lake powell research project bulletin

number 38

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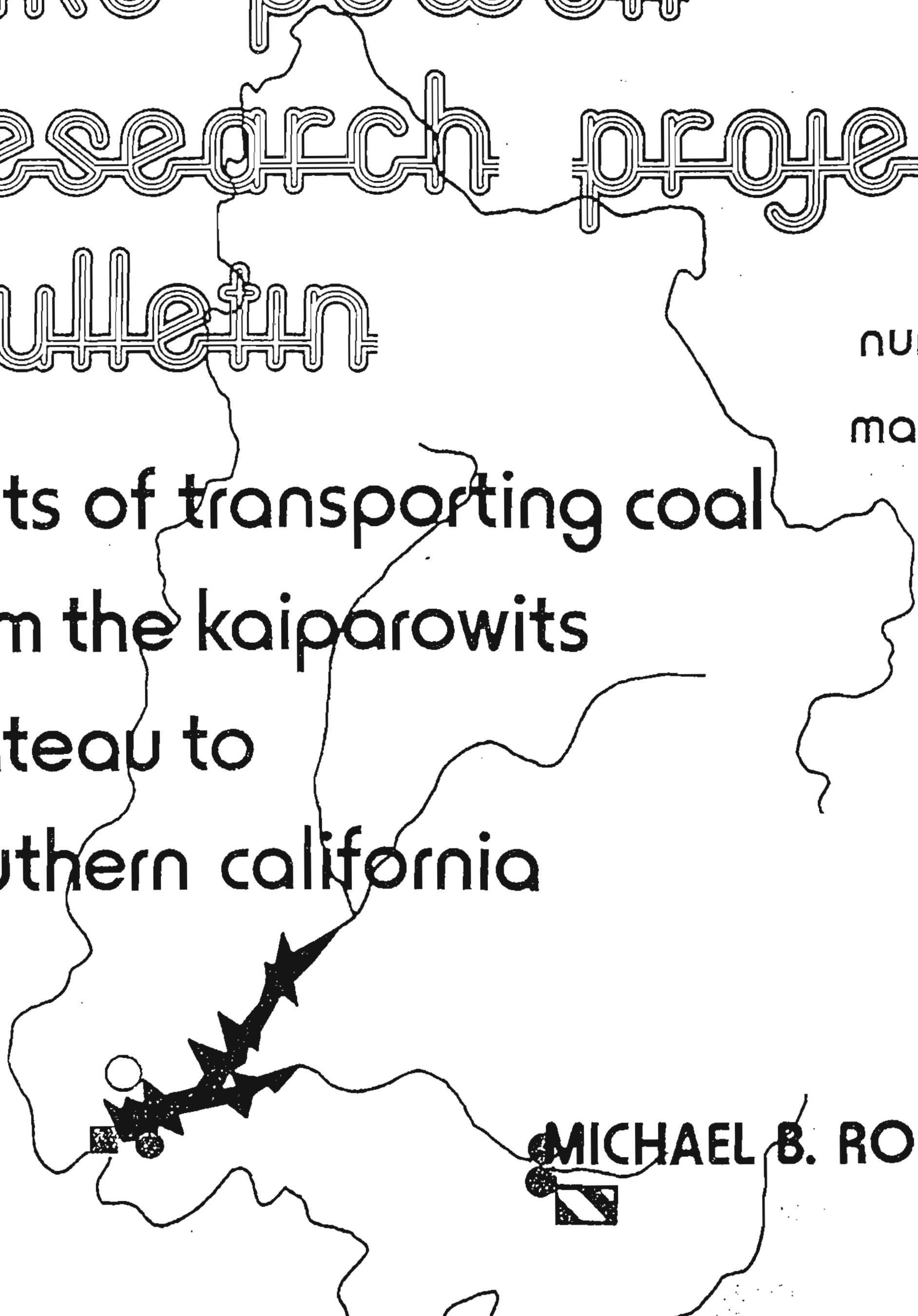
costs of transporting coal from the kaiparowits plateau to southern california



MICHAEL B. ROGOZEN

National Science Foundation
[Re]search Applied to National Needs

LAKE POWELL RESEARCH PROJECT BULLETIN

BULLETIN EDITORS

Jeni M. Varady and Orson L. Anderson

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IN THE LAKE POWELL REGION

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COSTS OF TRANSPORTING COAL FROM THE KAIPAROWITS PLATEAU TO SOUTHERN CALIFORNIA

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March 1977

LAKE POWELL RESEARCH PROJECT

The Lake Powell Research Project (formally known as Collaborative Research on Assessment of Man's Activities in the Lake Powell Region) is a consortium of university groups funded by the Division of Advanced Environmental Research and Technology in RANN (Research Applied to National Needs) in the National Science Foundation.

Researchers in the consortium bring a wide range of expertise in natural and social sciences to bear on the general problem of the effects and ramifications of water resource management in the Lake Powell region. The region currently is experiencing converging demands for water and energy resource development, preservation of nationally unique scenic features, expansion of recreation facilities, and economic growth and modernization in previously isolated rural areas.

The Project comprises interdisciplinary studies centered on the following topics: (1) level and distribution of income and wealth generated by resources development; (2) institutional framework for environmental assessment and planning; (3) institutional decision-making and resource allocation; (4) implications for federal Indian policies of accelerated economic development of the Navajo Indian Reservation; (5) impact of development on demographic structure; (6) consumptive water use in the Upper Colorado River Basin; (7) prediction of future significant changes in the Lake Powell ecosystem; (8) recreational carrying capacity and utilization of the Glen Canyon National Recreation Area; (9) impact of energy development around Lake Powell; and (10) consequences of variability in the lake level of Lake Powell.

One of the major missions of RANN projects is to communicate research results directly to user groups of the region, which include government agencies, Native American Tribes, legislative bodies, and interested civic groups. The Lake Powell Research Project Bulletins are intended to make timely research results readily accessible to user groups. The Bulletins supplement technical articles published by Project members in scholarly journals.

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ABSTRACT

The proximity of the as yet undeveloped Kaiparowits Plateau coalfield to a potentially large Southern California market and the high quality of the field's coal prompted research into the following questions: (1) Of what order of magnitude would coal transportation costs from Kaiparowits to Southern California be? (2) Which transportation mode is less expensive in this case, unit train or coal slurry pipeline? (3) How would Kaiparowits transportation costs compare to those for transportation to California from developed coalfields in Wyoming, Utah, and New Mexico?

Marketing of Kaiparowits coal will require substantial construction of new rail, tunnels and bridges for railroads, or pipelines, pump stations, and slurrification and dewatering facilities for coal slurry pipelines. Models were developed to estimate, for each mode, capital investment re-requirements, annualized capital cost, operating cost, and total annual cost of delivering 10 million tons per year. The rail cost model was applied to 27 alternative combinations of new and existing rail lines, and the lowest cost route was selected. For that route, the delivery cost would be about $10.20 per ton. The rail transportation cost for Kaiparowits coal would be from $1.90 to $3.70 per ton higher than that for the alternate coal sources, mainly because the latter would not require new construction. When coal quality is considered, however, Kaiparowits would compare favorably with distant sources having lower-heating-value coal.

For this particular case (the results are not generalizable), the per-ton cost of coal slurry pipeline transportation would be about half that for rail. Capital investment costs would also be twice those for pipelines. The total

delivered fuel cost at Barstow, California, would be $0.94 per million British thermal unit (Btu) for rail and $0.74 per million Btu for a pipeline. The total fuel cost to a coal-fired powerplant would be about 7 to 9 mills per kilowatt-hour. The decisive factors in the advantage of slurry pipelines here is their shorter length and the need for new rail construction.

Other considerations not taken into account in the analysis presented here include the political and legal problems of obtaining water for the pipelines; the environmental impacts of extensive new rail construction; the use of diesel fuel for railroads versus electricity for pipeline operations; the greater potential of railroads for regional growth stimulation; and the certainty of long-term pipeline contracts versus the short-term nature of rail tariff agreements.

INTRODUCTION

Objectives of the Study

The Kaiparowits Plateau in southern Utah is the site of one of the largest undeveloped deep-mined coalfields in the United States, with recoverable resources estimated at 4 billion tons.[1] That virtually none of this coal is presently on the market is due primarily to relatively difficult mining conditions and, as seen in Figure 1, to a near total lack of road or rail connections between the coalfield and the outside world. Although the recent demise of a proposed mine-mouth electric powerplant project appeared to set development back further, the proximity of this coalfield to a potentially large California market and the high heating value and low sulfur content of its coal justify an examination of the economic feasibility of transporting the product to Southern California.

This Bulletin addresses three questions concerning coal transportation from Kaiparowits to Southern California:

- Of what order of magnitude are the transportation costs, and what percentage of total delivered fuel costs would they represent?

- Which transportation mode is less expensive: unit train or coal slurry pipeline?

- How would the lowest cost for either mode compare with that for rail transportation to Southern California from established coalfields in Wyoming, Utah, and New Mexico?

