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What's Burning at BYU: The Role of Combustion and Our Work to Understand It

L. Douglas Smoot

PRE-FLAME OBSERVATIONS—INTRODUCTORY COMMENTS

I have been fascinated by combusting or exploding fuels for as long as I can remember. When I was a boy, firecrackers were a favorite, though not always lawful, hobby. As my wife and I sit at a fireplace, she reflects on our home and family, and I think of the cellulose in the wood pyrolyzing and thermally cracking to produce soot. I have spent the past twenty-four years researching one aspect or another of this ''burning subject.''

I have been continuously at BYU since the fall of 1967 and have conducted research during this entire period in a field that we call ''combustion.'' This is a very general term that refers to an interdisciplinary subject of broad interest and application. Topics may range from forest fires to rockets, from jet engines to power plants, from automobile motors to candles, and from coal mine explosions to fireplaces. The word *combustion* refers to the chemical reaction of a fuel with an oxidizer such as oxygen, with significant release of heat. Such chemical processes are complicated by the transfer of heat, the turbulent flow of the reacting fluids, or the motion of droplets or particles. Illustration 1 shows many of the physical and chemical processes that take place during combustion of coal in a large furnace that generates power for our use. Because of the complexity of these processes, the understanding of combustion requires broad insight from several fields.

I have organized this presentation after the manner of a burning candle, so often used as the symbol of combustion. A candle is first lit by an ignition source; it radiates light and heat to its surroundings; it provides a flame to start other fires; and it burns brightly until it is extinguished. Thus it proceeds through the phases: (1) ignition,

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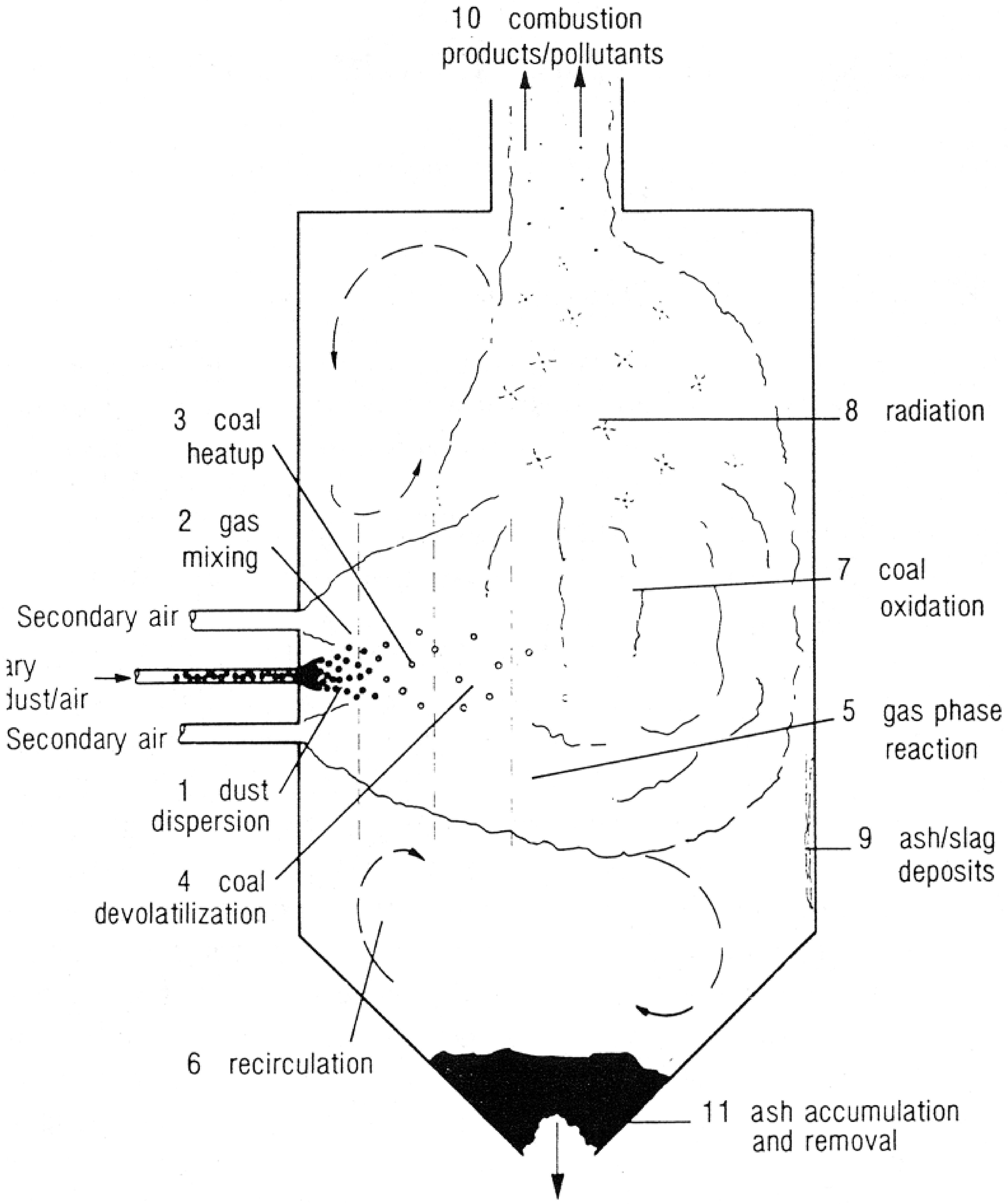


ILLUSTRATION 1. PHYSICAL AND CHEMICAL PROCESSES DURING COMBUSTION OF COAL IN A LARGE FURNACE

(2) radiation, (3) flame spreading, (4) combustion, and (5) extinguishment. My presentation will follow these same phases with these introductory comments referred to as ''pre-flame observations.''

