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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References and Notes

1. J. Muller and R. Bass, "An Interim Report on Some Ways of Conserving Oil" (mimeographed; Federal Energy Office, Washington, D.C., 1 October 1973).
2. J. Muller, "Energy Conservation and the Potential Shortage of Distillate Fuel Oil" (mimeographed; Department of the Interior, Office of Energy Conservation, Washington, D.C., 20 September 1973).
3. Stanford Research Institute and the Office of Science and Technology, *Patterns of Energy Consumption in the United States* (Government Printing Office, Washington, D.C., January 1972).
4. Basic data sources for X_2 and X_4: Department of Commerce, *Statistical Abstract of the United States, 1971* (Government Printing Office, Washington, D.C., 1971). For X_1: "United States Energy Fact Sheets by States and Regions 1971" (mimeographed; Department of the Interior, Washington, D.C., February 1973). For X_5 "Gas Facts, 1971 Data" (American Gas Association, Arlington, Va., 1972); "Fueloil markets," *Fueloil Oil Heat* 3, 12 (December 1971); Bureau of Labor Statistics, "Retail Prices and Indexes of Fuels and Utilities" (mimeographed; Department of Labor, Washington, D.C., December 1971). For X_6: *Statistical Yearbook of the Electric Utility Industry for 1971* (Edison Electric Institute, New York, 1972). For X_7: Department of Commerce, *Climatological Data: National Summary, 1971* (Government Printing Office, Washington, D.C., 1971).
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).

24 July 1974; revised 23 August 1974

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*).

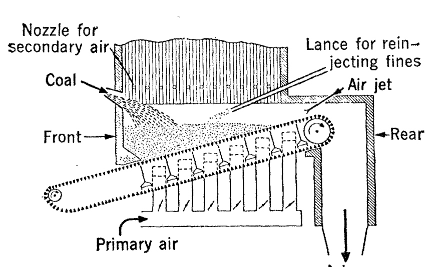


Fig. 1. Schematic of the Ignifluid gasification fluidized bed.

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.

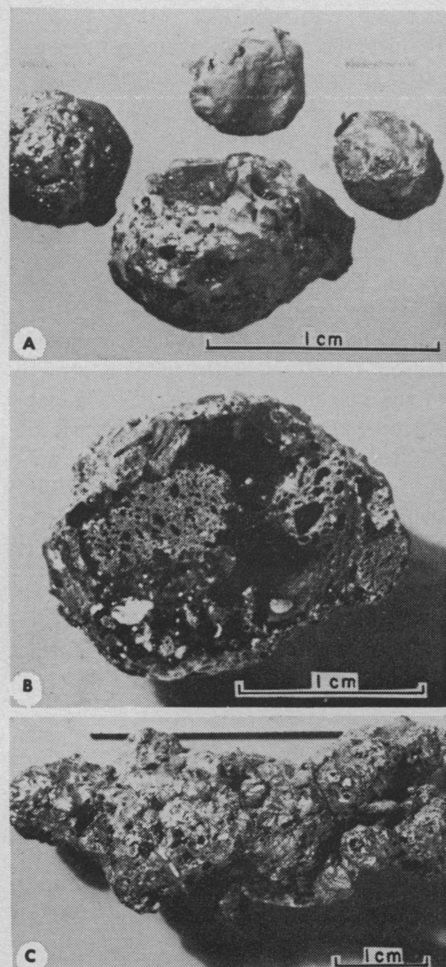
It is convenient to consider the agglomerating process as occurring in four stages:

1) In the first stage, small glassy beads appear on the surface of a particle undergoing gasification (Fig. 3, A and B). Some of the beads appear to have oozed from microcracks (Fig. 3, B and C), having migrated at least a short distance from the particle's interior.

2) In the second stage, the ash beads grow by several mechanisms. As coke is consumed by its gasification, molten ash continues to accumulate on the coke particle's surface, and nearby beads merge. The particle can also capture ash beads from another particle when the two touch each other in the fluidized bed. Figure 3D shows a single ash bead, about 300 μm in diameter, that grew on the surface of a coke particle.

