium concentration and the ash content of the coals. ERDA's favored Scenario V has been used as the basis of this figure. If coal deposits were exploited with an eye to their uranium content and they turn out to be extensive enough, the average concentration could be high enough to provide several tens of thousands of tons of U_3O_8 per yr.

COST

Workers at Oak Ridge National Laboratory have done a preliminary analysis of the cost of U_3O_8 from low-grade ore.[14] If the same methodology is applied, the cost of U_3O_8 from the 1600-MWe CUB of Table 1 would be about $25/lb (see Table 3). Nearly all the costs scale directly with the grade of ore. Thus, although the concentration of uranium in the coal would place it in the low-grade range (less than about 100 ppm), the concentration in the ash would place it in the intermediate-grade range (about 100–500 ppm) and in a CUB it might be produced

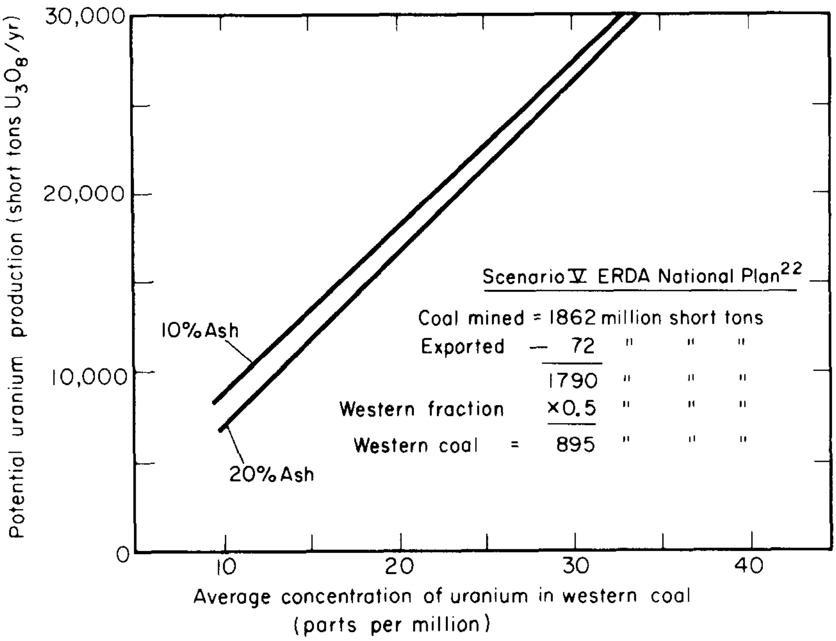

Fig. 3. Potential Uranium production in 2000 from Coal–Uranium Breeders.

at a cost that would be competitive with uranium produced from relatively high-grade ores (less than $30/lb).

In addition to the savings in mining cost which has been listed in Table 3, the costs of sulfuric acid, hot water, steam and electricity would also be substantially less in a CUB than in a free-standing mill. Reducing the costs for sulfuric acid in particular would have a significant effect on the final cost. Some of these savings might counter-balance the costs of attaining good recovery from the slag and of maintaining coordination between the coal plant and the uranium mill.

The capital requirement is minimal as compared to the requirement for a large coal power plant or a gasification plant. The uranium mill would add only about $9.00 per installed kilowatt or $60 per 1000 ft^3/day capacity to the cost of construction of coal plants. This is, at most, 2% of the present cost of such facilities. The uranium mill doubles as an ash disposal facility for the coal plant and eliminates the capital requirement for this facility. In addition, the CUB supplants the need for capital to build uranium mines. The cost of the sulfuric acid plant would also be low compared to the coal plant.

Table 3. Comparative costs of uranium from CUB and shale

Uranium Mill	Shale[14]	CUB
Capacity factor	90%	58%
U in ore	60 ppm	250 ppm (25 in coal)
Recovery	70%	85%
Output (short tons U_3O_8/year)	325	132
Capital investment (millions)	$110.8	$13.8
Cost $/lb U_3O_8		
Capital Charge (20% return)	33.94	10.49
Waste Treatment	31.73	6.27
Mine and Mill	60.63	11.98
Subtotal	126.30	28.74
Mining Cost @ $2.01/ton	(20.39)	-4.00
Total (1974 dollars)	$126.30	$24.74

ENVIRONMENTAL IMPACTS

While a CUB using present control technologies will not be totally innocuous, its land impact and emissions will be less than that of a separate coal plant, uranium mine, and uranium mill.[23] In fact, the high uranium content of the western coals may require special handling of the ash whether or not it is processed to remove the uranium.[12] The use of waste heat from the coal plant for the mill will reduce the need for additional energy use with its attendant environmental impact and the direct use of the recovered sulfur avoids the need for disposal or transportation to market.