Before we light the candle, I must acknowledge the contributions of many. It has been said by someone that in art it is ''I,'' but in science it is ''we.'' So much of what I say is due to others. Just at BYU, I have worked with over sixty research students and at least ten faculty members directly in our combustion work. I have received continuing support from administrators at every level. I have found only encouragement at this university for creative endeavor. In fact, it is difficult to identify any one accomplishment for which I have been solely responsible.

But my sense of acknowledgment goes far beyond this. My wife and children—all present at this lecture, and who by Friday will number seven, counting marriage unions—are each bright candles in my soul. My parents and hers, all here, add fuel to my flame. And I glow more brightly when I listen to you, my university associates, talk about the flames in your lives such as ''The Bard and the Lord,'' ''Families and Contracts,'' ''Scriptural Fingerprints,'' ''Flora and Fauna,'' ''Bridges in Our Lives,'' or ''Nineteenth-Century Mormon Communities.'' So much about the fire of a great university derives from the different fuels of our various disciplines. And as I walk this campus I sense the sacrifice of those before me, particularly, for me, my great-grandfather Abraham Owen Smoot; and this fans my flame of dedication to this university. But now, let me tell you about the burning candle of my professional life. In the Sermon on the Mount, Jesus said, ''Neither do men light a candle, and put it under a bushel, but on a candlestick; and it giveth light unto all that are in the house'' (Matt. 5:15). I only hope my candle will give light to all that are in this house.

IGNITION—WHEN DID THE FIRE START?

The history of combustion parallels the history of mankind. Natural fires must have occurred before man's footprints were made in the sands of the earth. Volcanic lava, lightning, and the desert sun must have helped to form the earth. I learned, during last year's lecture-trip to mainland China, that Peking Man, according to present knowledge, performed the first combustion experiments a half-million years ago. The ashes of organized fires remain in these prehistoric caves as a record of these early researchers.

F. J. Weinberg suggests that mankind learned to ignite fires as recently as thirty thousand years ago. Then followed the use of fire for making tools, somewhere from five thousand to ten thousand years ago. Ancient civilizations expressed these events in myths. According to the Greeks, Prometheus brought man the fire he stole from Zeus, the god of lightning and thunder. In the legends of Japan, Earth Mother, Izanami, after having given birth to the various deities, gave birth to the god of fire, who burned her terribly and caused her death.[1] Well before the time of Christ, Empedocles of Acragas (fifth century B.C.) had thought of fire as one of the basic elements of primal matter.[2] From Vergil's sixth eclogue (43–37 B.C.), we read:

> He sang how in the mighty Void, the seeds of Earth and of Air and of Ocean, and of Fire—that pure thing—ranged themselves together; and how from these principles all the Elements arose, systematically cohering in the tender globe of the World.[3]

Following the alchemists, in rapid and recent succession, came the early explorations of combustion and the role of oxygen by Priestley and Lavoisier in the 1770s;[4] the discovery of the nature of the explosion, propagation, and flammability of premixed gases by Le Châtelier in 1883;[5] and the description of the candlelike diffusion flame by Burke and Schumann in 1928.[6] Of course, these discoveries only illustrate the vast scientific contributions on which our present understanding of combustion is based. Thus the role of fire has been with us from the first and has pervaded all facets of our lives.

RADIATION—HOW DOES THE FLAME WARM US?

Fire has continued from early man to pervade our lives and warm our souls. In the scriptures, we find frequent reference to fire, sometimes to brighten our souls, as in Isaiah 50:11: "Behold, all ye that kindle a fire, that compass yourselves about with sparks: walk in the light of your fire, and in the sparks that ye have kindled"; and sometimes to quench our natural tendencies, as in Doctrine and Covenants 43:33: "And the wicked shall go away into unquenchable fire, and their end no man knoweth on earth."

Reference to fire is also common in our best literature. You will remember Pippin, the discontented youth in the country of Gaul, who sought life's fulfillment through power, war, and love. Recall these lines from near the end, where Leader tries to entice Pippin to a spectacular, if destructive end:

> When *he* does it, it's just a trick. But when you do it, it'll be for real.
>
> When I do it? You mean you want me to get into that thing and set myself on fire?
>
> Wait a minute. . . .
>
> You will step into that flame, Pippin. . . .
> Become part of that flame. . . .
> Become flame itself. . . .
> And for the moment shine with unequalled brilliance. . . .
> And in that flame you'll become a glorious synthesis of life and death.[7]

Shakespeare also dramatized with fire. From the *Taming of the Shrew,* can you hear Grumio in Petruchio's house, warming himself by the fire?