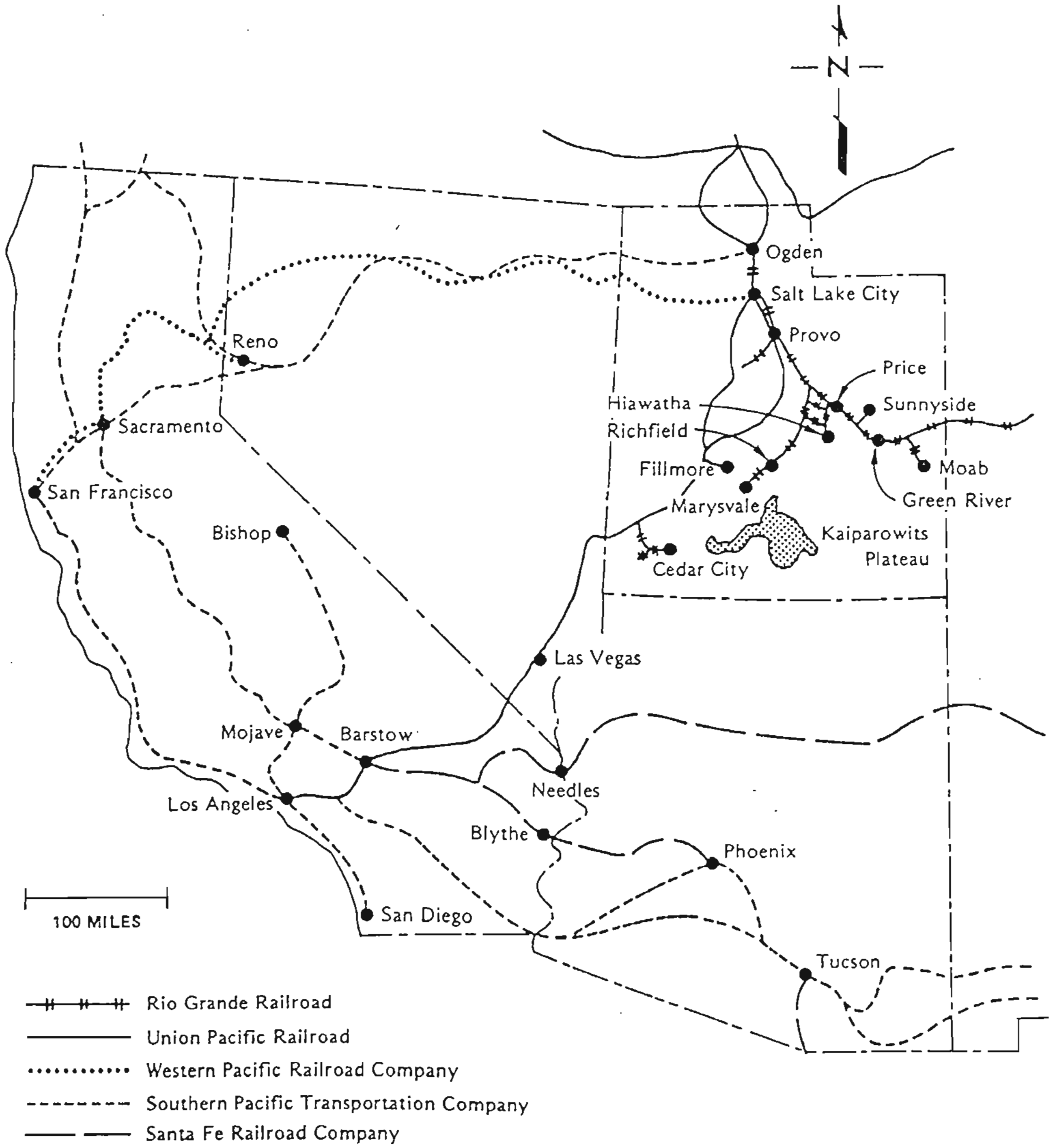

Figure 1: Rail Network of the Southwest

Ground Rules and General Assumptions

To make this analysis realistic and comparable with similar studies, several major assumptions were necessary. It was assumed that a nominal 10 million tons of coal would be shipped annually from Kaiparowits (or from the coal sources with which Kaiparowits is compared) to powerplants near Barstow, Cadiz, or Blythe, California. The powerplant sites were among seven evaluated recently by the Institute of Geophysics and Planetary Physics and the Environmental Science and Engineering Program at the University of California at Los Angeles in their assessment of the potential use of coal-fired powerplants to generate electricity for the California State Water Project.[2] Given an average heating value of 12,000 British thermal units per pound (Btu/lb) for Kaiparowits coal,[3] and a powerplant thermal efficiency of 35 percent, the 10 million tons per year would be converted into 2.5×10^{10} kilowatt-hours per year (kWh/yr) of electricity, produced by 3,500 megawatts (MW) of busbar generating capacity operating with a 70-percent load factor. The 10-million-ton throughput would be sufficient to make slurry pipelines, at least on first examination, appear competitive with railroads.[4]

It is important to distinguish between transportation costs and tariffs. The latter are set through negotiations between shipper and carrier. In the case of railroads, at least, there is no clear and consistent relationship between the tariff and the actual cost of a particular movement, apart from subjectively interpreted Interstate Commerce Commission (ICC) strictures against "predatory pricing"; that is, tariffs cannot be set below a railroad's "out-of-pocket" costs for the run in question. Unfortunately, the problem of allocating fixed costs, such as for infrastructure, and railroad-wide costs, such as for advertising, to specific movements is still unsolved, and railroad personnel admit to the impossibility of allocating costs to everyone's satisfaction.[5] The costs developed in this Bulletin therefore represent a lower bound for the tariffs which would actually be charged. In addition, it is assumed that coal transportation bears the full burden of project financing, which would not be true were the new railroad segments to be used for transportation of other commodities. In the case of coal slurry pipelines, coal would be the only product transported, so that tariffs would presumably bear a more consistent relationship to costs.

The following are other assumptions made in this study:

- Capital costs will be converted to annualized capital costs through multiplication by a single "fixed charge rate," F , which is defined as the sum of interest or return on investment, depreciation, insurance, and all taxes; all financing would be for 30 years

- Unit trains, running over single track, will be used for rail transportation

- Capital costs will be escalated at 6 percent per year, while future capital expenditures are discounted at 12.5 percent

- Costs are expressed in January 1977 dollars

A final note: it is not the purpose of this Bulletin to compare rail and slurry transportation in general. Recent studies performed for the U.S. Congress, Office of

Technology Assessment,[6,7] show how both the economics and the environmental impacts of coal transportation are highly route-dependent. The reader is referred to these studies for more detailed information on this subject.

TRANSPORTATION ROUTES FROM KAIPAROWITS TO SOUTHERN CALIFORNIA

Identification of Alternative Rail Routes

In a recent study for the California Department of Water Resources,[2] a team of investigators from the University of California at Los Angeles (Institute of Geophysics and Planetary Physics and the Environmental Science and Engineering Program) identified 14 potential new rail segments which, in various combinations, could connect the Kaiparowits Plateau coalfields with existing main or branch lines. Segment trajectories were first tentatively laid out on large-scale maps, then modified after field investigation. Figure 2 shows the segments, which are summarized in Table 1 and described in detail in Reference 8. The region's irregular terrain and the need to limit railroad grades to 1 percent make extensive cuts and fills necessary for many of the segments. In addition, certain segments would require tunnels and/or bridges to be built. Table 2 lists lengths and special construction requirements for each segment.

A subsidiary objective of this Bulletin was to determine the lowest-cost "route," which is defined as a sequence of new and existing rail segments, from the coalfield to Southern California. Because all 27 possible routes pass through Lund, Utah, that town was considered the end point of each alternative route. In the route optimization, however, the total

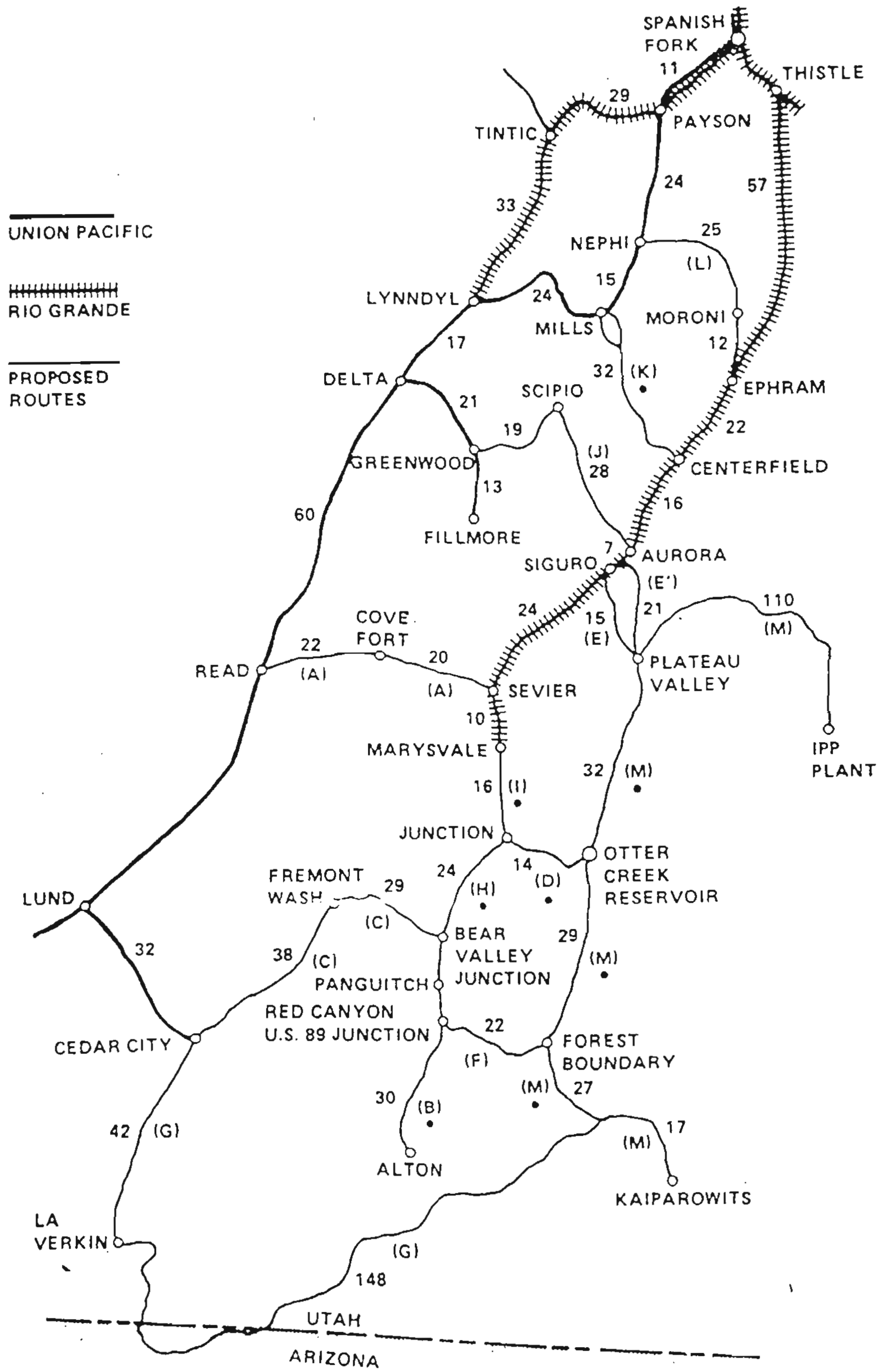

Figure 2: Existing and Proposed New Railroad Routes, Southern Utah

Table 1: Summary of New Rail Segments, Southern Utah

Map Symbol	Designation	Distance (miles)	Comments
A	Sevier-Read	42	Very steep grades; 10-mile tunnel needed
B	Alton-Bear Valley Junction	46	Some cuts; no tunnels; probably no severe construction problems
C	Bear Creek Canyon	67	3-mile tunnel and much earthwork would be necessary; narrow canyon needs investigating; some 2.1 percent downgrade
D	Otter Creek Reservoir-Junction	14	No difficulties apparent
E	Peterson Creek	31	Probably infeasible; downgrade in canyon is excessive
E'	Little Lost Creek	21	Has a few 4-percent grades; canyon very narrow in places
F	Red Canyon	23	Some severe downgrade; narrow canyon in places; adverse impact on recreation
G	Southern Terraces	185	Very long; many tunnels and bridges necessary; very rough terrain over about one-fourth of route; very severe construction problems above La Verkin and near pass south of Cedar City