Recently, there has been concern expressed about the possible long-term effects of radon emission from uranium mill tailings.[24] The concern is that, even though the emission rate and subsequent radiation dose rate to the public are low, the emissions will continue for many thousands of years. Thus, the total effect of the tailings from one reactor-year's uranium requirement, summed over many hundreds of generations, might be large although, certainly, it would be masked by the effects due to other sources of radon. This kind of very low but very long term effect taxes our ability to perform meaningful measurements and comparisons between technologies. The conceptual and methodological difficulties are severe.

However, if it is decided to pursue an LWR program vigorously in this country (a decision that would have to consider the radon emissions as well as other, probably more important, impacts), then it would certainly be better from an environmental standpoint to obtain uranium as a by-product of coal production than from conventional uranium mines and mills. The radon emissions over long periods from uranium tailings depend on the amount and the density of the Thorium-230 left in them (TH-230 is a long-lived daughter product of Uranium-238 and a precursor of radon). The ash from a CUB would have a concentration of TH-230 about ten times lower than those of uranium mill tailings. Therefore, more of the radon will decay before seeping out of the ash piles than out of mill tailings. More importantly, since the coal will be mined anyway and coal production will expand whether or not nuclear power is pursued,[22] there would be no additional radon impact from the CUBs which would not have existed otherwise. The retention of uranium and most of its daughter products in the ash in the power plant part of a CUB is roughly equal to the particulate capture efficiency.[13] Thus, the long-term radiation dose commitment from this emission is a small part of that from the ash pile.

In addition, there are other metals in some coals, for example thorium and germanium[18] which also might be economically recoverable as by-products and thus increase supplies and decrease impacts accordingly. Interest in the recovery of alumina from coal dates back at least to 1930[25] and has increased recently.[26] A process is being developed by ERDA[27] to recover aluminum, iron, and sulfur from coal. It also might be feasible to extract uranium and other metals from the coal as part of an upgrading step before combustion.[28]

CONCLUSION

Western coals have large amounts of uranium which could provide a significant fraction of our total uranium demand at a reasonable price if facilities are constructed which combine coal-power plants or coal-gasification plants with uranium mills. There is a kind of natural ratio of coal power plants to converter reactors of between 4:1 to 0.5:1. This represents the energy contained in the uranium found in coal. In addition, significant environmental advantages would result from the production of uranium as a by-product of coal use rather than in separate facilities. The amounts and concentrations of uranium in coal are not accurately known but there are extensive surveys of uranium resources now being conducted as part of the National Uranium Resources Evaluation Program[29] and as part of coal investigations.[30] To be useful, they should carefully tabulate coal deposits by uranium content so that the desirability of combined facilities can be determined. It will be necessary to know the extent and recoverability of intermediate-grade uranium resources in order to make an informed decision about developing an extensive plutonium-breeder industry with its complicated questions of safety, security and economics.

Acknowledgement—I am grateful for the comments of M. A. Lieberman and G. I. Rochlin and the assistance of the Lawrence Berkeley Laboratory in the preparation of the figures.