> Was ever man so weary? I am sent before to make a fire, and they are coming after to warm them. Now, were not I a little pot, and soon hot, my very lips might freeze to my teeth, my tongue to the roof of my mouth, my heart in my belly, ere I should come by a fire to thaw me: —but I, with blowing the fire, shall warm myself; for, considering the weather, a taller man than I will take cold.
>
> (4.1.3–11)

Or do you recall Petruchio in reference to the taming of Kathrina:

> And where two raging fires meet together, they do consume the thing that feeds their fury. Though little fire grows great with little wind, yet extreme gusts will blow out fire and all.
>
> (2.1.132–35)

From early art through the Dutch masters and on to modern art, men have captured fire on canvas. Rembrandt used the path of the fire's light to immortality as is suggested in his painting *The Holy Family.*

More than this, fire warms our bodies. Few of us have stopped to consider the role of fire in our way of life. The present annual world consumption of energy is equivalent to one hundred and forty million barrels of oil per day, with the United States consuming over one-third of the total. More than 97 percent of this total comes from the burning of wood and the fossil fuels—coal, oil, and gas. Most of the balance is from hydroelectric and nuclear energy sources.[8]

Nearly all of the world's transportation moves on fire's released energy—aircraft, cars, trucks, ships, trains. Agnew estimates that the spark ignition and combustion of a small quantity of gasoline occurs over ten quintillion times (10^{19}) each year (or three hundred billion times a second) in the United States alone. And he documents the significant contributions of combustion research on today's auto engines in control of knock, increased mileage per gallon, and reduction in pollutants.[9]

Most of the world's industrial power is generated from the combustion of fossil fuels. The power in our homes, whether electric or gas, whether in the fireplace or the furnace, is provided through combustion. We cook through fire, directly or indirectly. When you bake a roast, do you envision the remote coal fire of a large power generating plant? The weapons in our national defense arsenal, from conventional weapons such as rifles and cannons to advanced rockets, burn fuels to achieve their destination. And we relax by fire. Who here does not love the warmth of a log fire on a winter's night?

Our high standard of living is related somewhat to the use of energy from combustion. Illustration 2 shows the relationship between the