3) Molten ash has a high surface tension (*4*) and does not readily wet coke. As the molten beads grow, they eventually separate from the coke surface, and this begins the third stage of the Godel phenomenon. In the turbulent currents of the fluidized bed, a loose bead may be accreted by ash agglomerates or another bead present in the bed, or it may be captured by ash still attached to a coke surface by molten matter that is rooted into capillary pores of the coke particle. Carryover material from the Ignifluid bed, which is predominately particles of coke, also contains a few ash beads that were swept up by the rising gas (*5*). Figure 3E shows a particle of coke that resided in the bed sufficiently long to have experienced the first three stages of the Godel phenomenon; ash beads of various size, including a large one, are scattered across the surface, and there are patches of coke surface that are bare of beads.

4) The final stage involves coalescence and growth of the ash agglomerates themselves (Fig. 2). Ash agglomerates may also grow by plucking ash beads still attached to a coke surface. Some agglomerates are round, while others (usually the larger ones)



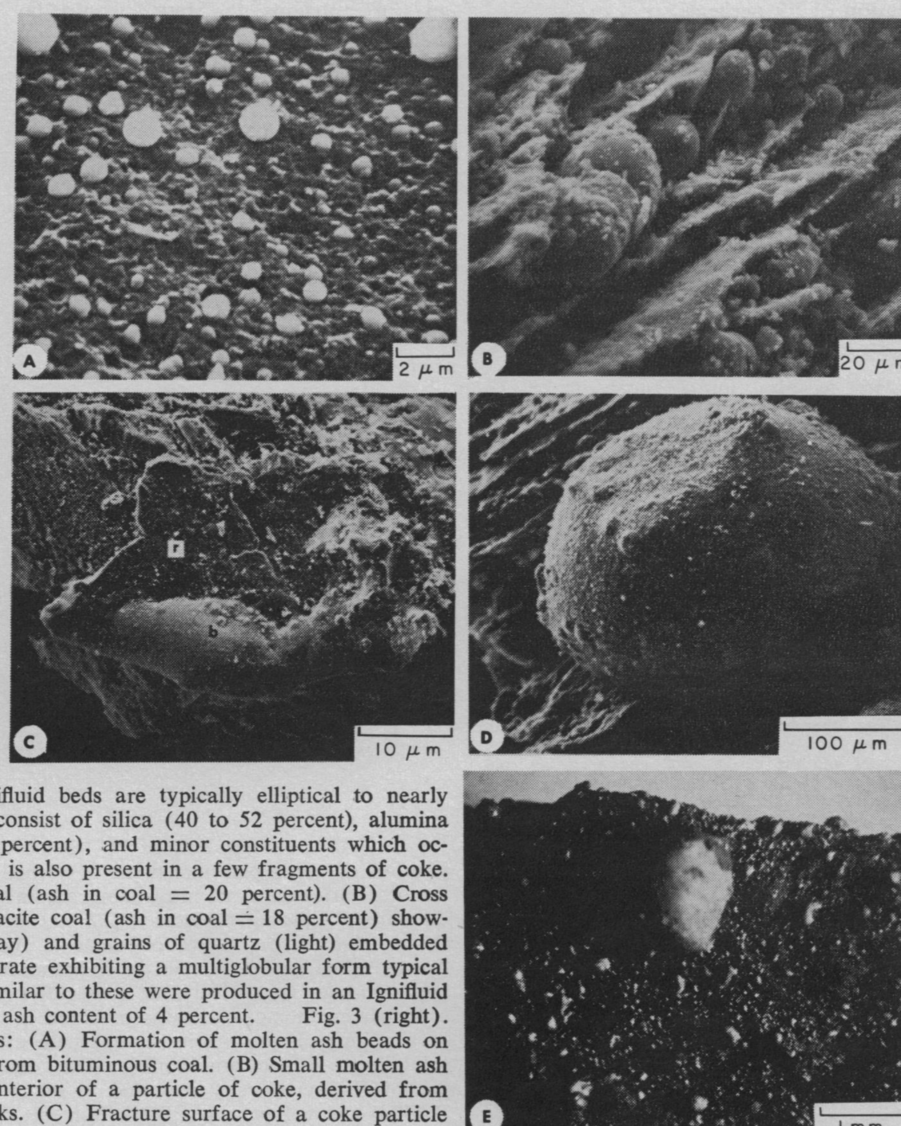


Fig. 2 (left). Ash agglomerates from Ignifluid beds are typically elliptical to nearly spherical, fragmental, and vesicular. They consist of silica (40 to 52 percent), alumina (24 to 30 percent), iron oxide (11 to 14 percent), and minor constituents which occur mainly as glass. Carbon ($\sim$ 5 percent) is also present in a few fragments of coke. (A) Agglomerates from an anthracite coal (ash in coal = 20 percent). (B) Cross section of agglomerate derived from anthracite coal (ash in coal = 18 percent) showing large vesicular fragments of glass (gray) and grains of quartz (light) embedded in a glassy shell and matrix. (C) Agglomerate exhibiting a multiglobular form typical of the large agglomerates. Agglomerates similar to these were produced in an Ignifluid gasification of a bituminous coal having an ash content of 4 percent. Fig. 3 (right). Stages of development of ash agglomerates: (A) Formation of molten ash beads on the surface of a particle of coke derived from bituminous coal. (B) Small molten ash beads appear to have emerged from the interior of a particle of coke, derived from anthracite coal, by oozing along microcracks. (C) Fracture surface of a coke particle showing emergence of an elongated bead (*b*) on the outer surface of the particle and the feeder veinlet or sheetlike root (*r*) attached to the bead. The veinlet is terminated by an irregular fracture across the photograph near the center. (D) Agglomerate bead on the surface of a coke particle; this bead formed by assimilating many smaller beads, which are partly preserved on the large bead. (E) Surface of a coke particle showing numerous ash beads with a wide range of sizes. [Photographs (A) through (D) are scanning electron micrographs taken by S. Russell at the University of Illinois Center for Electron Microscopy, Urbana.]

