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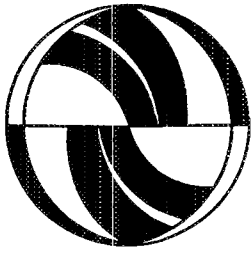
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**A Cointegration Rank Test of  
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**The University of California  
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**A Cointegration Rank Test of Market Linkages with an  
Application to the U.S. Natural Gas Industry**

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**UCTC No. 201**

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### **Abstract**

This research applies recently developed cointegration techniques to the measurement of market linkages when the data are nonstationary. Likelihood based tests for cointegration are applied to data from natural gas spot markets. The results indicate that natural gas spot markets at dispersed locations in the pipeline network are strongly connected. Most of the market pairs examined in the gas pipeline network satisfy a more stringent condition for perfect market integration.

**Key Words:** Market Linkages, Unit Roots and Cointegration.

## I. Introduction

The relationship between geographically separate markets is often evaluated on the basis of price differentials. The magnitude of the price differential and its time varying properties indicate the efficacy of potential arbitrage at disciplining prices across locations. When the pattern of prices is such that there exist no profitable arbitrage opportunities, the spatially separate markets are said to be integrated together.<sup>1</sup> Such an arbitrage-proof pattern of prices is characteristic of allocative efficiency.

In the simplest characterization of spatial market integration the price in the first market,  $p_1$ , is said to differ from the price in the second market  $p_2$ , by transportation cost  $t_{1,2}$  at each point in time. A test of whether the two prices are drawn from the same market is often based on the estimable model

$$p_{1,t} = \beta_0 + \beta_1 p_{2,t} + \mu_t \quad (1)$$

where  $\mu_t$  is a random disturbance that is independently and identically distributed with zero mean and finite variance.<sup>2</sup> In the case of perfect market integration, the market price at each location reflects all available information such that there exists no strategy from which traders can profit consistently by buying a commodity at one location and selling at another. This definition of market integration implies the testable restriction that  $\beta_1 = 1$  in equation (1). A less stringent definition of market integration would let  $\beta_1$  differ from 1 by only a small amount. This less stringent definition implies the testable restriction that  $|\beta_1 - 1| \leq c$  for some arbitrary constant  $c$ . For example, if  $c$  were set equal to 0.1 and the marginal significance level were 5%, this definition would restrict  $\beta_1$  to lie in the closed interval  $[0.9, 1.1]$  with at least 95% probability.<sup>3</sup>

The method used to test the parameter restriction on  $\beta_1$  depends on whether the price series are stationary or not. The asymptotic distribution theory used to construct a test statistic is valid only when the data are stationary. When the price series are not stationary, asymptotic statistical inference cannot be made. Granger (1986) finds that many economic time series are not stationary and that they contain a unit root. When the data are nonstationary, the usual  $t$ -test of the hypothesis that  $\beta_1 = 1$  is not valid.<sup>4</sup>

Recently, the theory of cointegration as developed by Granger (1986) and Engle and Granger (1987) has been used to test for market integration when the data are nonstationary.<sup>5</sup> The cointegration method accounts for the nonstationarity of the data and has intuitive appeal as well: the nonstationarity of the first series explains the nonstationarity of the second series. The Engle-Granger cointegration test for an equilibrium relationship between  $p_1$  and  $p_2$  consists of two steps: first estimate equation (1), the cointegrating regression that specifies the long-run equilibrium between the two prices; second, test the residuals of the cointegrating regression for stationarity using a unit root test. If the residuals are stationary, the null hypothesis of no cointegrating relationship between  $p_1$  and  $p_2$  is rejected. While this procedure allows cointegration to be tested, it does not allow inference to be made directly on the parameters of the cointegrating regression. The least-squares estimator of the cointegrating parameters is consistent, but making inference on the parameters based on the estimated standard errors can be misleading (Stock, 1987). This limitation decreases the usefulness of the Engle-Granger cointegration procedure in this application, because testing parameter restrictions on  $\beta_1$  is of primary interest.