REFERENCES

1. U.S. Atomic Energy Commission, *Proposed Final Environmental Statement: the LMFBR Program*, WASH-1535, U.S. Government Printing Office (USGPO), Vol. 4 (1974).
2. Cornell University, *Report of the Cornell Workshops on the Major Issues of a National Energy Research and Development Program*, College of Engineering, Ithaca, NY, 1973. See also P. H. Mutschler, J. J. Hill and B. B. Williams, *Uranium From the Chattanooga Shale*, IC-8700, Bureau of Mines, USGPO (1976).
3. T. J. Cochran and A. Tamplin, *Bypassing the Breeder: A Report on Misplaced Federal Energy Priorities*, National Resources Defense Council, Washington, D.C., 1975; J. P. Holdren, *Energy Syst. Policy* **1**, 205 (1975); and Joint Economic Committee, *The Fast Breeder Reactor Decision: An Analysis of Limits and the Limits of Analysis*, U.S. Congress-94-2, USPGO (April 1976).
4. U.S. Energy Research and Development Administration (ERDA), *Report of the Liquid Metal Fast Breeder Reactor Review Group*, ERDA-1, USGPO (1974).
5. R. L. Miller and J. R. Gill, *Sci. Am.* **191**, 36 (Oct. 1954).
6. N. M. Denson, *Uranium in Coal in the Western United States*, Bulletin-1055-A, U.S. Geol. Survey (1959); also, see R. F. Abernathy and F. H. Gibson, *Rare Elements in Coal*, IC-8163, Bureau of Mines (1963).
7. M. Eisenbud and H. G. Petrow, *Science* **144**, 288 (17 April 1964).
8. U.S. ERDA, *Statistical Data of the Uranium Industry*, GJO-100 (76), Grand Junction Office, Colorado (1 Jan. 1976).
9. M. Lieberman, *Science* **192**, 431 (30 April 1976).
10. J. F. Hogerton, *Nuclear News* **19**, 73 (June 1976).
11. W. R. Kube and J. L. Elder (Eds.), *Technology and the Use of Lignite*, IC-8343, U.S. Bureau of Mines (1971).
12. Argonne National Laboratory, *Social Costs for Alternative Means of Electric Power Generation for 1980 and 1990*, ANL-8093, Argonne, Ill., Vol. 2 (1973).
13. J. W. Kaakinen, R. M. Jorden, M. H. Lawasani and R. E. West, *Environ. Sci. Tech.* **9**, 862 (Sept. 1975); and D. H. Klein *et al.*, *Environ. Sci. Tech.* **9**, 973 (Oct. 1975).
14. A. D. Ryon and K. B. Brown, *A Cursory Survey of Uranium Recovery from Chattanooga Shale*, ORNL-74-5-36, Oak Ridge National Laboratory, Oak Ridge, Tennessee (1974) and reprinted in WASH-1535 (Ref. 1); also, see IC-8700 (Ref. 2).
15. International Atomic Energy Agency, *Processing of Low-Grade Uranium Ores*, Symposium, Vienna (1967).
16. B. C. Mariacher, *Extraction of Uranium from Lignite Ores*, U.S. Patent 2,925,321 (16 Feb. 1960).
17. H. A. Green, *Recovery of Uranium from Lignite*, U.S. Patent 3,092,445 (4 June 1963).
18. O. B. Bucklen *et al.*, *Coal Associated Minerals of the U.S., Part 7: Uses, Specifications and Processes Related to Coal-Associated Minerals*, (RDR-8(7)), Coal Research Bureau, National Technical Information Service, PB-168, 116 (1965); also, see Ref. 15.
19. A. R. Cameron and G. Leclair, *Extraction of Uranium from Aqueous Solutions by Coals of Different Rank and Petrographic Composition*, Paper 74-35, Geological Survey of Canada, Ottawa (1975).
20. G. W. Moore, *Econ. Geol.* **49**, 652 (1954).
21. For example, see W. C. Woodmansee, *Uranium*, in *Bureau of Mines, Minerals Yearbook* (1974); and Refs. 19, 30.
22. USERDA, *A National Plan for Energy Research Development and Demonstration: Creating Energy Choices for the Future*, ERDA-48, USGPO, Vol. 1 (1975).
23. K. R. Smith, J. Weyant and J. P. Holdren, *Evaluation of Conventional Power Sources*, ERG-5, Energy and Resources Group, University of Calif., Berkeley (1975).
24. D. D. Comey, *Bull. At. Scient.* **31**, 43 (Sept. 1975). See also B. Cohen, *Bull. At. Scient.* **32**, 61 (Feb. 1976) and response by Comey, p. 63.
25. W. M. Guertler, *Process of Recovering Alumina from Coal and its Ashes*, U.S. Patent 1,873,642 (23 Aug. 1932).
26. Developments to Watch, *Coal Age* **79**, 146 (March 1974); R. A. Busch, R. R. Bacher, L. A. Atkins and C. D. Kealy, *Physical Property Data on Fine Coal Refuse*, RI-8062, Bureau of Mines (1975); and (same authors) *Coal Min. Process.* **13**, 46 (Aug. 1976).
27. USERDA, *Weekly Anouncements*, #76-308, **2**, 2 (8 Oct. 1976).
28. C. E. Capes, E. E. McIlhinney, D. S. Russel and A. F. Sirianni, *Environ. Sci. Tech.* **8**, 35 (Jan. 1974).
29. USERDA, *ERDA Investigating Relationship Between Organic Matter and Uranium Deposits*, News Release #76-99 (19 Nov. 1976) and other News Releases from the ERDA Grand Junction Office, Colorado; USERDA *National Uranium Resource Evaluation, Preliminary Report*, GJO-111(76), Grand Junction Office (June 1976).
30. For example, see E. M. Wewerka, *Trace Element Characterization and Removal/Recovery from Coal and Coal Wastes*. Numbered from LA-6497-PR, Progress Reports, Los Alamos National Laboratory, NM, Numbers 1 and 2, covering 1 July 1975 to 31 Dec. 1975, dated Sept. 1976.