Table 1 (continued)

Map Symbol	Designation	Distance (miles)	Comments
H	Bear Valley Junction-Junction	24	No grade problems but Circleville Canyon is narrow in places
I	Junction-Marysvale	16	Some contouring above Marysvale; otherwise no serious problems
J	Aurora-Holden	47	5-mile tunnel needed to avoid steep grades
K	Centerfield-Mills	32	No problems
L	Moroni-Nephi	25	2 to 3 percent downgrade in narrow canyon
M	Kaiparowits-Intermountain Power Project Plant	215	Feasible route determined by Morrison-Knudsen survey; 7-mile tunnel required

Table 2: New Railroad Construction Requirements

Segment[a]	Bridges (miles)	Tunnels (miles)	Cuts/Fills[b] (10^6 cu. yds.)[c]	Miles of Terrain for New Rail		
				Average	Rough	Very Rough
A	-	9.0	-	38.0	4.0	-
B	-	-	1.0	42.0	4.0	-
C	-	3.2	0.47	62.5	3.0	1.5
D	-	-	-	14.0	0.5	-
E	-	-	-	20.5	10.5	-
E'	-	-	-	14.5	2.0	4.0
F	-	4.0	-	20.5	1.0	-
G	3.5	4.5	11.0	126.0	30.0	29.0
H	-	-	-	20.0	4.0	-
I	-	-	-	11.0	4.0	1.0
J	-	-	-	41.0	3.0	3.0
K	-	-	0.03	31.0	1.0	-
L	-	-	-	22.0	3.0	-
M_1	0.5	-	-	13.0	4.0	-
M_2	0.5	7.0	-	16.0	8.0	3.0
M_3	-	-	-	22.0	6.0	1.0
M_4	-	-	-	32.0	-	-

Source: Data from Ronald Hudson (unpublished survey)
[a]See Figure 2.
[b]Cuts and fills beyond normal for rail construction. Included in variable C_2 in the cost model at $4 per cubic yard
[c]In millions of cubic yards

route distance, i.e., that from Kaiparowits to a Southern California powerplant site, was used in the calculations.

Figure 3 shows the rail segment network used for the optimization. Circled numbers represent nodes, or places where segments are joined. All possible sequences of segments were enumerated, as seen in Table 3. The characteristics of the routes thus defined are listed in Table 4. The total annual cost for each route was calculated by the methods described in the following subsection, and the minimum-cost route was identified.

Identification of Alternative Coal Slurry Pipeline Routes

As part of the same coal transportation study mentioned previously,[2] two alternative coal slurry pipeline routes from Kaiparowits to Southern California were identified. Because pipeline operation can tolerate grades of up to 16 percent,[9] slurry pipeline routes can be more direct than those for railroads. An attempt was made, where possible, to follow existing transportation corridors, such as that for the Black Mesa pipeline. Figure 4 shows the alternative routes examined.

RAIL TRANSPORTATION COST MODEL

To estimate capital, operating, and total annual rail transportation costs for various routes, an updated version of a previous cost model designed by the author[10] was used. While symbols have been changed throughout the model, it is only in the operating cost algorithm that one finds substantial departures from the original. As will be seen in the following subsection, it was felt that a straightforward accounting of cost items would be preferable to the tariff regression formula used before.

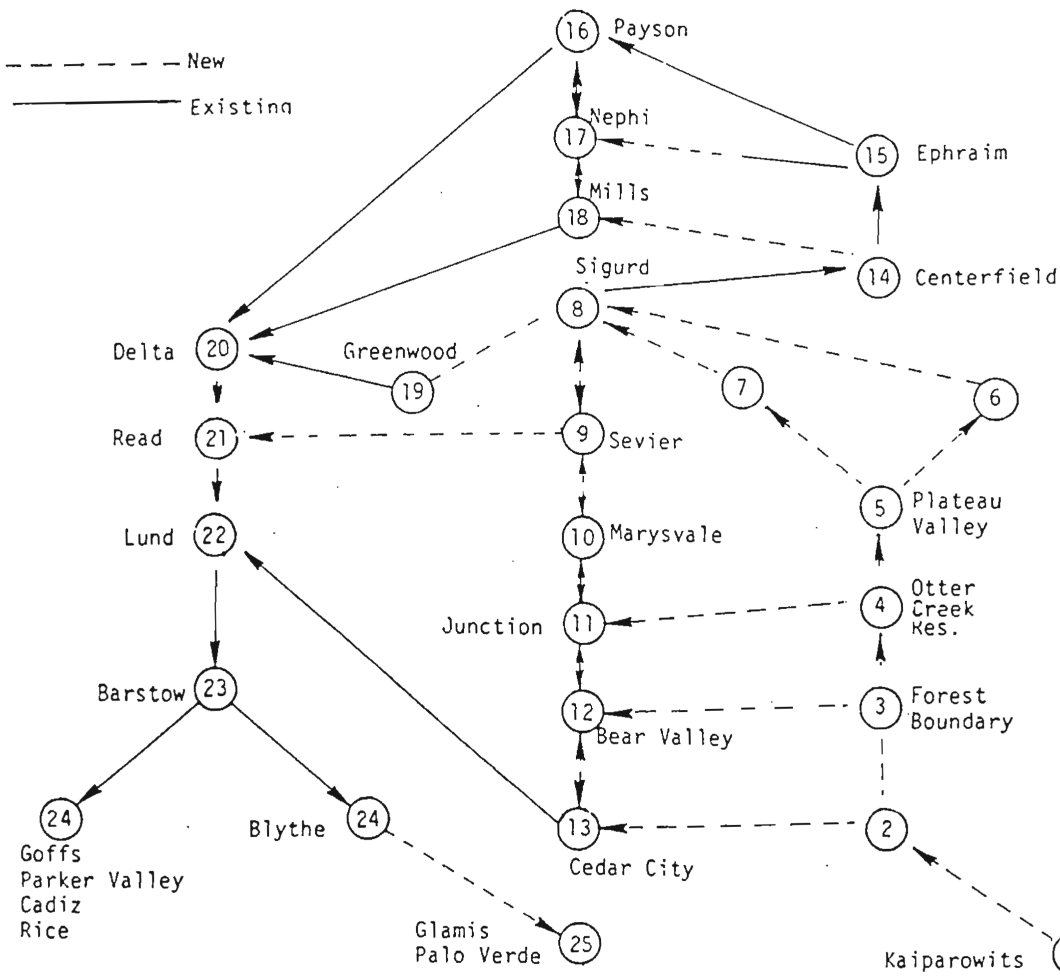

Figure 3: Kaiparowits-Southern California Rail Network

Table 3: Definition of Alternative Routes from Kaiparowits to Lund

Route Number	Nodes														
1	1	2	3	4	5	6	8	9	10	11	12	13	22		
2	1	2	3	4	5	6	8	9	21	22					
3	1	2	3	4	5	6	8	14	15	16	17	18	20	21	22
4	1	2	3	4	5	6	8	14	15	16	20	21	22		
5	1	2	3	4	5	6	8	14	15	17	16	20	21	22	
6	1	2	3	4	5	6	8	14	15	17	18	20	21	22	
7	1	2	3	4	5	6	8	14	18	17	16	20	21	22	
8	1	2	3	4	5	6	8	14	18	20	21	22			
9	1	2	3	4	5	6	8	19	20	21	22				
10	1	2	3	4	5	7	8	9	10	11	12	13	22		
11	1	2	3	4	5	7	8	9	21	22					
12	1	2	3	4	5	7	8	14	15	16	17	18	20	21	22
13	1	2	3	4	5	7	8	14	15	16	20	21	22		
14	1	2	3	4	5	7	8	14	15	17	16	20	21	21	22
15	1	2	3	4	5	7	8	14	15	17	18	20	21	22	
16	1	2	3	4	5	7	8	14	18	17	16	20	21	22	
17	1	2	3	4	5	7	8	14	18	20	21	22			
18	1	2	3	4	5	7	8	19	20	21	22				
19	1	2	3	4	11	10	9	21	22						
20	1	2	3	4	11	10	9	8	19	20	21	22			
21	1	2	3	4	11	12	13	22							
22	1	2	3	12	13	22									
23	1	2	3	12	11	10	9	21	22						
24	1	2	3	12	11	10	9	8	19	20	21	22			
25	1	2	13	22											
26	1	2	13	12	11	10	9	21	22						
27	1	2	13	12	11	10	9	8	19	20	21	22			

Table 4: Characteristics of Alternative Routes from Kaiparowits to Lund

Route Number	D_r (miles)	New Rail (miles)	$\sum_k b_k (D_s)_k$ (miles)	Tunnels (miles)	Bridges (miles)	Cuts and Fills (10^6 cu. yds.)[a]
1	299	233	270	17.2	1	0.47
2	240	168	193	16.0	1	0
3	440	126	152	7.0	1	0
4	439	126	152	7.0	1	0
5	429	151	178	7.0	1	0
6	382	151	178	7.0	1	0
7	417	158	185	7.0	1	0.03
8	340	158	185	7.0	1	0.03
9	302	173	206	7.0	1	0
10	293	227	260	17.2	1	0.47
11	234	162	184	16.0	1	0
12	434	120	142	7.0	1	0
13	433	120	142	7.0	1	0
14	423	145	169	7.0	1	0
15	376	145	169	7.0	1	0
16	411	152	175	7.0	1	0.03
17	334	152	175	7.0	1	0.03
18	296	167	197	7.0	1	0

[a] In millions of cubic yards

Table 4 (continued)

Route Number	D_r (miles)	New Rail (miles)	$\sum_k b_k (D_s)_k$ (miles)	Tunnels (miles)	Bridges (miles)	Cuts and Fills[a] (10^6 cu. yds.)
19	203	145	165	16.0	1	0
20	313	150	179	7.0	1	0
21	210	178	202	10.2	1	0.47
22	181	149	167	14.2	1	1.47
23	222	164	187	20.0	1	1.0
24	332	169	196	11.0	1	1.0
25	239	207	282	4.5	4	11.0
26	414	356	444	13.5	4	11.47
27	524	361	454	7.7	4	11.47