exhibit composite structures that resulted from coalescence and fusion of smaller agglomerates. The degree of fusion varies over the full range from weak adherence to complete assimilation (*6*).

This is the Godel phenomenon. The tendency of ash to sinter above about 1050°C, which has constrained fluidized bed gasification, has been put to constructive use in the Ignifluid boiler. Separation of ash and coke is nearly complete. Some small fragments and residues of coke are trapped or become embedded in the glass matrix of the ash agglomerates, accounting for a carbon content of about 5 percent. Carbon losses are minor elsewhere. For a coal feed that contains 20 percent mineral matter, clinkers rejected at 5 percent carbon represent carbon utilization of 99 percent.

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References and Notes

1. The following articles provide further description of the Ignifluid boiler: A. Godel and P. Cosar, *AIChE Symp. Ser.* **67**, 210 (1967); A. M. Squires, *Science* **169**, 821 (1970); *Sci. Am.* **227**, 26 (October 1972); J. Yerushalmi and A. M. Squires, in *Conference Proceedings, Power Generations—Clean Fuels Today*, Monterey, Calif., 8 to 10 April 1974 (EPRI-SR-1, Special Report Clean Fuels Conference) (Electric Power Research Institute, Monterey, Calif., 1974), p. 45.
2. A. M. Squires, *Science* **184**, 340 (1974).
3. J. W. R. Rayner, *J. Inst. Fuel* **25**, 50 (1952).
4. P. Nicholls and W. T. Reid, *Trans. Am. Soc. Mech. Eng.* **62**, 141 (1940).
5. The carryover material is collected by mechanical means and recycled to the gasification bed.
6. The characteristics of the ash agglomerates vary widely depending on the type of feed coal and the design, size, and operating conditions of the particular Ignifluid installation. A detailed discussion of this subject will be presented in a monograph on the Ignifluid boiler and the Godel phenomenon (J. Yerushalmi and A. M. Squires, in preparation).
7. Supported by grant GI-34286 from the RANN (Research Applied to National Needs) program of the National Science Foundation to City College. We gratefully acknowledge courtesies extended during visits to Ignifluid boilers by Messrs. Benhachem, Sfali, and Leleu of the Office National d'Electricite de Roches Noires, Casablanca, Morocco; by Messrs. Perrin, Loyez, and Lejeune of Usines Solvay, Dombasle-sur-Meurthe, France; by Messrs. Castebert and Menager of Centrale de la Taupe, Vezezou sur Auzon, France: by the late Albert Godel of Paris; and by Messrs. Svoboda, Cosar, Genevray, CouArc'h, and especially Mr. Vaille of Fives-Cail Babcock, Paris. We are also grateful to Commonwealth Edison Co. for sending R. M. Lundberg to accompany us in France, where he helped greatly in gathering and interpreting information.