Johansen (1988,1991) and Johansen and Juselius (1990) develop and demonstrate a new method for analyzing a set of cointegrated variables; the new method can be used to test for market linkages. Johansen's test for cointegration is based on the method of maximum likelihood and allows inference to be made on the cointegrating parameters using likelihood ratio tests. The method also allows the rank of the cointegrating relationship to be tested. This allows inference to be made on the number of cointegrating relationships in the set of variables. Johansen's procedure is further distinct from the Engle-Granger procedure because it specifies the full vector autoregression model. The vector autoregression model characterizes the joint distribution of the data without imposing *a priori* structural relations. Economic hypotheses can then be tested as parameter restrictions using likelihood ratio statistics.

## II. Cointegration and Market Linkages

A time series is integrated of order  $d$  if the series is stationary after being differenced a minimum of  $d$  times; such a series is denoted  $I(d)$ . By definition an  $I(0)$  series is stationary. An  $I(1)$  series is nonstationary and must be differenced one time to obtain a stationary series. A common example of an  $I(1)$  series is a random walk. When the price in market 1,  $p_1$ , and the price in market 2,  $p_2$ , are both  $I(1)$ , their linear combination

$$\mu_t = p_{1,t} - \beta_0 - \beta_1 p_{2,t} \quad (2)$$

would generally also be an  $I(1)$  series. However, if there exists a parameter vector  $(\beta_0, \beta_1)$  such that  $\mu_t$  is stationary, then  $p_1$  and  $p_2$  are defined to be cointegrated. The cointegrating or equilibrium relationship between  $p_1$  and  $p_2$

$$p_{1,t} - \beta_0 - \beta_1 p_{2,t} = 0 \quad (3)$$

represents the long-run equilibrium error between the two price series. In this light, the cointegration relation between the two price series can be viewed as a partial adjustment or “error correction” model. It is useful to discuss briefly the error correction model since Johansen’s cointegration analysis is expressed in this form.

Engle and Granger (1987) show that if the null hypothesis of noncointegration cannot be rejected, an error correction model of the cointegrated price series is appropriate. For example, the error correction model for  $p_1$  could be expressed as a least-squares regression of changes in  $p_1$  on past changes in  $p_1$  and  $p_2$ , and on lags of the residual from the cointegrating regression:

$$\Delta p_{1,t} = \sum_{i=1}^k A_i \Delta p_{1,t-i} + \sum_{i=1}^k B_i \Delta p_{2,t-i} + C \hat{\mu}_t + \epsilon_t \quad (4)$$

where  $\Delta$  is the difference operator,  $\epsilon_t$  is a random disturbance,  $\hat{\mu}_t$  is the estimated residual from the cointegrating regression, and  $A, B$ , and  $C$  are parameters. An analogous regression equation could be expressed for the changes in  $p_2$ . The intuition that underlies the error correction formulation is clear: agents react to prior deviations from equilibrium,  $\hat{\mu}_t$ , causing the current period change in the cointegrated price series.



Cointegration is a necessary condition for two price series to have been drawn from the same market. The implication is that  $p_2$  will be a good predictor of  $p_1$ . If the two price series are not cointegrated, then  $\mu_t$  will be nonstationary; this implies that  $p_1$  and  $p_2$  would tend to drift apart widely (Engle and Granger, 1987, p. 253). Clearly, this is inconsistent with the hypothesis that the two price series were generated in the same market since arbitrage between the two markets would bound the difference in prices.

Cointegration is a necessary but not a sufficient condition for market integration. Market integration requires that the estimated price adjustment parameter  $\beta_1$  satisfy the condition  $|\beta_1 - 1| \leq c$  where  $c$  is an acceptably small number; in the case of perfect market integration  $c$  would be equal to zero. However, the price series could move closely over time and still not come from the same market. So, the test for market integration must combine cointegration testing and testing restrictions on the model's parameters. The Engle-Granger method for testing cointegration is not applicable to the latter problem, since the distribution of the least-squares estimator of the cointegrating parameters is unknown. However, Johansen's procedure allows general linear restrictions on the cointegrating parameters to be tested using a likelihood ratio test and his method is applied in this study.

### III. Empirical Method

Cointegration allows estimation and testing on a long-run equilibrium relationship in the presence of short-run deviations from equilibrium. Johansen's method tests for cointegration within a larger vector autoregressive (VAR) model that incorporates the relationships between the system of economic variables. The VAR model describes the variation in the data without restriction. Johansen has shown that the test for cointegration can be expressed as a test of reduced rank of a regression coefficient matrix. The coefficient matrix can be estimated consistently using linear regression techniques and the test statistic can be computed from the solution to an eigenvalue problem (eqn. 10 below). Additionally, linear restrictions on the cointegrating parameters can be tested by computing a likelihood ratio test statistic which follows a  $\chi^2$  distribution.