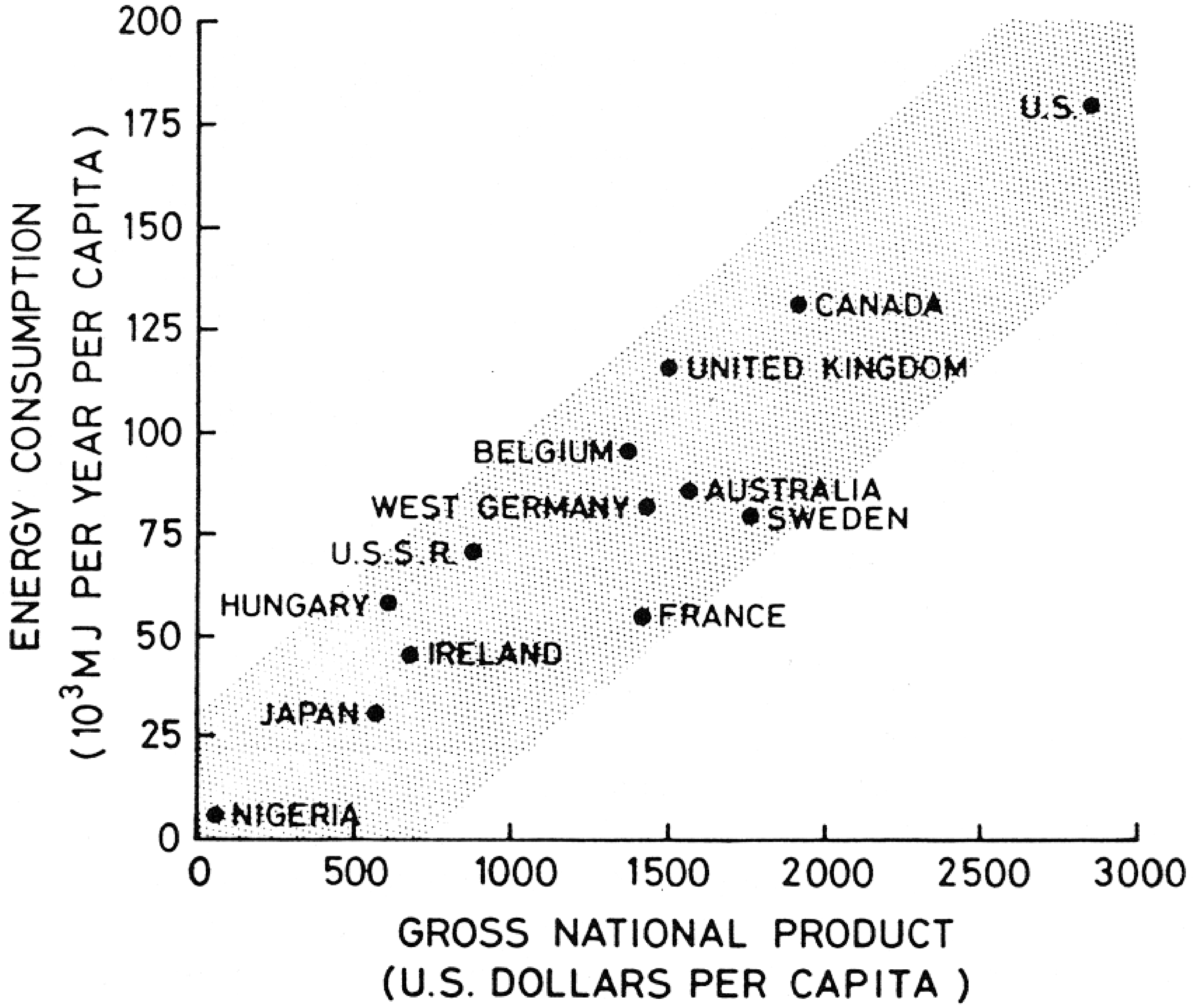


ILLUSTRATION 2. THE RELATIONSHIP BETWEEN ENERGY CONSUMPTION AND GROSS NATIONAL PRODUCT, PER CAPITA[7]

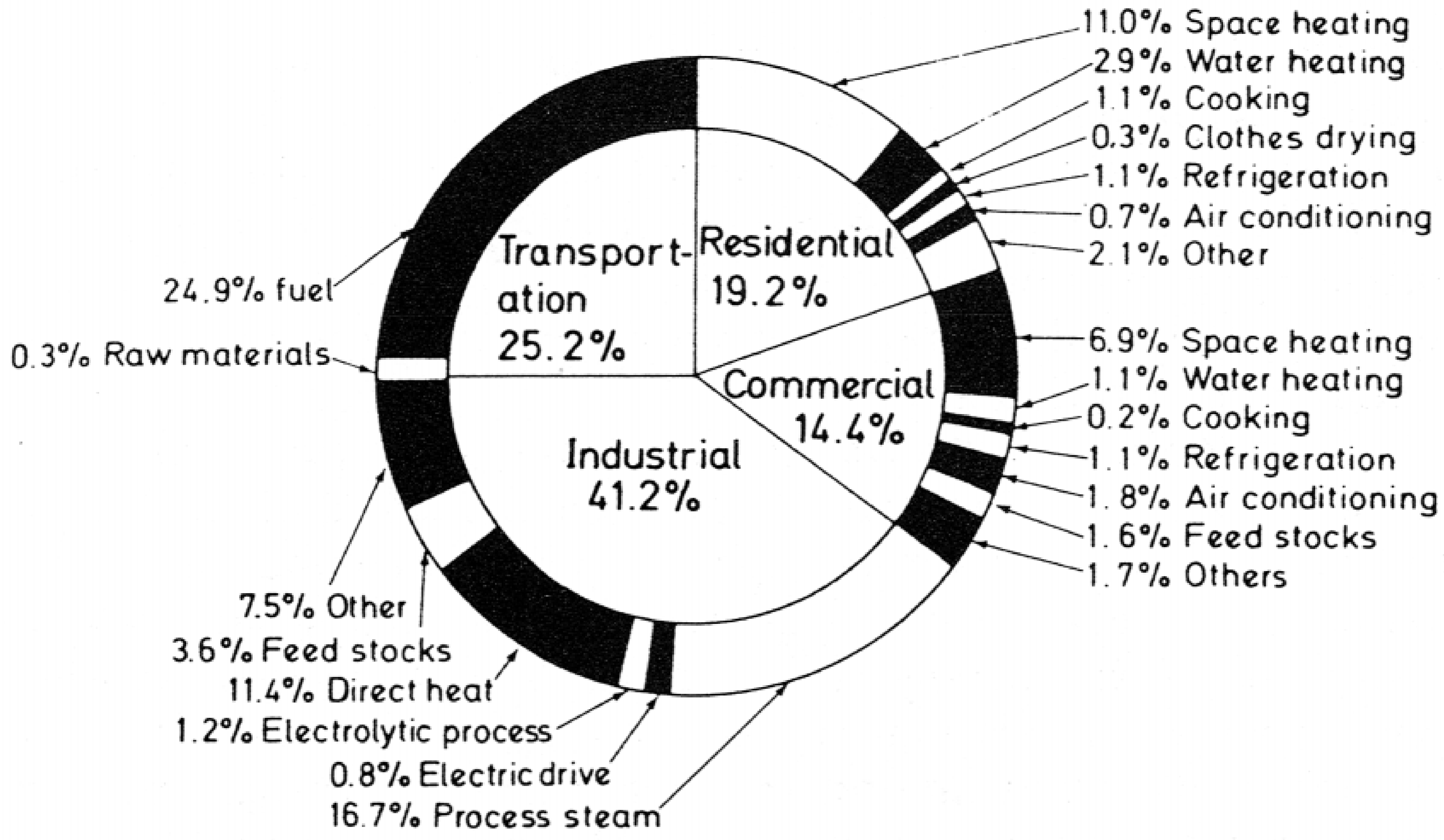


ILLUSTRATION 3. PATTERNS OF ENERGY CONSUMPTION IN THE UNITED STATES—CONSUMER CATEGORIES AND MAJOR END[7]

gross national product for several nations and their energy consumption. Per capita energy consumption in the United States is about four hundred thousand megajoules per year, which some have estimated to be equivalent to the work that could be done by twenty-five servants working around the clock for every United States citizen.[10] And nearly all of this energy is made available to us through controlled combustion processes. How is this energy used in our country? Illustration 3 shows proportions of use in transportation (25 percent), by industry (41 percent), in our homes (19 percent), and in commerce (14 percent).