[a] In millions of cubic yards

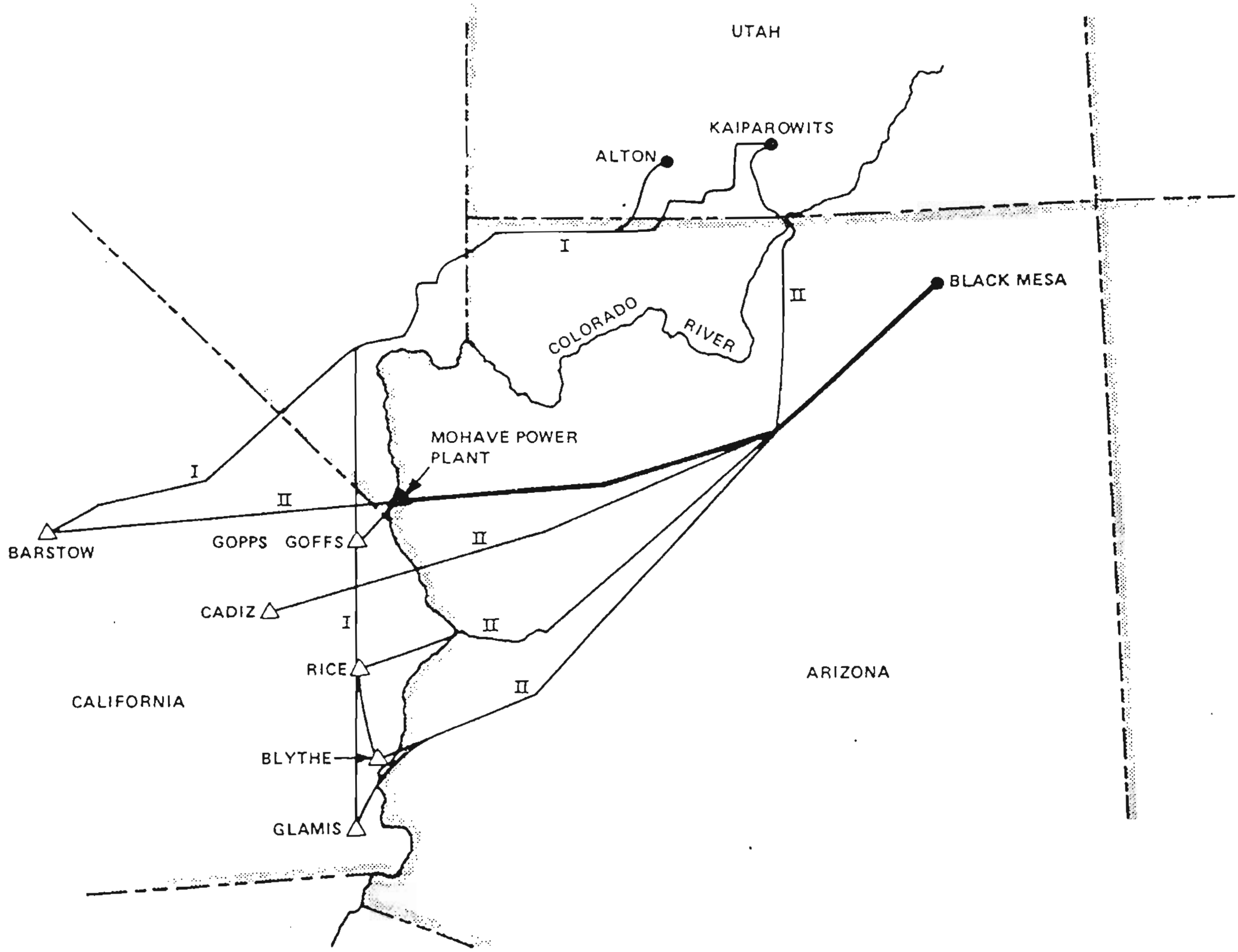

Figure 4: Proposed Coal Slurry Pipeline Routes

Logistics

If recent trends continue, a high percentage of the coal to be shipped by rail from western mines will travel by "unit trains." While the definition of a unit train is, along with tariffs, subject to negotiation between shipper and carrier for each movement, in general the term applies to a train dedicated to carrying a single commodity nonstop between designated points and according to a strict schedule. A unit train typically consists of about 70 to 110 hopper cars, up to six locomotives, and a caboose. The following analysis assumes such a configuration, including 100 hoppers with 100 tons net capacity each. Unit train systems operate night and day, all year round. Equations (1) through (3) describe the logistics of unit train operations:

$$\text{Cycles per year} = \frac{\text{operating hours per year}}{\text{hours per cycle}} \tag{1}$$

$$\text{Tons per cycle} = \frac{\text{tons per year}}{\text{cycles per year}} \tag{2}$$

$$\text{Trains per cycle} = \frac{\text{tons per cycle}}{\text{tons per train}} \tag{3}$$

The values to the right of the equal signs in the above three equations depend upon annual tonnage, haulage distance, and the time taken by loading and unloading, crew changes, and various other delays. To estimate operating hours per year, we assume a 5-percent downtime for the system:

$$\begin{aligned}\text{Operating-hours per year} &= (365\text{ days/year})(24\text{ hours/day})(0.95)\\ &= 8322\end{aligned}$$

Six elements enter into the hours per cycle (round trip) as seen in equation (4):

$$\text{Hours per cycle} = \text{loaded transit time} + \text{unloaded transit time} + \text{inspection time} + \text{crew change time} + \text{loading time} + \text{unloading time} \quad (4)$$

It was assumed, after discussions with railroad representatives, that reasonable loaded and unloaded train speeds for Utah-California runs would be 25 and 35 miles per hour, respectively.[11] Field observations and discussions with mining and powerplant operators[12] resulted in estimates of 2 to 5 hours, respectively, for loading and unloading one train. Federal regulations require inspections every 500 miles,[13] and current labor agreements require a crew change every 100 miles.[14] It is assumed that these two delays take 30 and 15 minutes, respectively. Letting D_r be the one-way haulage distance, equation (4) may be rewritten:

$$\begin{aligned}\text{Hours per cycle} &= \frac{D_r}{35} + \frac{D_r}{25} + 2 + 5 \\ &\quad + \frac{(0.5)(2)D_r}{500} + \frac{(0.25)(2)D_r}{100} \\ &= 7 + 0.0756\ D_r \qquad (5)\end{aligned}$$

It may be noted in passing that the average train speed (taking idle time into account) is found from equation (6):

$$\text{Average speed (miles/hour)} = \frac{2D_r}{7 + 0.0756\ D_r} \qquad (6)$$

For the haulage distances considered here, the average speed would be about 24 miles per hour.

Substituting equation (5) and the value for operating-hours per year into equation (1) results in equation (7):

$$\text{Cycles per year} = \frac{8322}{7 + 0.0756\ D_r} \tag{7}$$

If the haulage distance were 800 miles, for example, a single train would make 123 trips per year. Railroads, however, normally have several trains dedicated at any given time to unit train service. To find the number of trains in the coal haulage "fleet," we first substitute equation (7) into equation (3), letting T (tons/yr) be the annual tonnage hauled:

$$\text{Tons per cycle} = \frac{(7 + 0.0756\ D_r)T}{8322} \tag{8}$$

The number of trains in service at any given time is then found from equation (3), assuming that each train carries 10,000 tons of coal:

$$\text{Trains per cycle} = 1.20 \times 10^{-8}\ (7 + 0.0756\ D_r)T \tag{9}$$

If the railroad in the preceding example carried 10 million tons per year, then, by equation (9), about eight trains would be in service at any given time.

Capital Cost of New Rail, Tunnels, and Bridges

Coal transportation from Kaiparowits would require substantial construction of new rail line, tunnels, and bridges. The costs of these items depend heavily upon local topography and geology, and can be estimated accurately only after a detailed engineering analysis has been made. For the present model, it was necessary to assume unit costs on a per-mile basis for these capital items.

To estimate the unit cost of new single-track construction over "average" terrain, we considered the cost estimates for three proposed new railroads in Utah and New Mexico; these are shown in Table 5. In addition, new-single-track cost has been estimated to be $300,000 per mile[15] and double-track construction has been reported to reach $1,584,000 per mile.[16] As all these estimates assume different land costs, types of signalling systems, ancillary equipment, construction wage rates, and means of financing, they are not directly comparable. To remain within the reported cost range, we have assumed that new rail construction will cost $1,000,000 per mile.[17]

As was described previously, a preliminary survey of potential routes between Kaiparowits and existing rail lines revealed a wide variety of terrains, ranging from gentle alluvial valleys to steep cliffs and narrow canyons. Potential new rail segments were judged to have "average," "rough," or "very rough" terrain. For the three types, the rail construction unit cost was multiplied by a terrain factor, b, which equals 1, 1.5, and 3, respectively. If D_s (miles) is the length of new rail segment k, then the corresponding capital cost, C_1 (\$), is given by equation (10):

$$C_1(\$) = 1.0 \times 10^6 \sum_k b_k (D_s)_k \qquad \begin{array}{l} \text{Average terrain: } b = 1.0 \\ \text{Rough terrain: } b = 1.5 \\ \text{Very rough terrain: } b = 3.0 \end{array} \qquad (10)$$

In certain cases a potential new rail segment traverses two or more terrain types. The rail construction cost is then found by weighting the terrain factors by the corresponding mileages. For example, if a segment has 20 miles of average, 10 miles of rough, and 10 miles of very rough terrain, the terrain factor becomes:

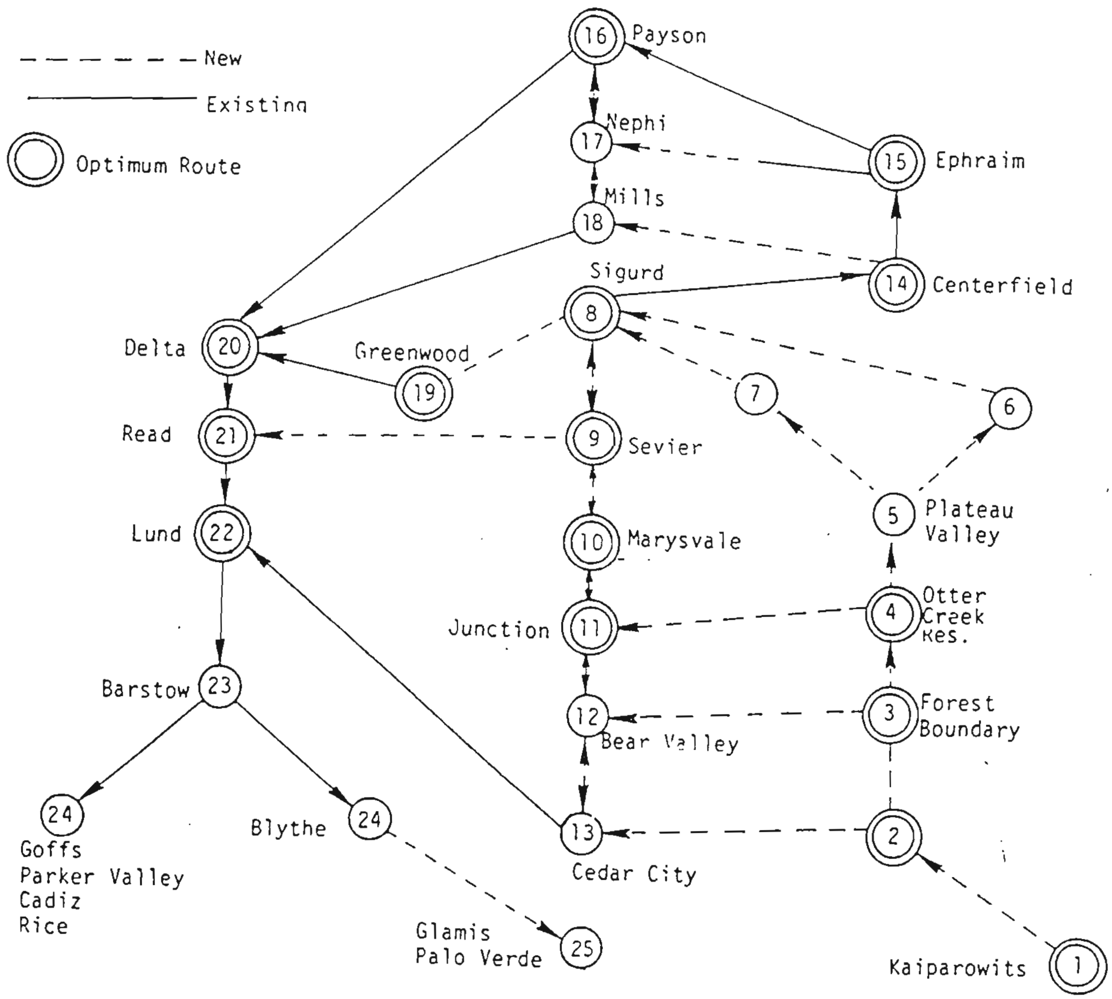

Figure 5: Optimum Rail Route from Kaiparowits to Southern California

Table 5: Estimates of New Rail Unit Costs

Project	Cost[a]	Distance (miles)	Cost ($/mile)	Reference
Star Lake-Prewitt	50	70	714,000	50
Emery-Wellington	70	65	1,077,000	51
Kaiparowits-Caineville	450	190	2,368,000	52

[a]In millions of dollars

Table 6: Unit Construction Costs Used in the Model

Item	Unit Cost
New Rail	$ 1,000,000/mile
Rail Upgrading	$ 140,000/mile
Tunnel	$ 10,000,000/mile
Bridge	$ 12,000,000/mile
Cuts and Fills[a]	$ 4/cubic yard

[a]Included in variable C_2 in the model

$$b = \frac{1(20) + 1.5(10) + 3.0(10)}{20 + 10 + 10} = 1.625$$

As there has been relatively little new long-distance rail construction in the United States during the past several years, unit costs for railroad bridges and tunnels were unavailable. A survey of costs reported in Engineering News-Record showed tunnel costs ranging from $10 million to $173 million per mile and bridge costs between $12 million and $1.5 billion per mile.[18] As seen in Table 6, bridge and tunnel costs were set conservatively at the lower end of the reported ranges. In later equations, C_2 represents the sum of tunnel and bridge costs.

Capital Cost of Rail Replacement and Upgrading

Rail in unit train service is used more intensively than is that in conventional freight movements. It has been estimated that a given stretch of rail must be replaced after the passage of 500 million gross tons.[19] Hopper cars and locomotives weigh 31 tons[20] and 175 tons[21] respectively. If H_t and L_t are the number of hoppers and locomotives per train, respectively, and a caboose weighs about as much as a hopper car, then the weight of an empty train, $W_{t,e}$, is

$$W_{t,e} \text{ (tons)} = 31 \ (H_t + 1) + 175 \ L_t \qquad (11)$$

A loaded train has a weight $W_{t,1}$, given by

$$W_{t,1} \text{ (tons)} = (31 + 100) H_t + 31 + 175 \ L_t \qquad (12)$$

The weight exerted during one round trip is therefore

$$W_T \text{ (tons)} = W_{t,e} + W_{t,1} = 162 \ H_t + 62 + 350 \ L_t \qquad (13)$$

Assuming six locomotives and 100 hopper cars per train, W_T would be 18,362 tons. Let R be the number of trainloads per year; because each train carries 10,000 net tons,

$$R = \frac{T}{10,000} \tag{14}$$

The gross weight exerted by the R trainloads per year is

$$\text{Gross tons exerted per year} = W_T R = 1.84\ T \tag{15}$$

The fraction of track mileage which must be replaced annually is

$$\text{Replacement fraction} = \frac{1.84\ T}{5.00 \times 10^8} \tag{16}$$

In the scenarios examined in this Bulletin, haulage of 10 million tons per year would necessitate replacement of about 3.7 percent of the trackage per year. The cost of rail replacement is given by equation (17):

$$\text{Rail replacement cost (\$/yr)} = \frac{1.84\ T(140,000)D_r}{5.00 \times 10^8}$$

$$= 5.15 \times 10^{-4} T\ D_r \tag{17}$$

Because only first investment costs are estimated, it is necessary to calculate the present worth of a 30-year series of capital expenditures for replacement rail. Assuming an inflation rate of 6 percent and a discount rate of 12.5 percent, the present value of all rail replacements, C_3, is

$$C_3(\$) = 5.15 \times 10^{-4}\ T\ D_r \left[1 + \sum_{n=1}^{29} \left(\frac{1.06}{1.125}\right)^n\right]$$

$$= 7.42 \times 10^{-3}\ T\ D_r \tag{18}$$

Capital Cost of Loading and Unloading Facilities

Unit trains serving the newer coal mines in the West are loaded two cars at a time in enclosed silos having a storage capacity of about 10,000 tons each. A recent study of loading costs in the Gillette, Wyoming, area estimated capital costs for facilities of various sizes.[22] Equation (19) was derived from results presented in that study. C_4 is the capital investment cost.

$$C_4(\$) = 0.222\ T + 5.57 \times 10^6 \tag{19}$$

A loading facility able to handle 10 million tons per year would thus cost about $7.8 million. It is assumed that three 3.33-million-ton capacity unloading facilities costing $\$1.12 \times 10^7$ each would be necessary.[23] The capital cost for unloading facilities, C_5 ($), is therefore $\$3.36 \times 10^7$.

Capital Cost of Rolling Stock

We assume that a 10-percent reserve of hopper cars, locomotives, and cabooses will be part of the "fleet" of rolling stock. The number of trains in service at any given time was given by equation (9). The size of the hopper car, locomotive, and caboose fleets is estimated by equations (20), (21), and (22), respectively:

$$\begin{aligned} H_f &= (1.1)(100)[1.20 \times 10^{-8}\ T(7 + 0.0756\ D_r)] \\ &= 1.32 \times 10^{-6}\ T(7 + 0.0756\ D_r) \end{aligned} \tag{20}$$

$$\begin{aligned} L_f &= (1.1)(6)[1.20 \times 10^{-8}\ T(7 + 0.0756\ D_r)] \\ &= 7.92 \times 10^{-8}\ T(7 + 0.0756\ D_r) \end{aligned} \tag{21}$$

$$C_f = (1.1)(1)[1.20 \times 10^{-8}\ T(7 + 0.0756\ D_r)]$$
$$= 1.32 \times 10^{-8}\ T(7 + 0.0756\ D_r) \qquad (22)$$

Although freight cars in general service have an average useful life of about 25 years[24] and locomotives last 30 years or more, rolling stock in unit train service is subject to much more intensive use. As a consequence, their useful lifetimes have been estimated to be about 15 years,[25] after which they are switched to less demanding service or are scrapped. To simplify computation, we assume that all rolling stock is replaced every 15 years. The present worth of original and replacement stock is found by multiplying the first-year capital cost by equation (23):

$$\text{Present worth factor} = 1 + \left(\frac{1.06}{1.125}\right)^{15} + \left(\frac{1.06}{1.125}\right)^{30} = 1.578 \qquad (23)$$

Table 7 lists the unit costs of rolling stock. The capital investment costs of hopper cars, C_6, locomotives, C_7, and cabooses, C_8, are found by multiplying the unit cost of each vehicle by the respective fleet sizes and by equation (23):

$$C_6(\$) = (30{,}000)(1.578)[1.32 \times 10^{-6}\ T(7 + 0.0756\ D_r)]$$
$$= 0.0625\ T(7 + 0.0756\ D_r) \qquad (24)$$

$$C_7(\$) = (550{,}000)(1.578)[7.92 \times 10^{-8}\ T(7 + 0.0756\ D_r)]$$
$$= 0.0687\ T(7 + 0.0756\ D_r) \qquad (25)$$

$$C_8(\$) = (43{,}000)(1.578)[1.32 \times 10^{-8}\ T(7 + 0.0756\ D_r)]$$
$$= 8.96 \times 10^{-4}\ T(7 + 0.0756\ D_r) \qquad (26)$$

Table 7: Unit Costs of New Rolling Stock

Item	Unit Cost (dollars)
Hopper Car	30,000
Locomotive	550,000
Caboose	43,000

Source: Reference 27

The total first-year capital investment cost for any route, C_I, is found by summing costs C_1 through C_8:

$$C_I(\$) = \sum_{i=1}^{8} C_i = 1.0 \times 10^6 \sum_k b_k (D_s)_k + \sum_k (C_2)_k$$
$$+ 7.42 \times 10^{-3}\ T\ D_r + 0.222\ T$$
$$+ 5.57 \times 10^6 + 3.36 \times 10^7$$
$$+ 0.0625\ T(7 + 0.0756\ D_r)$$
$$+ 0.0687\ T(7 + 0.0756\ D_r)$$
$$+ 8.96 \times 10^{-4}\ T(7 + 0.0756\ D_r) \qquad (27)$$

where the subscript k denotes one of the segments of which the route is composed. Equation (27) may be simplified to equation (28):

$$C_I(\$) = 1.0 \times 10^6 \sum_k b_k (D_s)_k + \sum_k (C_2)_k$$
$$+ 1.15\ T(1 + 0.0152\ D_r)$$
$$+ 3.92 \times 10^7 \qquad (28)$$

The annualized capital cost, C_A, is found by multiplying equation (28) by the fixed charge rate, F. Since F is assumed to be 0.15 in this Bulletin, the annualized capital cost is

$$C_A(\$/yr) = 1.5 \times 10^6 \sum_k b_k (D_s)_k + \sum_k (C_2)_k$$
$$+ 1.15\ T(1 + 0.0152\ D_r)$$
$$+ 5.88 \times 10^6 \qquad (29)$$

