are listed in Table 1. The values of δW were calculated with $\theta = 0.5$, which appears to be the optimum for all three processes. As is shown in Table 1 for the separation of uranium hexafluorides, the proposed new technique may give a value of δW about 500 times higher than the gaseous diffusion process and 100 times higher than the curved-jet process.

A complete analysis of the economics of the separations must include the energy inputs and the capital and maintenance costs. In the velocity-slip process some of the gas will be lost if the beam is passed through a skimmer and a collimator. In conventional nozzle systems the fraction passed by the skimmer may be as low as 1 percent (*5*). However, with the type of radial velocity selector we described above, it may not be necessary to collimate the beam, so nearly all the molecules in the jet will enter the velocity selector. For the gaseous diffusion process the separated streams must be compressed to the initial pressure of the feed to each stage. In both the velocity-slip and curved-jet processes the separated streams of UF_6 plus light gas must be recompressed at a much higher pressure ratio. However, the much higher values of $\alpha - 1$ and δW per stage in the velocity-slip process offset the advantage of a lower pressure ratio and gas flow in the gaseous diffusion process, even if the total molar flow is 100 times the UF_6 flow and the pressure ratio required is 100 times greater than for the gaseous diffusion process. Thus, the velocity-slip process is estimated to require a lower energy input per unit of separative work obtained than either the gaseous diffusion process or the curved-jet process.

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Energy Conservation Policies of the Federal Energy Office: Economic Demand Analysis

Abstract. *Forecasts for crude petroleum consumption are presented which take into account attempts by the Federal Energy Office to regulate residential and commercial thermostats. On the basis of an economic demand model, it is found that lowering all thermostats by 6°F would lower the projected residential and commercial petroleum demand in 1973 by 12 percent. This amount is compared to forecasts made by the Federal Energy Office and to the effect of a price increase of $0.10 per gallon for heating oil.*

An important component of federal energy conservation policy is the recommendation that residential and commercial thermostat settings be lowered by 6°F (*1*). This recommendation was based primarily on engineering heat loss studies and some tersely specified statistical analyses that tended to ignore fundamental economic considerations (*1, 2*). In this report we describe an economic demand study that includes ambient indoor temperature as an explanatory variable. We then use this model to evaluate the likely impact of the 6°F policy on the demand for crude oil for space heating regionally and nationally.

Space heating is estimated to account for 77 percent of the gas, oil, and coal consumed in the residential and commercial sector, and for 82 percent of the oil alone consumed in that sector (*3*). A cross-sectional econometric model was formulated for the demand for these fuels in 1971. The following variables were used (*4*):

X_1 = total oil, natural gas, and coal consumed in the residential and commercial sector by state for the year 1971. Measured in 10^{12} British thermal units (Btu's) (1 Btu $= 1.06 \times 10^3$ joules).

X_2 = total population in each state in the year 1971. Measured in thousands of people.

$X_3 = (X_1/X_2) \times 10^3$ = total oil, natural gas, and coal consumed per capita in the residential and commercial sector by state in 1971. Measured in 10^6 Btu per capita.

X_4 = mean personal income per capita by state for 1971. Measured in dollars per capita.

X_5 = weighted average residential and commercial price of oil, natural gas, and coal for each state in 1971. The weights used are consumption levels by fuel for each state in 1971. Measured in dollars per 10^6 Btu.

X_6 = average residential and commercial price of electricity in each state in 1971. Measured in dollars per 100 kwh.

X_7 = weighted average total heating degree-days by state for 1971. The weights used are 1970 population levels for all Standard Metropolitan Statistical Areas and selected other cities with reporting weather stations. Measured in degree-days per year.