But we have also known, from the time we were little children, that the fire that warms our bodies can also burn. I refer here to more destructive fires that consume buildings and forests and bring explosive death in our coal mines. These problems are secondary to the indirect hazards of combustion that presently and appropriately focus our national attention. The worldwide burning of fossil fuels has brought us carbon monoxide from our automobiles, smog over our large cities, and acid rain downwind from our generating plants. With the present public rejection of nuclear power, and with no near-term alternatives to the use of fossil fuels to provide our energy, these problems will require our increased attention.

The atmosphere that we breathe is made mostly of nitrogen and oxygen, which we know as life-giving gases. Yet, when nitrogen and oxygen combine during high temperature combustion, a new compound, nitrogen oxide, is formed which is a hazardous pollutant to humans, animals, and plants, and causes smog. About one trillion pounds per year of this pollutant are emitted from automobiles, power stations, and aircraft around the world. This is equivalent to two hundred pounds per year for every soul living in the world.[11]

About two hundred times more per year of sulfur oxides (or one hundred billion tons per year) are also emitted, with 70 percent coming from fossil-fueled (mostly coal) electric generating stations.[12] These sulfur oxides in the atmosphere combine with rainwater to form an acid that threatens our forests and marine life. We also worry, though without firm evidence, about the possibility of increasing carbon dioxide concentration in our atmosphere causing undesirable changes in our weather. We call this the "greenhouse" effect.

We suffer in still other ways from this fire that otherwise frees us from a life of hard labor. We kill over forty-five thousand souls per year on our country's highways with vehicles powered by combustion. We and our adversaries use fire to power our defense weapons that bring us an uncertain peace while we sleep with an uneasy sense of security.

Thus, we see that fire provides us with the high standard of living that we enjoy while presenting us significant challenges that we must solve through research to wisely use our combustible resources. And that is where our research comes in.

FLAME-SPREADING—HOW DID WE GET STARTED AT BYU?

Just as a flame spreads across the logs in a fireplace or through a forest, so has combustion research expanded at BYU from modest beginnings. This is not the place to give a comprehensive history of combustion research work at BYU. But a brief summary of some key decisions and events may illustrate why we are burning what we burn. However, I must emphasize that this brief historical perspective will not account for combustion-related research conducted by those not associated with the Combustion Laboratory.

For me, it all started with Sputnik, the first Russian launch of a space capsule in 1958. The American response to this development brought to the state of Utah a new business in solid propellants for missile power. Hercules and Thiokol were among early pioneers in these fuels. By 1960, when I joined the BYU chemical engineering faculty of four, fresh from Ph.D. work at the University of Washington, the state's propulsion work was expanding and in need of technical help. I had never taken courses in combustion or propulsion, but summer employment and consulting opportunities were irresistibly challenging. This was my first introduction to combustion. A four-year period of full-time employment at Lockheed Propulsion Company from 1963 to 1967 helped to develop the critical experiences in the marketing of research ideas.

After I returned to BYU in 1967, my combustion research work dealt with rocket exhausts, hybrid propellants, and air-breathing rockets. Early contracts from the Navy, Air Force, and NASA provided a foundation. Professor Ralph Coates joined Professor Duane Horton and myself in 1968, and much of the early aerospace combustion work at BYU was conducted by this group of three, without a doctoral program and with limited test facilities. This general focus continued for a very few more years until it seemed apparent that propulsion-related combustion research would decline. In the early seventies, Professor Coates started a small coal research program, and shortly afterwards the three of us obtained a new contract with the U.S. Bureau of Mines to study coal-dust explosions.

Not many universities were doing energy-related combustion research. So, when the oil crisis of 1973 occurred, we were in the right place at the right time, even though our experience was limited. Since then, our work in the combustion of fossil fuels, particularly coal, has continued to expand. My two early associates developed separate research efforts, and both subsequently left the university. I started to think about burning coal in gasifiers and furnaces. Somehow, it seemed a natural transition from burning metal particles in rocket propellants to coal particles in furnaces. The basic physical and chemical processes were similar. And coal is the world's most plentiful fossil fuel reserve. Coal makes up nearly three-quarters of the world's known fossil fuel reserves and nearly 90 percent of the known reserves in North America.[13] The United States has nearly a third of the world's known coal reserves. With declining United States oil reserves, we now import about half of our oil needs. Since fossil fuels provide nearly all of our energy needs and since coal is the most abundant reserve, the need for further research on this fuel seemed particularly important. Yet, at the time of the oil embargo, research in the United States on this fuel was modest, indeed.