Rail Operating Costs

Operating costs in this model are limited to those for fuel, labor, rolling stock maintenance, track maintenance, and overhead. The sum of these provides a lower bound for actual operating costs, inasmuch as other railroad expenses cannot readily be allocated to specific unit train movements. Except where otherwise noted, cost equations were derived from unit cost information presented by General Research Corporation in a recent study for the U.S. Congress, Office of Technology Assessment.[7]

Fuel Cost

Locomotives consume between 2 and 7 gallons per mile, depending upon load, terrain, and speed. For runs similar to those considered here, fuel consumption was reported by Union Pacific Railroad to be 2.6 gallons per mile.[26] This fuel was assumed to cost $0.35 per gallon.[27] To find the number of locomotive-miles traveled, we first note that equation (14) gives the number of train trips per year as T/10,000. Assuming six locomotives per train and noting that the length of a round trip is $2D_r$, we have the following expression for locomotive-miles per year:

$$\text{Locomotive-miles/year} = \frac{(6)(2D_r)T}{10{,}000}$$

$$= 1.20 \times 10^{-3}\ T\ D_r \qquad (30)$$

Equation (31) gives C_9, the annual fuel cost:

$$C_9(\$/\text{yr}) = (0.35)(2.6)(1.20 \times 10^{-3}\ T\ D_r)$$

$$= 1.09 \times 10^{-3}\ T\ D_r \qquad (31)$$

Labor Cost

The labor cost for fully loaded train operation was assumed to be \$550 per train crew per 100 miles.[27] From equation (14) the number of crew-miles per year is $(2D_r)(10^{-4}T)$. The labor cost, C_{10} , is thus given by equation (32):

$$C_{10}(\$/yr) = \frac{550}{100}(2 \times 10^{-4}\ T\ D_r)$$

$$= 1.10 \times 10^{-3}\ T\ D_r \qquad (32)$$

Operating Cost for Loading and Unloading Facilities

Equation (33), which gives the operating costs for loading facilities, C_{11} , was derived from data tabulated in Reference 28:

$$C_{11}(\$/yr) = 5.38 \times 10^{-2}\ T + 4.46 \times 10^{5} \qquad (33)$$

Reference 29 gives the operating cost of a 3.3-million-ton-per-year unloading facility as \$1,090,000 per year. Since three such facilities would be needed, the unloading facility operating cost, C_{12} , would be $\$3.27 \times 10^{6}$ per year.

Track Maintenance

Equation (34), which gives the annual track maintenance cost per mile, was derived from data tabulated in Reference 30:

$$\text{Track maintenance cost } (\$/\text{mile/yr}) = 3.42 \times 10^{-4}\ T + 5.30 \times 10^{3} \qquad (34)$$

The annual track maintenance cost, C_{13}, is then found by multiplying equation (34) by the route length, D_r:

$$C_{13}(\$/yr) = (3.42 \times 10^{-4}\ T + 5.30 \times 10^{3})\ D_r \tag{35}$$

Rolling Stock Maintenance

Operating and maintenance costs for each hopper car, locomotive, and caboose are assumed to be, respectively, \$0.03, \$0.44, and \$0.02 per mile per year.[27] To find annual costs, we multiply these values times the number of vehicle-miles per year for each type of rolling stock. The result is shown in equation (36), where C_{14} is the total annual rolling stock operating and maintenance cost:

$$\begin{aligned} C_{14}(\$/yr) &= 2 \times 10^{-4}\ T\ D_r(1.1)[(0.03)(100) \\ &\quad + (0.44)(6) + (0.02)(1)] \\ &= 1.25 \times 10^{-3}\ T\ D_r \end{aligned} \tag{36}$$

Overhead Cost

As noted previously, overhead cannot be allocated with any certainty to specific unit train movements. It was assumed that overhead was equal to 5 percent of the revenue for the movement, and that the revenue was 6 mills per ton-mile.[30] Equation (37) gives C_{15}, the overhead cost:

$$C_{15}(\$/yr) = (0.05)(0.006)\ T\ D_r = 3.0 \times 10^{-4}\ T\ D_r \tag{37}$$

Total Operating Cost

The total operating and maintenance costs, C_O, are found by summing costs C_9 through C_{15}:

$$C_O(\$/yr) = 5.38 \times 10^{-2}\, T(1 + 7.58 \times 10^{-2}\, D_r) + 5.30 \times 10^{3}\, D_r + 3.72 \times 10^{6} \qquad (38)$$

Total Annual Rail Cost

The total annual cost for rail shipment, C_T, is found by summing equations (28) and (38). If it is assumed that F is 0.15, then the result is given by equation (39):

$$C_T(\$/yr) = 1.5 \times 10^{6} \sum_k b_k (D_s)_k + \sum_k (C_2)_k + 6.71 \times 10^{-3}\, T\, D_r + 5.3 \times 10^{3}\, D_r + 2.27 \times 10^{-1}\, T + 9.60 \times 10^{6} \qquad (39)$$

For the case at hand, where T is 10 million tons per year, equation (39) may be simplified for computational purposes to

$$C_T(\$/yr) = 1.5 \times 10^{6} \sum_k b_k (D_s)_k + \sum_k (C_2)_k + 7.24 \times 10^{4}\, D_r + 1.19 \times 10^{7} \qquad (40)$$

SLURRY PIPELINE COST MODEL

Assumptions

The following analysis is based in large part upon an independent study of coal slurry pipeline costs performed for the U.S. Congress, Office of Technology Assessment, by General Research Corporation (GRC).[7] GRC estimated the costs of four hypothetical slurry pipeline systems, one of which would transport coal from Price, Utah, to Barstow, California, using a route coincident with Alternative I in

Figure 4. Where possible we have derived general pipeline cost formulae from data reported in the GRC case studies. Where this was not possible we used the costs calculated by GRC for throughputs or distances similar to those contemplated in the present analysis.

In any discussion of slurry transportation, it is important to distinguish between "contract coal" and "dry coal."[31] All coals, as mined, have at least some water bound in their organic and inorganic matrices and held in surficial micropores. Contract coal is coal whose physical and chemical characteristics must lie within ranges specified in a contract between the mine and the purchaser. Dry coal is the solid fraction which would theoretically remain if all the moisture could be removed from the coal. In the present analysis it is assumed that the 10 million tons per year to be transported from Kaiparowits are of contract coal. The average moisture content of this coal is 11.3 percent.[3] The dry coal throughput is therefore 8.87 million tons per year. Following are the other assumptions we made:

- The slurry has a specific gravity of 1.165, as has the Black Mesa Pipeline coal;[32] for a coal with 11.3 percent moisture, it can be shown that the dry solids weight percentage (called the "consist") is 49.6

- Slurry velocity is between 5.6 and 6.0 feet per second

- Positive displacement pumps rated at 1,700 horsepower and having a 80-percent efficiency are used

- The system is in operation 95 percent of the time

- An emergency flushing reservoir is located at each pump station

Capital Costs for the Pipeline

From data provided by GRC,[34] we derived equation (41) for the required pipe outside diameter, d_o :

$$d_o(\text{inches}) = 8.12 \times 10^{-3}\ T_d^{0.5} \qquad (41)$$

where T_d is the dry coal throughput in tons per year. Substituting 8.87×10^6 for T_d, we find that a nominal 24-inch pipeline would be necessary. C_{15}, the cost of steel, wrapping, valves, right-of-way, excavation, welding, installation, and backfill[35] is given by equation (42):

$$C_{15}(\$) = 3.87 \times 10^5\ D_p \qquad (42)$$

where D_p is the length of the 24-inch outside diameter pipe in miles.

Capital Cost of Slurry Preparation, Dewatering, and Pumping Facilities

The slurry preparation cost, C_{16}, is found[36] from equation (43):

$$C_{16}(\$) = 1.9 \times 10^7 \left[\frac{(1 - m)T}{10^7}\right]^{0.8} \qquad (43)$$

where m is the moisture fraction. For the case of Kaiparowits coal, equation (43) simplifies to

$$C_{16}(\$) = 43.4\ T^{0.8} \qquad (44)$$

In a similar manner, the dewatering facility capital cost, C_{17}, may be shown to be[36]

$$C_{17}(\$) = 15.5\ T^{0.9} \tag{45}$$

To determine the pumping facility capital cost, we assume that there will be one station every 75 miles.[37] The number of stations will thus be $D_p/75$. The cost per pumping station, P_I, was derived from GRC data[38] to be

$$P_I(\$) = 4.82(1 - m)T^{0.83} \tag{46}$$

To find the cost of all the pumping stations C_{18}, we multiply equation (46) by the number of stations and, for the case of Kaiparowits coal, set m equal to 0.113. The result is equation (47):

$$C_{18}(\$) = 0.0582\ T^{0.83}\ D_p \tag{47}$$

$C_{I'}$, the total investment cost for a pipeline with length D_p and throughput T, is given by equation (48):

$$C_{I'}(\$) = 43.4\ T^{0.8} + 15.5\ T^{0.9} + 3.87 \times 10^5\ D_p(1 + 1.5 \times 10^{-7}\ T^{0.83}) \tag{48}$$

The annualized capital cost, $C_{A'}$, is found by multiplying equation (48) by the fixed charge rate, F. Since F is assumed to be 0.15 in this Bulletin, the annualized capital cost is given by equation (49):

$$C_{A'}(\$/yr) = 6.51\ T^{0.8} + 2.33\ T^{0.9} + 5.81 \times 10^4\ D_p(1 + 1.50 \times 10^{-7}\ T^{0.83}) \tag{49}$$

Operating Costs

Operating and maintenance costs for slurry preparation and dewatering facilities were determined from graphs prepared by GRC.[39] The annual totals for a 10-million-ton-per-year contract coal throughput (8.87 million tons per year dry coal) would be \$4.56 million and \$8.39 million, respectively.