We examined several different functional specifications for these variables, including linear and double-log regressions of total fuel demand (X_1) on X_2 and X_4 through X_7, and linear and double-log regressions of fuel demand per capita (X_3) on X_4 through X_7. While the various specifications assured us of the robustness of the degree-day coefficient, we report only our preferred specification, based on ordinary least squares

$$\begin{aligned}\log X_3 = & -\underset{(.5908)}{1.0771} + \underset{(.1649)}{0.2671} \log X_4 - \\ & \underset{(.0858)}{0.2800} \log X_5 + \underset{(.1079)}{0.5039} \log X_6 + \\ & \underset{(.0405)}{0.4955} \log X_7;\ R^2 = 0.847 \qquad (1)\end{aligned}$$

with R^2 = the multiple coefficient of determination, 43 degrees of freedom, an F ratio of 59.696, and the estimated standard errors of the coefficients reported parenthetically. In this model the coefficients of fuel price (X_5), electricity price (X_6), and degree-days (X_7) can be shown to be significant in a symmetric 95 percent confidence test. The coefficients in this double-log regression may be interpreted as elasticities of demand (*5*). The most important coefficients for our conservation policy evaluation are the heating degree-day elasticity measure of 0.496 and the fuel price elasticity of -0.280.

The heating degree-day is a measure of the duration and intensity of winter coldness. The number of heating degree-days per day is defined as the difference between 65°F and the mean daily outdoor temperature. Normal yearly heating degree-days is defined as the 30-year average for 1931 to 1960. Conceptually, the number of days per year for which heating degree-days occur is different for each year and for each weather station. Since we are interested in average experience both over time and across weather stations, we write the following expression for normal heating degree-days for weather station i

$$\overline{DD}_i = \sum_{a=1}^{A} (B - T_{ai}) = A(B - \overline{T}_i) \quad (2)$$

where $\overline{DD}_i$ is normal total heating degree-days per year for weather station i; B is the indoor reference base temperature, a constant which is equal to 65°F in most U.S. weather applications; T_{ai} is the normal mean outdoor temperature on day a for weather station i, provided $T_{ai} < B$; A is the normal number of days per year for which $T_{ai} < B$; and $\overline{T}_i$ is the normal mean outdoor temperature for the period $a = 1, \ldots, A$, $\overline{T}_i < B$. Hence, the basic expression for determining the effect of lowering thermostats is $\Delta\overline{DD}_i = A\Delta B$, where ΔB is the change in the reference base temperature due to a change in the average indoor temperature setting.

To estimate the parameter A, monthly data were obtained for 267 weather stations for which the normal mean daily temperature (October through April) was less than 65°F (*6*). From these data, the average value of A for the continental United States was determined to be 230 days, and this value was surprisingly invariant with respect to geographic location (*7*).

The application of the degree-day concept in engineering estimates of space heating energy requirements assumes continuous indoor heating to 68° to 72°F; indeed, this is the basis for the 65°F reference base used in calculating degree-days. Therefore, a lowering of thermostats by 6°F may be viewed as a shift in the reference base for calculating degree-days from 65° to 59°F. The Federal Energy Office (FEO) thermostat policy may be

Table 1. Impact of thermostat policy on oil demand at 1973 consumption levels. Normal degree-days per year is a weighted average, with the 1971 state populations used as weights. On demand values, see (*8*). One barrel of crude petroleum equals 5.623×10^6 Btu.

Census region	Normal degree-days per year	Demand (10^{12} Btu)			Savings (Btu)		Savings (oil)	
		1971	1973 est.	0.8 × 1973 est.	Btu $\times 10^{12}$	% of 1973 est.	10^6 Barrels per year	Barrels per day
New England	6189	970.6	1051.8	841.4	94.44	8.98	16.80	46,027
Mid-Atlantic	5341	1845.4	1999.9	1599.9	208.30	10.42	37.04	101,479
North Central	6325	1721.6	1865.6	1492.4	162.53	8.71	28.90	79,178
South Atlantic	2972	823.6	892.6	714.1	165.48	18.54	29.43	80,630
South Central	2659	576.5	624.8	499.8	137.28	21.97	24.41	66,877
Mountain	5001	219.9	238.3	190.6	30.31	12.72	5.39	14,767
Pacific	2787	342.1	370.7	296.6	63.40	17.10	11.80	30,904
United States		6499.7	7043.7	5634.8	861.74	12.23	153.25	419,862

evaluated in the estimated demand model by perturbing the degree-day variable; that is, $\Delta DD = 230\Delta B = 230(-6) = -1380$.