The basic unrestricted vector autoregressive model of prices can be written as<sup>6</sup>

$$P_t = \sum_{i=1}^k A_i P_{t-i} + \gamma + \mu_t \quad (5)$$

where  $P_t$  is an  $n \times 1$  vector of prices, the  $A_i$  are  $n \times n$  parameter matrices,  $\gamma$  is a vector of constants, and  $\mu_t$  is a vector of stochastic disturbances distributed independently and identically with mean zero and finite variance. The price series contained in  $P_t$  are assumed to be  $I(1)$  as this is required for the statistical procedures discussed here to be valid; the price series are tested for this property in the empirical results section.

To distinguish between stationarity achieved by forming linear combinations and that achieved by differencing, the model can be written in the error correction form as

$$\Delta P_t = \sum_{i=1}^{k-1} \Gamma_i \Delta P_{t-i} + \Gamma_k P_{t-1} + \gamma + \mu_t \quad (6)$$

where  $\Delta$  is the difference operator. Johansen (1989, 1990) has shown that the coefficient matrix  $\Gamma_k$  contains sufficient information to determine the cointegrating relationships between the variables: the rank of  $\Gamma_k$  is the number of cointegrating relationships between the variables in  $P_t$ . In testing for cointegration between 2 time series,  $P_t = (p_{1,t}, p_{2,t})'$  and the hypothesis of cointegration between the elements of  $P_t$  is equivalent to the hypothesis that the rank of  $\Gamma_k = 1$ . If the rank of  $\Gamma_k$  were less than 1, then the variables in  $P_t$  are not cointegrated with one another.

Johansen's procedure begins with estimation of the following two regression equations

$$\Delta P_t = \sum_{i=1}^{k-1} \Gamma_i \Delta P_{t-i} + \mu_{1t} \quad (7)$$

$$P_{t-k} = \sum_{i=1}^{k-1} \Gamma_i \Delta P_{t-i} + \mu_{2t}. \quad (8)$$

Define the product moment matrices of the regression residuals to be  $S_{ij} = \sum_{t=1}^T \hat{\mu}_{it} \hat{\mu}_{jt}' \forall i, j = 1, 2$ . The likelihood function, concentrated with respect to  $\Gamma_1, \dots, \Gamma_{k-1}$ , can be expressed in terms of  $\Gamma_k$  and the  $S_{ij}$  matrices.

Johansen has shown that the likelihood ratio test statistic for the null hypothesis of at most  $r$  cointegrating relationships can be written as

$$-2 \ln Q(r) = -T \sum_{i=r+1}^n \ln(1 - \lambda_i) \quad (9)$$

where  $\lambda_1 > \dots > \lambda_n$  are the eigenvalues that solve the equation

$$|\lambda S_{22} - S_{21} S_{11}^{-1} S_{12}| = 0.^7 \quad (10)$$

The likelihood ratio statistic  $-2 \ln Q(r)$  converges in distribution to  $(n - r)$ -dimensional Brownian motion. This distribution is nonstandard and must be generated through simulation. Johansen and Juselius (1990) and Osterwald-Lenum (1992) tabulate the quantiles of the distribution for  $n - r = 1, \dots, 5$  and  $n - r = 1, \dots, 10$ , respectively.

The maximum likelihood estimate of the cointegrating vector is the first eigenvector of  $S_{21} S_{11}^{-1} S_{12}$  with respect to  $S_{22}$ . The test for market integration can be expressed as a test of a linear restriction on the cointegrating vector: the restriction is that  $\beta_1 = 1$ . The hypothesis can be represented by a matrix of linear restrictions on the cointegrating vector  $\beta$

$$H_0 : \beta = H \pi \quad (11)$$

where  $H$  is the matrix of linear restrictions and  $\pi$  is a matrix of unknown parameters. In general Johansen (1988, 1991) and Johansen and Juselius (1990) show that the likelihood ratio statistic for  $H_0$  is given by

$$-2 \ln Q(H) = -T \sum_{i=1}^r \ln \left( \frac{1 - \lambda_i}{1 - \lambda'_i} \right) \quad (12)$$

where  $\lambda'_1 > \dots > \lambda'_n$  are the eigenvalues of  $H' S_{21} S_{11}^{-1} S_{12} H$  with respect to the matrix  $S_{22}$ .