The transmission water requirement, W_T, for a coal slurry pipeline was determined by using equation (50), which was derived by the author in a previous study:[33]

$$W_T \text{ (acre-feet/year)} = 1.51 \times 10^{-3} (0.51 - m)T \qquad (50)$$

The water needed to refill the emergency flushing reservoirs, W_E, is given by equation (51) which was also derived by the author:[40]

$$W_E \text{ (acre-feet/year)} = 3.08 \times 10^{-8} (1 - m)T\,E_n \qquad (51)$$

where E_n (inches/yr) is the net excess of evaporation over precipitation along the pipeline route. For the case under consideration, E_n is about 75 inches,[41] so that the total annual water requirement, W, becomes

$$W \text{ (acre-feet/yr)} = 6.02 \times 10^{-4}\ T \qquad (52)$$

Assuming an annual water cost (including annualized capital cost, water rights, pumping, and conveyance costs) of \$100 per acre-foot, the annual water cost, C_{19}, is given by equation (53):

$$C_{19} \text{ (\$/yr)} = 0.0602\ T \qquad (53)$$

The annual operating and maintenance cost per pump station, P_o , was derived from GRC data[42] for values of T between 7.5 and 15 million tons per year and is shown in equation (54):

$$P_o \text{ (\$/yr)} = 0.140\ T + 1.05 \times 10^5 \quad (54)$$

This cost includes the costs of power, maintenance materials and supplies, labor, and administration. Since there are $D_p/75$ pump stations, the total operating cost for pumping is $P_oD_p/75$, or C_{20} , as seen in equation (55):

$$C_{20} \text{ (\$/yr)} = (1.87 \times 10^{-3}\ T + 1.40 \times 10^3)\ D_p \quad (55)$$

The total annual operating cost for slurry pipelines is given by adding C_{19} , C_{20} , and the costs for slurry preparation and dewatering:

$$C_{O'} \text{ (\$/yr)} = 0.0602\ T + (1.87 \times 10^{-3} T + 1.40 \times 10^3) D_p + 1.30 \times 10^7 \quad (56)$$

Total Annual Slurry Pipeline Cost

The total annual cost for slurry pipeline transportation, $C_{T'}$, is found by adding equations (49) and (56). If it is assumed that F is 0.15, then the result is given by equation (57):

$$\begin{aligned} C_{T'} \text{ (\$/yr)} = {} & 6.51T^{0.8} + 2.33T^{0.9} \\ & + 5.81 \times 10^4\ D_p(1 + 1.5 \times 10^{-7}\ T^{0.83}) \\ & + 0.0602T + (1.87 \times 10^{-3}T + 1.40 \times 10^3)\ D_p \\ & + 1.30 \times 10^7 \end{aligned} \quad (57)$$

For the case at hand, where T is 10 million tons per year, equation (57) may be simplified for computational purposes to

$$C_{T'} \ (\$/yr) = 8.38 \times 10^4 \ D_p = 2.08 \times 10^7 \qquad (58)$$

APPLICATION OF COST MODELS

Optimum Rail Route Determination

Table 8 shows the results of applying the rail cost model to the 27 alternative routes from Kaiparowits to Barstow, California. The least expensive route is No. 20, which is marked by double circles in Figure 5. It should be noted that the next four routes in order of increasing cost, Nos. 22, 17, 21, and 18, have costs within $0.10 per ton of the optimum route. Given the rough nature of several of the unit cost estimates, especially that of new rail, tunnel, and bridge construction, any of a dozen low-cost routes could very well be the least expensive one. The model appears to be relatively insensitive to these construction unit costs; raising the latter by 10 percent would increase total annual costs by 1 or 2 percent.

Table 9 summarizes the costs of transporting coal by any of the five lowest-cost routes to three alternative Southern California powerplant sites. Increasing the total route distance increases the cost differential among alternative routes, but the difference between the costs of Routes 20 and 18 is still only $0.03 per million Btu at most.

Table 8: Calculation of Alternative Route Costs

Route No.	Costs (millions of dollars per year): Capital Investment	Costs (millions of dollars per year): Annualized Capital	Costs (millions of dollars per year): Operating	Costs (millions of dollars per year): Total Annual	Cost: (dollars per ton)	Cost: (cents per million Btu)
1	627	94.1	36.1	130.1	13.01	54.2
2	526	78.9	33.3	112.2	11.22	46.8
3	430	64.5	42.6	107.0	10.70	44.6
4	430	64.5	42.5	107.0	10.70	44.6
5	454	68.1	42.0	110.1	11.01	45.9
6	445	66.9	39.9	106.7	10.67	44.5
7	459	68.9	41.5	110.3	11.03	46.0
8	446	66.8	37.9	104.8	10.48	43.7
9	460	68.9	36.2	105.2	10.52	43.8
10	616	92.4	35.8	128.2	12.82	53.4
11	516	77.4	33.1	110.5	11.05	46.0
12	419	62.8	42.3	105.1	10.51	43.8
13	419	62.8	42.2	105.0	10.50	43.8
14	444	66.6	41.8	108.4	10.84	45.2
15	436	65.4	39.6	105.0	10.50	43.7
16	448	67.2	41.2	105.0	10.50	43.7
17	435	65.2	37.7	102.8	10.28	42.9
18	450	67.5	35.9	103.3	10.33	43.1

Table 8 (continued)

Route No.	Cost (millions of dollars per year) Capital Investment	Annualized Capital	Operating	Total Annual	Cost (dollars per ton)	(cents per million Btu)
19	492	73.7	31.6	105.4	10.54	43.9
20	435	65.2	36.7	101.9	10.19	42.5
21	474	71.0	32.0	103.0	10.30	42.9
22	478	71.6	30.6	102.3	10.23	42.6
23	561	84.1	32.5	116.6	11.66	48.6
24	499	74.9	37.6	112.4	11.24	46.8
25	580	87.0	33.3	120.3	12.03	50.1
26	864	129.6	41.4	171.0	17.10	71.2
27	836	125.3	46.4	171.7	17.17	71.6

Table 9: Rail Transportation Costs, Kaiparowits to Southern California (10 million tons per year)

Route Number	Barstow D_r (miles)[a]	Barstow Cost (millions of dollars per year)	Barstow Cost[b] (cents per million Btu)	Cadiz D_r (miles)[a]	Cadiz Cost (millions of dollars per year)	Cadiz Cost[b] (cents per million Btu)	Blythe D_r (miles)[c]	Blythe Cost (millions of dollars per year)	Blythe Cost[b] (cents per million Btu)
20	704	101.9	42.5	807	109.4	45.6	911	116.9	48.7
22	572	102.3	42.6	675	109.7	45.7	779	117.2	48.8
17	725	102.8	42.9	828	110.3	45.3	932	117.8	49.1
21	601	103.0	42.9	704	110.4	46.0	808	118.0	49.2
18	687	103.3	43.1	790	116.7	48.6	894	124.2	51.7

[a] Assumes new 5-mile spur from main line to powerplant site.

[b] Assumes coal with heating value of 12,000 Btu per pound.

[c] Assumes new 17-mile spur from main line to powerplant site.

Comparison with Other Rail-Based Coal-Supply Scenarios

To see whether the extensive new construction required for rail transportation from Kaiparowits would raise transportation costs enough to make this coal significantly more expensive than coal from other western sources, the rail transportation cost model was applied to 12 other coal-source powerplant scenarios, none of which would require appreciable new construction. Book Cliffs, Utah, and Grand Hogback and Carbondale (GHC), Colorado, represent relatively high-Btu, deep-mined coal sources, while the Star Lake, New Mexico, and Kemmerer, Wyoming, coalfields provide surface-mined, relatively low-Btu coal. Book Cliffs and Star Lake are at about the same distance from Southern California, while GHC and Kemmerer are more distant.

Table 10 shows the costs of transporting coal from Kaiparowits and the four alternative sources to the three representative Southern California powerplant sites. For the shipment of 10 million tons per year of coal, the Kaiparowits transportation cost is from 17 to 89 percent more expensive than those of the alternatives shown. When the quality of the coal is taken into account, Kaiparowits is at less of a disadvantage. The shipping cost in cents per million Btu is at most 67 percent higher than that of the least expensive alternative. That the cents-per-million-Btu cost of transporting Kemmerer coal to California is only slightly lower than that for Kaiparowits indicates that the latter source may be competitive (at least as far as transportation is concerned) with low-quality coal from distant sources.

Table 10: Rail Transportation Costs, Various Coal Sources, to Southern California

		Barstow			Cadiz			Blythe		
Coal Source	Coal Heating Value (Btu per pound)	D_r (miles)[a]	Cost (millions of dollars per year)	Cost (cents per million Btu)	D_r (miles)[a]	Cost (millions of dollars per year)	Cost (cents per million Btu)	D_r (miles)[b]	Cost (millions of dollars per year)	Cost (cents per million Btu)
Kaiparowits[d]	12,000	704	101.9	42.5	807	109.4	45.6	911	116.9	48.7
Book Cliffs	12,800[e]	703	64.9	25.4	801	72.0	28.1	905	80.6	31.5
Star Lake	9,500[f]	710	65.4	34.4	606	57.9	30.5	710	66.5	35.0
Kemmerer	9,700[g]	883	77.9	40.2	981	85.0	43.8	1,085	93.6	48.3
Grand Hogback and Carbondale	12,000	947[c]	83.3	34.7	1,045[c]	90.4	37.7	1,149[c]	99.7	41.6

[a] Assumes new 5-mile spur from main line to powerplant site and, for all sources except Kaiparowits, Grand Hogback, and Carbondale, a new 10-mile spur from coal source to main line.

[b] Assumes new 17-mile spur from main line to powerplant site.

[c] Assumes new 15-mile spur from coal source to main line.

[d] Route 20

[e] Reference 43

[f] Reference 44

[g] Reference 45

[h] Reference 46

Coal Slurry Pipeline Costs

Table 11 shows the results of applying the slurry pipeline cost models to the hypothetical pipeline routes shown in Figure 4. Shipment of 10 million tons per year would cost about $50 million per year.

Comparison of Rail and Slurry Transportation Costs

It is beyond the scope of this Bulletin to compare rail and slurry pipelines in general. Indeed, as recent studies for the U.S. Congress have shown,[6,7] generalizations made from route-specific economic and environmental analyses are likely to be invalid. Table 12 shows three measures of the cost of transporting 10 million tons per year from Kaiparowits to Southern California by the two modes. By the measure of dollars per ton--which is of most concern to the utility receiving the coal--the slurry pipeline alternative is decidedly cheaper. Indeed, for Cadiz and Blythe, the slurry cost would be less than half that for railroad shipment. The decisive factors in the advantage of slurry pipeline transportation in this case were the pipeline's shorter distance and the need for extensive new rail construction. This was discovered by running the model for the same respective rail and slurry pipeline distances but without any new rail, tunnel, or bridge construction. For any throughput up to about 7 million tons per year, rail shipment is less expensive; at all higher throughputs, slurry pipelines are cheaper.

When rail and slurry pipeline costs are compared on the basis of mills per ton-mile, the cost differential is much smaller; indeed, for shipment to Cadiz and Blythe, rail ton-mile costs are lower than those for pipelines. This is a prime example of the danger of using the ton-mile measure

Table 11: Slurry Pipeline Transportation Costs, Kaiparowits to Southern California

Destination	Route Length (miles)	Annualized Capital Cost (millions of dollars per year)	Operating Cost (millions of dollars per year)	Total Annual Cost (millions of dollars per year)
Barstow	395	32.4	21.5	53.9
Cadiz	350	29.5	20.6	50.1
Blythe	370	30.8	21.0	51.8

Table 12: Comparison of Rail and Slurry Transportation Costs, Kaiparowits to Southern California

Destination	Cost (dollars per ton)		Cost (mills/ton-mile)		Capital Investment (millions of dollars)	
	Rail	Slurry	Rail	Slurry	Rail	Slurry
Barstow	10.19	5.39	14.5	13.6	435	216
Cadiz	10.94	5.01	13.6	14.3	452	197
Blythe	11.69	5.18	12.8	14.0	471	205

to compare costs of different transportation modes. Here rail ton-mile costs are lower simply because the cost in mills per ton is divided by a larger distance than that for pipelines.