We now proceed to forecast the impact of the FEO policy by the following steps.

1) Convert the effective change in degree-days into a proportional change by dividing by the normal yearly heating degree-days in the continental United States (5053). That is, the proportional effective reduction in degree-days that would result from a 6°F thermostat cutback is

$$\%\Delta DD = \frac{1380}{5053} = 0.273 = 27.3\%$$

2) This proportional reduction is now multiplied by the degree-day elasticity (0.496) to obtain the expected proportional influence on Btu's of heating oil demand per capita associated with the FEO policy

$$\%\Delta(\text{Btu per capita}) = 0.273(0.496) = 0.135 = 13.5\%$$

3) The proportional change in Btu's per capita when multiplied by 1973 estimated residential and commercial consumption for the continental United States (5634.8×10^{12} Btu) yields the total absolute forecasted change in heating oil demand in Btu's (*8*).

$$\Delta(\text{Btu demand}) = 0.135(5634.8 \times 10^{12}) = 760.7 \times 10^{12} \text{ Btu}$$

4) This change in Btu demand is then converted to an equivalent change in demand for barrels of crude oil by dividing by the conversion factor 5.623×10^6 Btu per barrel of crude oil. That is, the yearly reduction in demand likely to be delivered from the FEO's thermostat policy is

$$\Delta(\text{barrels per year}) = \frac{760.7 \times 10^{12}}{5.623 \times 10^6} = 135.3 \times 10^6 \text{ barrels per year}$$

which is equivalent to 370,685 barrels per day.

This forecasting procedure was also applied to each state; in particular, normal yearly heating degree-days for each state was used in step 1 of the procedure. The resulting estimates were then summed for seven groups of states and are presented in Table 1. We find that lowering all thermostats by 6°F (100 percent compliance) would result in a saving of 420,000 barrels of crude petroleum per day or about 12 percent of projected residential and commercial petroleum demand in 1973. This is considerably different from the saving of 900,000 barrels per day predicted in one FEO estimate (*1*, p. 3).

In a similar way we have evaluated the effect of a $0.10 per gallon increase in heating oil prices. On the basis of our price elasticity estimate of -0.3, such a price increase would lead to an additional reduction in heating oil demand of 8 percent of 1973 demand. The combined savings due to thermostat and price policies would be 20 percent of 1973 demand.

Most energy conservation estimates have been based on engineering formulas, experiments on test homes, and so forth. This report has demonstrated how conservation estimates may be derived from an economic model in conjunction with basic heating engineering information. Our forecasts indicate that a combination of reduced thermostats and higher prices can account for a significant saving in petroleum. To the economist, energy growth in the United States over the last 20 years occurred not because of need but because real energy prices declined to bargain levels. Between 1951 and 1971, real electricity prices declined approximately 43 percent while refined petroleum prices fell 17 percent. These declines resulted in the substitution of energy for labor, capital, and other raw materials. With some allowance for the persistence of habit and durable stocks of heating appliances, there is no reason to believe that this process is not reversible.

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5. It should be noted that price discrimination is widely practiced in the energy markets, especially in the case of natural gas and electricity. Strictly speaking, it is marginal prices on which the relevant consumption decisions are based. However, in a double-log demand equation, only the intercept term differs when estimated with average or with marginal price data. Consequently, the estimated elasticities obtained with average revenue data are identical to those that would be obtained with marginal price data.
6. ASHRAE, *Guide and Data Book: Systems, 1970* (American Society of Heating, Refrigerating and Air Conditioning Engineers, New York, 1970), p. 621.
7. This statement is based on several regressions between normal heating degree-days and normal mean daily temperature for the 7-month period October through April. Partitioning the data by three climatic zones resulted in regression estimates for *A* which ranged from 226 to 237. Regression results are available from the authors.
8. This figure for 1973 consumption was estimated by projecting 1971 consumption for each state at a growth rate of 4.1 percent per annum and then taking 80 percent of this projected total to consider only that portion used for space heating. During the period 1960 to 1968, residential space heating grew at an annual rate of 4.1 percent and commercial space heating at 3.8 percent (*3*, p. 6).