## IV. An Application to Natural Gas Markets

Since the Federal Energy Regulatory Commission permitted gas pipelines to function as contract carriers in 1985, natural gas spot markets have flourished. Prior to that time, gas pipelines were merchant carriers; as merchants they were required to own the gas that they transported and could

not transport gas on behalf of other parties. Customers could only purchase gas from the pipeline to which they were connected.<sup>8</sup> Now that pipelines are contract carriers, the natural gas market functions much like any other product market: the good is bought and it is shipped. The linkages between geographically separate natural gas spot markets are quantified using the cointegration methods discussed in the previous section.

Natural gas spot market prices at twenty nodes throughout the U.S. gas pipeline network are tested for cointegration and for market integration during 1989–1990. The twenty nodes are located within six geographic regions: West Texas-Waha, East Texas-Houston/Katy, South Texas-Corpus Christi, North Texas-Panhandle, Oklahoma-Beaver County, and South Louisiana-Onshore. Eleven major interstate pipelines are represented in the sample and Table 1 lists the markets where prices were obtained by geographic region and by pipeline company. The data consist of daily observations on the spot price and were obtained from the *Gas Daily*, an industry periodical. The data are based on prices for injection into the pipeline at the location for which the price is listed. The prices are reported on a dollar per million Btu basis for spot deals with a duration of 30 days or less, and they account for the quality of the gas because they are quoted as dollars per unit of thermal energy (\$/MMBtu).

Each price series is tested for a unit root using the augmented Dickey-Fuller (ADF) test (Dickey and Fuller, 1979). The  $ADF(\rho)$  test for each series  $p_t$  is given by the  $t$ -statistic for  $\phi$  in

$$\Delta p_t = \phi p_{t-1} + \sum_{i=1}^{\rho} \beta_i \Delta p_{t-i} + \mu_t \quad (13)$$

where  $\Delta$  is the difference operator. The  $t$ -statistic on  $\phi$  is compared to the Monte Carlo generated critical values reported by MacKinnon (1990). Table 1 reports the results of the unit root test for  $\rho = 1$  and  $\rho = 4$ . The null hypothesis of a unit root could not be rejected for any of the price series and this conclusion is not sensitive to the number of lagged residuals included in the ADF testing equation.<sup>9</sup> In addition, the ADF test was performed on the first differences and the results showed that the first differences of the price series are stationary. These results indicate that all of the natural gas price series analyzed are  $I(1)$ .

Due to the large number of price series involved, the ANR pipeline located in the Louisiana Onshore region was selected as a base node for comparison. This node is located at the primary hub of the gas pipeline network and near the delivery point for the natural gas futures contract.<sup>10</sup> Each pair of price series was tested for cointegration using Johansen's procedure.<sup>11</sup> Then, the parameter restriction that  $\beta_1 = 1$  was tested for each pair of price series. The results of the tests of cointegration and of parameter restrictions are reported in Table 2.

The null hypothesis of no cointegration was rejected at the 5% significance level for all market pairs. This is strong evidence that these natural gas spot markets are tightly linked together.<sup>12</sup> Moreover, even at the 1% marginal significance level, the null hypothesis of no cointegration can be rejected for seventeen of the nineteen market pairs. Also note that the  $-2\ln Q(r)$  statistic is especially large for the cointegration tests between the ANR pipeline and other pipelines in Louisiana.

While the evidence indicates that all of the market pairs are cointegrated, not all market pairs satisfy the stringent condition for perfect market integration. At the 5% significance level, the null hypothesis of perfect market integration ( $\beta_1 = 1$ ) can be rejected for six of the nineteen market pairs. In the thirteen market pairs where the perfect market integration hypothesis is not rejected, the marginal significance levels ( $p$ -values) range from 0.1103 to 1. High  $p$ -values indicate, in intuitive units, how far we are from rejecting the null hypothesis.<sup>13</sup> At the 1% significance level, we can reject perfect market integration for only one market pair: The ANR Pipeline in Louisiana and the Tennessee Pipeline in East Texas.