Two large contracts with the U.S. Department of Energy (then ERDA) and the Electric Power Research Institute on coal gasification and combustion in 1974 launched the BYU Combustion Laboratory. One of these two studies is still active after a decade while the second lasted about eight years. Since then, we have obtained about five million dollars in grants and contracts from DOE, EPRI, TVA, Utah Power and Light Company, Foster–Wheeler, Babcock and Wilcox, the U.S. Bureau of Mines, the National Science Foundation, and others. We have grown to include six faculty and about twenty-five to thirty graduate students. It requires more than a half-million dollars a year to do our research work. Since 1970, fifty-six students have completed master's degree work, and twelve students have completed doctoral work. Our research space has expanded from seven hundred square feet in 1968 to 10,500 square feet today.

Today, we are still working on the gasification and combustion of coal and on coal-dust fires and explosions. Our work has expanded to include combustion of coal–water mixtures, char combustion, and the dynamics of flowing particle–gas systems. We have, for a decade, worked on the development of computerized models for describing these combustion processes. These predictive methods have been adopted by about thirty organizations in the United States, Europe, and Japan. Since 1977, we have published two books, six invited review papers, over 120 publications, including fifty-three journal publications and thirty-five contract final reports. During our two decades of development, the university's contributions and encouragement have been significant. And, while we never received or expected to receive all we asked for, we were never discouraged.

COMBUSTION—HOW DOES THE FIRE BURN?

I have discussed what we burn but not why or how. Now, I'd like to illustrate our method of working, with just one example. I noted earlier that control of pollutants will be vital to acceptable increased use of our vast coal reserves. I also mentioned that the oxides of nitrogen, which form during most combustion processes, pollute our cities and hurt our lungs. The obvious question is easy—how can we burn fossil fuels efficiently while producing lower levels of nitrogen oxide? If you burn coal in just an ordinary fire, the oxides of nitrogen might exceed one part in a thousand parts in the gaseous products of combustion. That doesn't sound like much, but federal law requires a three-fold reduction from uncontrolled levels while the Japanese want a ten-fold reduction. This is certainly an international problem.

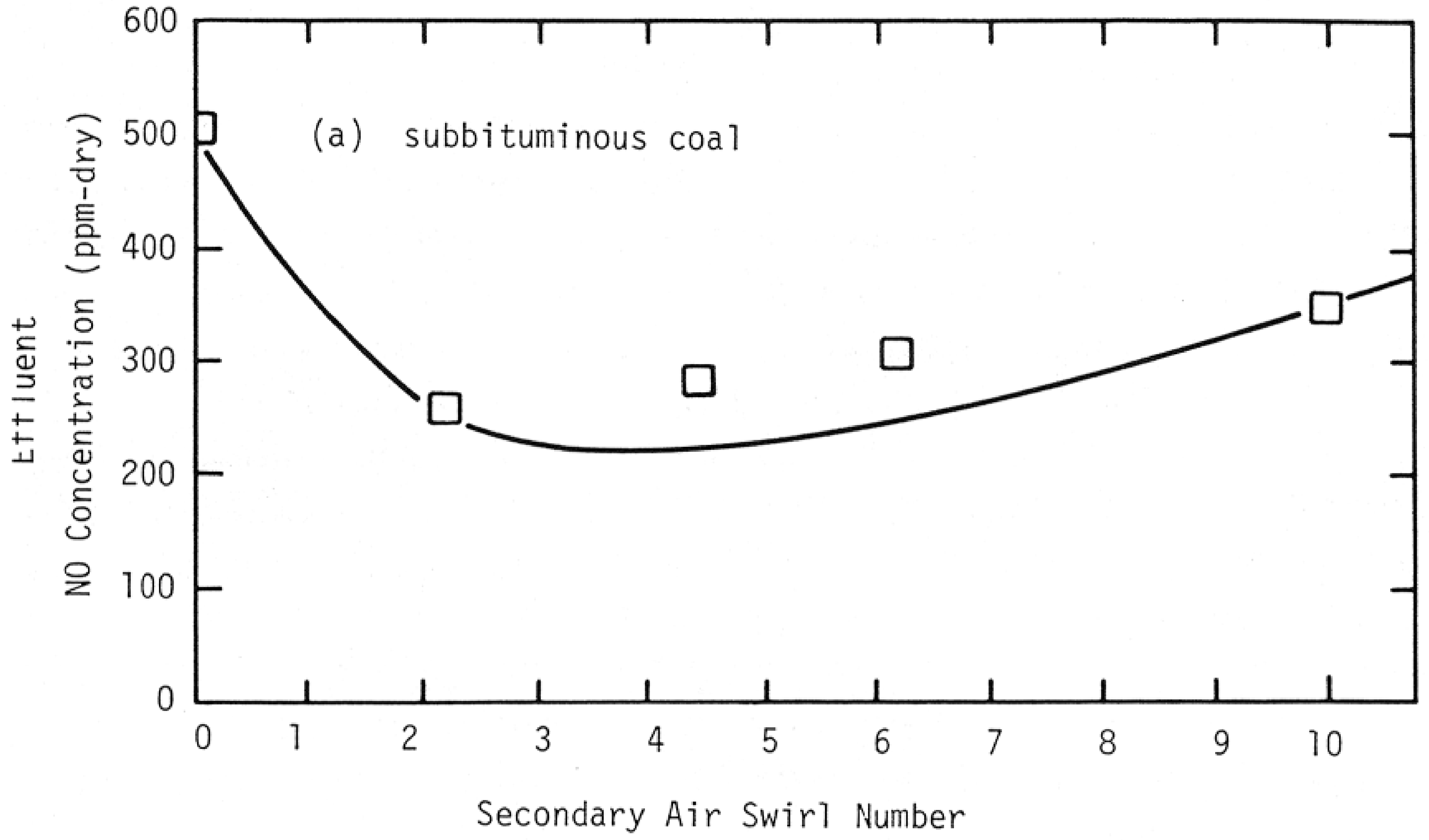
But just identifying this problem as a possible research topic isn't enough. We must ask other key questions. Is the research already being done? Can we contribute? Do we have the right background and equipment? Are we competitive? And inevitably, does some agency with money want to know the answers we can provide? Much creative work can be done with a pen and paper and some quiet time. But we need equipment and supplies and computers for our work. And graduate students these days expect to eat, and they want the research contracts to pay.