Finally, the initial capital investment cost for rail transportation would be about twice that for pipelines. In this case, due to the extensive rail construction, the annualized capital cost represents about the same percentage of the total annual cost (60 percent) for each transportation mode.

DISCUSSION

Development of the coal resources of the Kaiparowits Plateau will require either extensive new rail construction or a new coal slurry pipeline. In this particular case, the slurry alternative would be significantly cheaper, in terms of both capital investment requirements and annual costs. Rail transportation from Kaiparowits would be more expensive than transportation from other western coal sources, although other factors could compensate somewhat for this disadvantage. For example, other coal deposits may already be committed to other markets. Long-term, low-price contracts for coal purchase might be arranged (although such arrangements are not now made for rail movements), so that the sum of purchase and transportation costs may be competitive. For example, while Kaiparowits coal is not in commercial production, it may be reasonably assumed that its mine-mouth cost would be comparable to, and slightly higher than, the cost of coal from the Book Cliffs, Utah, coalfield.[47] This price, when escalated at 6 percent per year to 1977 dollars, would be $0.515 per million Btu. The total delivered fuel cost at

Barstow would thus be \$0.94 per million Btu, which, though comparatively high, is by no means unreasonable in today's energy market. Using the energy conversion assumptions given in the Introduction, one finds that the total fuel cost to a powerplant would be about 9 mills per kWh.

One topic which this Bulletin has not addressed is that of the "soft costs" of coal transportation.[48] These are defined as costs which are not readily quantifiable yet which may still heavily influence decision-making. For example, while coal slurry pipelines are demonstrably cheaper in this case, it may be legally or politically impossible to obtain the necessary 6,000 acre-feet per year of water and transport it from an Upper Colorado River Basin state to a Lower Basin state. The extensive new rail, tunnel, and bridge construction may incur a number of environmental impacts;[6] impact statements must be prepared and filed, and delays could add to the construction cost. Other soft-cost considerations are the use of diesel fuel for railroads versus electrical energy for pipeline operations; the greater potential of railroads for regional growth stimulation in areas presently unserved by major transportation networks;[49] and the certainty of long-term pipeline contracts versus the short-term nature of rail tariff agreements.

FOOTNOTES

1. Doelling, H. H., and R. L. Graham, "Kaiparowits Plateau Coal Field," Southwestern Utah Coal Fields--Alton, Kaiparowits Plateau and Kolob-Harmony, Utah Geological and Mineralogical Survey Monograph Series No. 1, page 102, 1972.

2. Carey, D. L., M. B. Rogozen, R. R. Purtich, and O. L. Anderson, editors, Study of Alternative Locations of Coal-Fired Electric Generating Plants to Supply Energy

From Western Coal to the Department of Water Resources, Institute of Geophysics and Planetary Physics and Environmental Science and Engineering Program, University of California, Los Angeles, for the California Department of Water Resources and the California Energy Resources Conservation and Development Commission, 1977.

3. Reference 1, page 93.

4. Numerous economic analyses have shown coal slurry pipelines to be noncompetitive with railroads when throughputs and haulage distances are small. As will be seen later in this Bulletin, the break point above which a Kaiparowits-Southern California pipeline would be less expensive than a railroad requiring no new construction is about 7 million tons per year.

5. Allan Boyce, Burlington Northern Railroad, St. Paul, Minnesota; discussion with author, Colorado Springs, Colorado, August 15, 1977.

6. Rogozen, M. B., L. W. Margler, M. K. Martz, and D. F. Hausknecht, *Environmental Impacts of Coal Slurry Pipelines and Unit Trains*, Final Report, Science Applications, Inc., for U.S. Congress, Office of Technology Assessment, November 1977.

7. Sauder, P. M., et al., *A Study of the Competitive and Economic Impact Associated with Coal Slurry Pipeline Implementation*, Draft Final Report, General Research Corporation and International Research and Technology Corporation for U.S. Congress, Office of Technology Assessment, October 1977.

8. Reference 2, pages 4-6 to 4-18.

9. Aude, T. C., T. L. Thompson, and E. J. Wasp, "Economics of Slurry Pipeline Systems," *Third International Conference on the Hydraulic Transport of Solids in Pipes*, British Hydromechanics Research Association, Bedford, England, 1974, page K2-22.

10. Reference 2, pages 9-11 to 9-21.

11. The train speeds reported here are based upon several discussions with officials of the Burlington Northern and Denver and Rio Grande Western Railroads during August and September 1977. Speeds would vary considerably over the routes assessed in this Bulletin.

12. Based upon site visit to Belle Ayr and Cordero mines near Gillette, Wyoming, August 15, 1977, and to the Comanche Generating Station, Pueblo, Colorado, August 16, 1977.

13. Buck, P., and N. Savage, "Determine Unit-Train Requirements," Power, 118(1), 1974, pages 90-91.

14. Allan Boyce, Burlington Northern Railroad, St. Paul, Minnesota; discussion with author, Gillette, Wyoming, August 15, 1977.

15. A Report to the Interagency Task Force, A Project Independence Blueprint, on the Modal Transportation Costs for Coal in the United States, Batelle Columbus Laboratories for TRW Systems, Inc., 1974, page 67. The 1974 cost for rail, ties, plates, spikes, anchors, ballast, labor, and signalling was $238,000 per mile. This was inflated to January 1977 dollars by applying construction cost indexes reported in U.S. Department of Commerce, Bureau of Economic Analysis, Survey of Current Business.

16. Ferguson, J. A., "Unit Train Transportation of Coal," Appendix E of The Coal Future: Economic and Technological Analysis of the Initiatives and Innovations to Secure Fuel Supply Independence, Center for Advanced Computation, University of Illinois, Urbana, 1975, page 28.

17. This was concurred in by Allan Boyce of the Burlington Northern Railroad. See Reference 14.

18. Reference 2, page 9-14.

19. Reference 6, page B-49. Note that this rail is moved to branch or yard service or is recycled.

20. Reference 7, page A-26.

21. Federal Energy Administration, Project Independence Blueprint, Final Task Force Report, Analysis of Requirements and Constraints on the Transport of Energy Materials, Vol. II, 1974.

22. Reference 7, page A-20.

23. Estimated from data in Reference 7, page A-22. It is assumed that coal will go to one destination.

24. Leilich, R. H., and J. Williams, Freight Car Requirements for Transporting Energy, 1974 to 1985, Peat, Marwick and Mitchell for the Federal Energy Administration, U.S. Department of Commerce and U.S. Department of Transportation, 1974.

25. Thomas A. Arnold, Denver and Rio Grande Western Railroad Company, Denver, Colorado, telephone conversation with author, September 30, 1977.

26. Reference 7, page A-25.

27. Reference 7, page A-18.

28. Reference 7, page A-21.

29. Reference 7, page A-23.

30. Reference 7, page A-19.

31. Reference 6, page B-4.

32. Dina, M. L., "Operating Experience at the 1580-MW Coal Slurry Fired Generating Station," presented at the International Conference on Slurry Transportation, Battelle Memorial Institute, Columbus, Ohio, February 3, 1976.

33. Reference 6, page B-4.

34. Reference 7, page A-47.

35. Derived from graph in Reference 7, page A-56.

36. Preparation and dewatering costs were scaled to a base cost for 10 million tons per year of coal. Scaling is based upon the ratio (throughput/10 million tons) raised to the 0.8 and 0.9 power, respectively. See Reference 7, pages A-50, A-51, and A-53, for details.

37. Pump station spacing can be anywhere from 50 to 100 miles, depending upon terrain, according to Edward J. Wasp, Vice President, Energy Transportation Systems, Inc., San Francisco, California; discussion with author, Washington, D.C., October 26, 1977.

38. Reference 7, page A-53.

39. Reference 7, pages A-57, A-58, and A-63.

40. Reference 6, page B-11.

41. Kohler, M. A., T. J. Nordenson, and R. D. Baker, Evaporation Maps for the United States, U.S. Weather Bureau Technical Paper 37, 1959, and Linsley, R. K., and J. B. Franzini, Water-Resources Engineering, McGraw-Hill Book Company, New York, 1964.

42. Reference 7, page A-59.

43. Doelling, H. H., "Coal in Utah - 1970," in H. H. Doelling, editor, Central Utah Coal Fields, Utah Geological and Mineralogical Survey Monograph Series No. 3, 1972, p. 548.

44. Kottlowski, F. E., E. C. Beaumont, and J. W. Shoemaker, "New Mexico," in Mining Information Services, 1974 Keystone Coal Industry Manual, McGraw-Hill Mining Publications, New York, 1974, p. 526.

45. Reference 2, page 3-88.

46. Average of ranges given in Reference 2, page 3-76.

47. Reference 2, page 3-45.

48. Reference 2, pages 9-1 and 9-2.

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50. Anonymous, "Santa Fe: Mapping a New 70-Mile Line," Railway Age, 177(5), 1976, page 28.

51. Woody, R. H., "Carbon-Emery Rails Seen," The Salt Lake Tribune, February 13, 1976.

52. Halliday, R. S., "Kaiparowits Mulling 190-Mile Rail Line," The Salt Lake Tribune, November 16, 1975, page 10D.

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GLOSSARY

algorithm	a computational procedure
British thermal unit (Btu)	a unit of energy, defined as the quantity of heat required to raise the temperature of one pound of water by one degree Fahrenheit
busbar	a connecting bar carrying heavy electrical current to supply several electrical circuits; in this Bulletin, "busbar costs" are those for electricity at the point where it leaves the powerplant, before transmission elsewhere
dewatering facility	a facility for separating coal from water at the end of a slurry pipeline; may consist of centrifuges, filters, etc.
hopper car	an open-top railroad car used for transporting bulk commodities such as coal, grain, ore, or gravel
load factor	the fraction of the time that a facility, such as a powerplant or slurry pipeline, is in operation
mill	one-thousandth of a dollar; one cent equals 10 mills
single track	a set of two rails, ties, and ballast
slurry	a suspension of a finely divided solid such as coal or iron ore in a liquid, such as water
slurry pipeline	a pipeline used to transport a suspension of solids in a carrier medium such as water
throughput	the quantity of material passing through a system; e.g., a pipeline may have a throughput of 10 million tons per year of coal

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