7 November 1974

Maternal Malnutrition and Placental Transfer of α-Aminoisobutyric Acid in the Rat

Abstract. *In the pregnant rat, dietary protein restriction reduces the transfer of ^{14}C-labeled α-aminoisobutyric acid from the maternal blood into the fetus. One of the causes of this phenomenon is a reduced capacity of the placenta to release into the fetus α-aminoisobutyric acid taken up from the maternal blood.*

Maternal restriction of protein and calories is known to cause retarded growth of the fetus in several species of eutherian mammals including man. The mechanisms mediating this effect are still poorly understood. Hammond in 1944 put forward the theory that the division of nutrients between the mother and the fetus is regulated by the metabolic rate of the fetal and maternal tissues (*1*). According to this theory, if there is only a limited supply of nutrients the fetus would be able to compete successfully with the mother because of the higher metabolic rate of its tissues. This implies that the fetus would be affected only after maternal reserves have been depleted. However, recent data from human populations demonstrate that even a moderate restriction of nutrients during pregnancy may cause some degree of fetal growth retardation (*2*).

Thus, in apparent discrepancy with Hammond's hypothesis, when maternal malnutrition is present, the fetus does not seem able to compete successfully with the mother. In order to explain this phenomenon, it seems necessary to consider other factors, besides the metabolic rate of the tissues, in the division of nutrients. One of these factors could be placental function. If maternal malnutrition affects the capacity of the placenta to transfer nutrients, the possibility of fetal competition would be neutralized and fetal growth retardation would result. There is evidence from observations on human populations and experiments in rats that maternal malnutrition interferes with cellular growth of the placenta and alters RNA metabolism (*3*). Moreover, morphometric studies of placenta from women suffering mild degrees of malnutrition demonstrate that malnutrition reduces the mass of peripheral villi (*4*). This

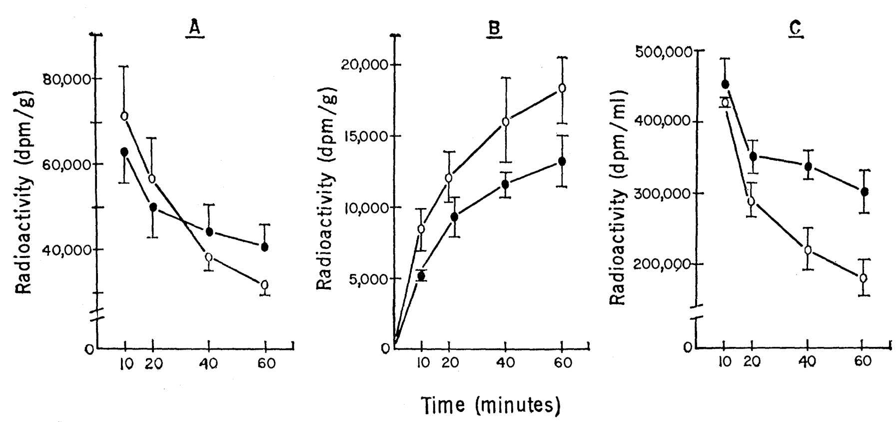

Fig. 1. (A) Concentration of ^{14}C-labeled AIB [disintegrations per minute (dpm) per gram of tissue] in placental tissue of normal (○) and malnourished (●) rats at different times after maternal intravenous administration of 1 μc per 100 g of body weight of α-amino[1-^{14}C]isobutyric acid (12.2 μc/mmole). Each point represents the mean ± the standard error of five placentas in the normal group and four placentas in the malnourished group. A total of five and four animals were used for the normal and malnourished, respectively, in consecutive experiments. Placentas were removed, and a 10 percent homogenate was prepared in distilled water. Radioactivity was measured in a 0.5-ml sample of the homogenate after digestion at 40°C with 2 ml of NCS solubilizer (Amersham/Searle). The digested sample was then neutralized with 0.1 ml of glacial acetic acid, and 15 ml of a scintillation fluid containing 0.01 percent POPOP and 0.4 percent PPO in toluene were added to the vials. (B) Concentration of [^{14}C]AIB (disintegrations per minute per gram of tissue) in fetuses of normal (○) and malnourished (●) rats. The number of cases in each point and the preparation of samples were similar to placentas. (C) Concentration of [^{14}C]AIB (dpm/ml) in the plasma of normal (○) and malnourished rats (●). Radioactivity was measured in 10 μl of plasma digested at room temperature with 0.2 ml of NCS solubilizer. As in previous samples 15 ml of the same scintillation fluid were used.