The pattern of the  $\chi^2$  statistics across various regions indicates that the spot market on the ANR pipeline in Louisiana is strongly linked to the markets in North Texas, Oklahoma, and the other Louisiana markets. With only one exception (Trunkline pipeline in East Texas) the perfect market integration hypothesis is rejected between ANR in Louisiana and spot markets located on pipelines in South, East, and West Texas. A further observation is that the ANR pipeline in Louisiana is tightly integrated with all pipelines in regions where ANR has at least one pipeline. This pattern of market link-

ages suggests that it may be difficult for ANR customers to execute certain inter-pipeline gas shipments to regions where ANR has no physical presence.

## V. Conclusion

Price series from spatially separate commodity markets may be nonstationary. For such price series, it is now widely accepted that conventional hypothesis testing procedures are not appropriate; cointegration tests are the appropriate method when the data are nonstationary. This research argues that the cointegration methodology developed by Johansen (1988, 1991) is the most fruitful way to test for spatial market linkages. The test for market integration is illustrated with an application to the natural gas spot markets located across the North American pipeline grid. Overall, the empirical findings show that the pipeline network connects the various spot markets such that gas prices at dispersed locations are cointegrated with one another. In the majority of market pairs examined, the hypothesis of perfect market integration could not be rejected; however, a distinct geographic pattern emerged from the market pairs in which market integration was rejected.

## Notes

1. It is important to understand the particular market institutions before making inference on the linkages between geographic markets. Prices at separate locations may be clearly linked even if there is no direct arbitrage taking place. For example, retail gasoline prices in Philadelphia may be highly correlated to those in Los Angeles even though gas stations do not compete for the same customers.
2. Stigler and Sherwin (1985) use this model as a way to describe “the extent of the market” by examining the correlation between prices and various transformations of prices. Making inference on a correlation gives the same  $t$ -statistic as making inference on the slope parameter in a bivariate regression with a constant term.
3. I am indebted to an anonymous referee for suggesting this more general way of quantifying the strength of market integration.
4. Monte Carlo results reported by Elam and Dixon (1988) for futures markets indicate that this incorrect test would be biased towards rejecting the hypothesis that the two prices are from the same market.
5. For studies that apply Engle-Granger cointegration tests see Ardeni (1989), Goodwin and Schroder (1991), Bessler and Covey (1991), Chowdhury (1991), and DeVany and Walls (1993).
6. This exposition of Johansen’s method of analyzing cointegrated systems closely follows Juselius (1991).
7. The eigenvalues can be found by solving the characteristic equation

$$|\lambda I - S_{22}^{-1/2} S_{21} S_{11}^{-1} S_{12} S_{22}^{-1/2}| = 0.$$

8. In the industry parlance, contract carriers are called *open access* pipelines. See Smith *et al.* (1987,1990) for the definitive study of merchant carriage in the gas pipeline industry and the original proposal for open access applied to natural gas pipelines. See De Vany and Walls (1992) and Walls (1992) for a detailed empirical and institutional analysis

of how natural gas commodity and transportation markets coordinate with one another under the open access system.

9. The augmented Dickey-Fuller test was also performed with a time trend; this did not alter the results reported in Table 1. Also, the Phillips-Perron unit root test (Phillips, 1987; Phillips and Perron, 1988) and the Bayesian odds ratio unit root test (Sims, 1988) gave the same qualitative results as the ADF test; this indicates that the results are robust to the particular testing methodology employed.
10. The delivery point of the natural gas futures contract listed on the New York Mercantile Exchange is located on Sabine Pipe Line Company's Henry Hub near Erath, Louisiana.
11. The optimal number of lags,  $k$ , to include in each model was determined by the Akaike (1973) information criteria.
12. These results indicate that the cointegration relations between natural gas spot market prices are stronger than previous empirical results have shown. Using Engle-Granger cointegration tests, De Vany and Walls (1993) found that the ANR pipeline in Louisiana was cointegrated with 10 out of 19 other pipeline nodes at the 5% marginal significance level. The results of Johansen's cointegration tests reported here would strengthen their conclusion that the Federal Energy Regulatory Commission's policy of open access has made natural gas markets more competitive.
13. Care must be taken in interpreting the  $p$ -values. Following the Neyman-Pearson theory of hypothesis testing, failure to reject a null hypothesis does not imply that the alternative hypothesis can be rejected and the null accepted. Furthermore, the size of the test provides no information about the confidence with which one can "accept" a null hypothesis.