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Agglomeration of Ash in Fluidized Beds Gasifying Coal: The Godel Phenomenon

Abstract. *In a bed of anthracite or bituminous coke fluidized by air at 10 to 15 meters per second at 1200° to 1400°C, molten ash forms beads on the surface of a coke particle, some exuding from its interior. The beads merge and detach themselves to grow further as loose fluidized ash agglomerates of low carbon content.*

A major problem in processes for the gasification of coal is extracting the inorganic ash matter from the reaction zone without incurring undue loss of carbon. Godel has provided a unique and elegant solution to this problem in his Ignifluid boiler (*1*).

The Ignifluid gasifies coal with air and burns the resulting fuel gas to raise steam. Air is introduced at high velocity through a traveling grate into a bed of coarse particles of coke arising from the devolatilization of the coal (Fig. 1). The air sets the bed into a state of continuous and vigorous agitation and creates what the chemical engineer terms a fluidized bed.

Ease of solid handling, temperature uniformity, and high rates of heat transfer are among the unique properties that have brought the fluidized bed into widespread use as a technique for contacting solid with gas. Since the emergence of the fluidized bed, engineers have sought to adapt it to the gasification of coal. The Winkler gasifiers that operated in Germany in the 1920's represented the first commercial application of fluidization, and after the success of the fluidized bed process for catalytic cracking of petroleum, fluidized gasification of coal was the focus of several research efforts in the 1940's and 1950's and, again, in recent years (*2*).

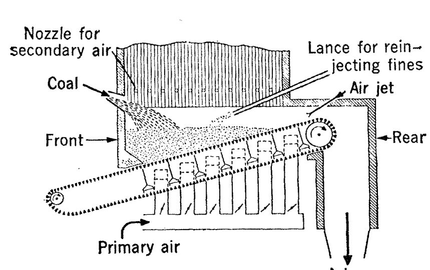

Fig. 1. Schematic of the Ignifluid gasification fluidized bed.

Operation of these processes has generally been confined to temperatures below 1000°C to avoid formation of ash clinkers, and has revealed three fundamental disadvantages:

1) Gasification below 1000°C by air is limited to coals of high reactivity, such as lignite.

2) The carbon content of a purge to extract ash is appreciable because of the complete mixing of solids and the need to maintain a sufficient carbon inventory in the gasification bed. In the absence of subsequent utilization, this purge represents serious carbon loss.

3) Production of ultrafine carbon particles appears to be inherent in fluidized bed gasification below 1000°C (*3*). Loss of this carbon as entrained dust can be serious.

Godel has obviated these disadvantages by running the Ignifluid at high fluidizing air velocities, 10 to 15 m/sec, and at a temperature of 1200° to 1400°C. At these temperatures the ash matter of all coals is sticky, and one might expect that a catastrophically massive clinker would form, but this does not happen. Godel discovered that small ash agglomerates form throughout the bed and remain fluidized, interspersed in particles of coke. The agglomerates grow in size at a controlled rate. The high-velocity fluidizing gas apparently produces an effect much like the continuous action of a poker. The ash agglomerates (Fig. 2) typically constitute 10 to 20 percent of the weight of the bed, and their carbon contents average only 5 percent. Ultimately, the ash agglomerates reach the grate and are carted into the ash pit.

This is what we refer to as the Godel phenomenon. In an effort to determine the mechanism by which the inorganic ash gathers into ash agglomerates, we inspected samples taken from operating beds at commercial Ignifluid installations in France and Morocco.

At about 1200° to 1400°C a portion of the ash matter melts to a glassy mass. Petrographic analysis shows that the ash agglomerates also contain crystalline matter, including a major quantity of quartz (SiO_2) and smaller amounts of mullite ($Al_6Si_2O_{13}$) and hercynite ($FeAl_2O_4$), which crystallized within the glass while the agglomerates were at high temperature. We note that our samples, once withdrawn from the gasification bed, cooled relatively slowly over a period of several hours.