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Table 1: Unit Root Tests on Daily Natural Gas Price Series

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$$\Delta p_t = \phi p_{t-1} + \sum_{i=1}^{\rho} \beta_i \Delta p_{t-i} + \mu_t$$


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Node	$\hat{\phi} \times 10^3$	$\frac{\rho=1}{t}$	$\hat{\phi} \times 10^3$	$\frac{\rho=4}{t}$
<u>West Texas</u>				
El Paso	-0.698	-0.382	-0.709	-0.388
Transwestern	-0.868	-0.426	-0.879	-0.433
<u>East Texas</u>				
NGPL	-1.016	-0.572	-1.001	-0.561
Tennessee	-0.653	-0.423	-0.639	-0.410
Trunkline	-0.754	-0.431	-0.749	-0.428
<u>North Texas</u>				
ANR	-0.438	-0.255	-0.447	-0.259
NGPL	-0.739	-0.343	-0.739	-0.341
Northern	-1.183	-0.504	-1.183	-0.501
Panhandle	-0.503	-0.307	-0.510	-0.310
<u>South Texas</u>				
NGPL	-0.664	-0.378	-0.664	-0.376
Tennessee	-1.175	-0.687	-1.183	-0.689
<u>Louisiana</u>				
ANR	-0.704	-0.424	-0.689	-0.418
Columbia	-0.704	-0.405	-0.698	-0.399
Tennessee	-0.665	-0.411	-0.658	-0.405
Texas Gas	-0.652	-0.445	-0.636	-0.435
Trunkline	-0.784	-0.402	-0.803	-0.414
United	-0.878	-0.489	-0.859	-0.478
<u>Oklahoma</u>				
ANR	-0.558	-0.317	-0.558	-0.315
NGPL	-0.715	-0.340	-0.715	-0.338
Northern	-0.971	-0.419	-0.971	-0.416

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MacKinnon Critical Values for the  $t$ -statistics:

-2.571 (1%); -1.941 (5%); -1.616 (10%).

Table 2: Cointegration Test Results

Base Node = ANR Pipeline in Louisiana					
Node	k	H: $\tau = 0$	$\hat{\beta}_1$	H: $\beta_1 = 1$	
		$-2 \ln Q(r)$		$\chi^2$	p-value
<u>West Texas</u>					
El Paso	3	37.28	0.85	5.89	0.0152
Transwestern	3	26.42	0.88	5.31	0.0212
<u>East Texas</u>					
NGPL	3	44.24	0.75	5.05	0.0246
Tennessee	3	70.93	0.85	7.34	0.0067
Trunkline	2	83.66	0.86	0.53	0.4666
<u>North Texas</u>					
ANR	4	28.97	0.83	2.46	0.1168
NGPL	2	50.95	0.85	2.14	0.1435
Northern	2	29.34	0.85	2.25	0.1336
Panhandle	3	22.59	0.87	2.55	0.1103
<u>South Texas</u>					
NGPL	3	58.22	0.73	5.26	0.0218
Tennessee	3	82.49	0.78	6.62	0.0102
<u>Louisiana</u>					
ANR	—	—	—	—	—
Columbia	2	83.84	0.92	0.48	0.4884
Tennessee	2	98.38	0.95	0.45	0.5023
Texas Gas	2	123.95	1.01	0.00	1.0000
Trunkline	3	54.40	1.21	0.61	0.4348
United	2	90.90	0.92	0.49	0.4389
<u>Oklahoma</u>					
ANR	2	27.09	1.31	0.45	0.5023
NGPL	2	101.61	1.27	0.96	0.3272
Northern	3	24.75	1.58	1.12	0.2899

For each pair of nodes, the null hypothesis of no cointegration is rejected. The critical values for the  $-2 \ln Q(r)$  statistic are 19.796 (10%), 21.894 (5%), and 26.409 (1%). The test statistic for  $H_0: \beta_1 = 1$  follows a  $\chi^2$  distribution with one degree of freedom. The critical values are 2.71 (10%), 3.84 (5%), and 6.63 (1%).