Well, in the midseventies we found positive answers to all of these questions. And we found ourselves with a research contract. Now, what did we do next? First we had to find out what was already known about the problem and its solution. For any technical research effort, a foundation of information is available in the library. We found that much was already known. Here are some things we learned from the work of others:

1. Most coals contain about 1 percent of nitrogen, called fuel nitrogen, as a part of the chemical structure of the coal.
2. When the coal burns, this fuel nitrogen is released and reacts with oxygen to produce the nitrogen oxide pollutants.
3. A very common way being considered to reduce the oxides of nitrogen was to keep oxygen away from the fuel nitrogen.[14]

We noted that most of the pollutant measurements were made in the exhaust and not in the combustor. We also determined that nobody had devised a way to predict the formation of nitrogen oxides during coal burning. So we set out to make measurements of this pollutant inside the combustor and to develop a computerized model to calculate this process.

Completing this kind of work didn't happen overnight. One doctoral student built a combustor and taught us how to make flame measurements,[15] and a second made our first nitrogen oxide measurements in a coal flame.[16] Two more then did detailed studies of this pollutant for different coals.[17] It took us about six years to do this work.



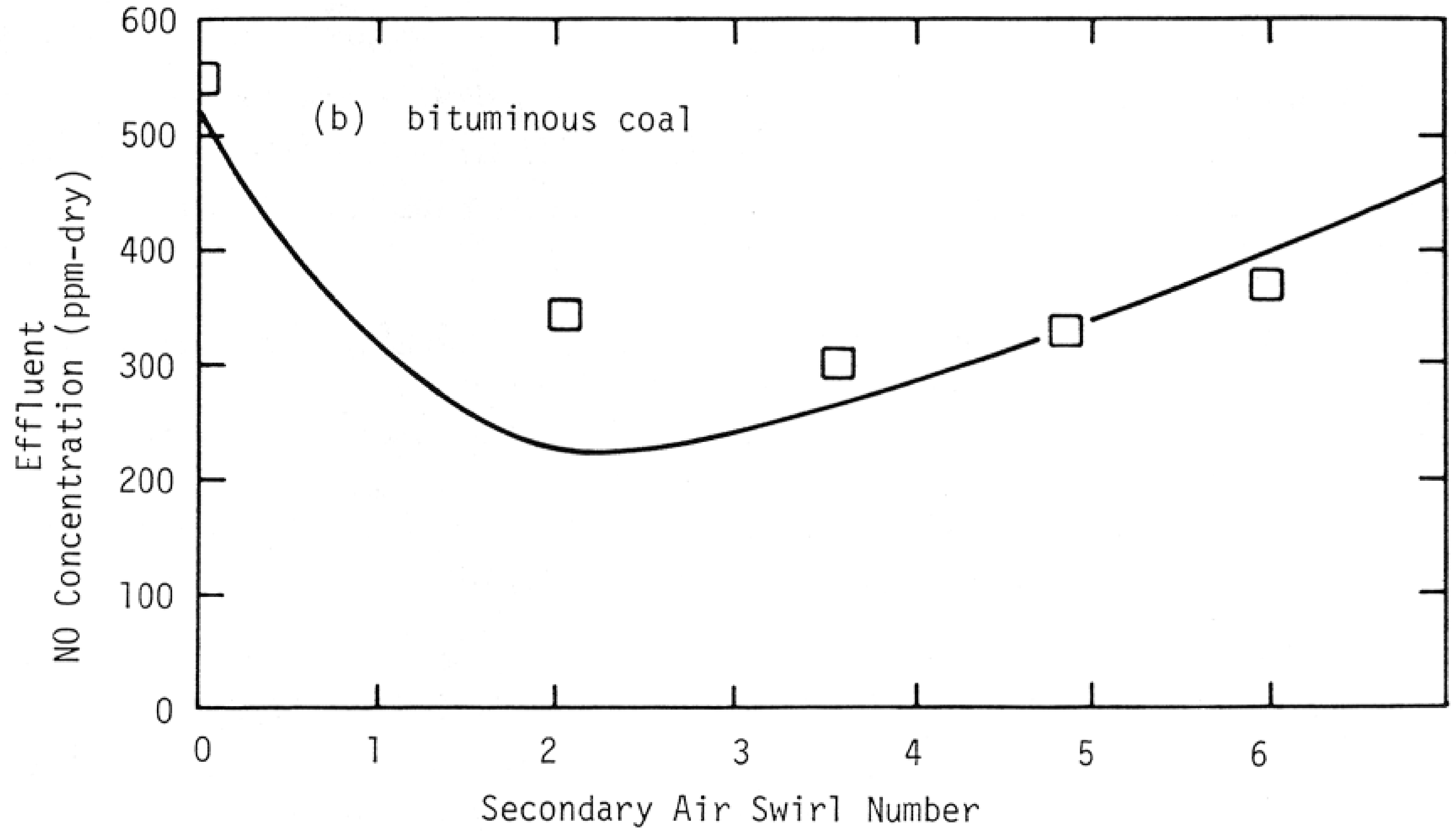


ILLUSTRATION 4. COMPARISON OF PREDICTED (—) AND OBSERVED (□) EFFECT OF SECONDARY SWIRL NUMBER, ON EFFLUENT NO CONCENTRATION FOR (A) A SUBBITUMINOUS COAL AND (B) BITUMINOUS COAL

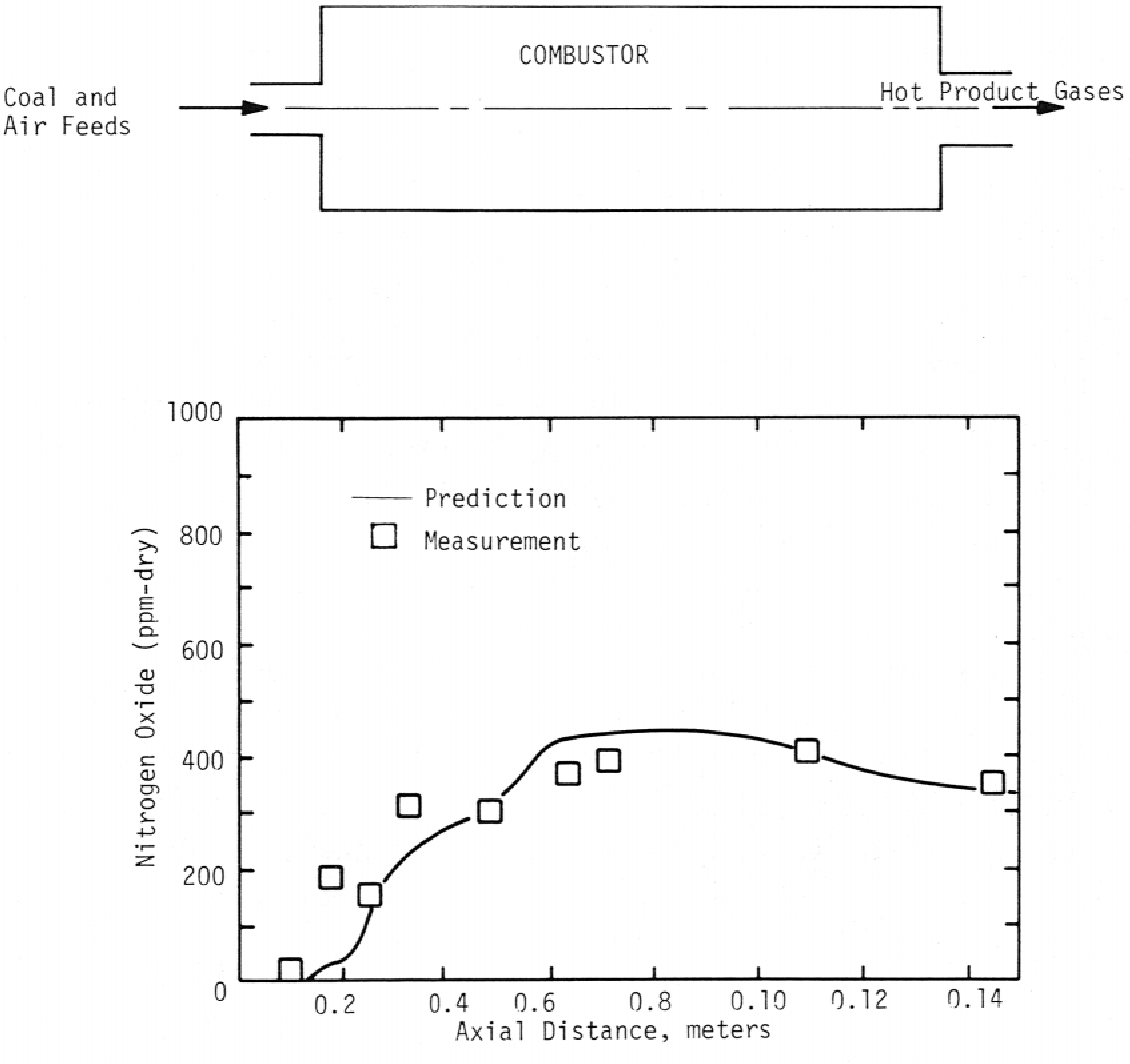


ILLUSTRATION 5. FORMATION AND DECAY OF NITROGEN OXIDE POLLUTANT DURING COMBUSTION OF A PULVERIZED UTAH BITUMINOUS COAL[9] [12]

Illustration 4 shows one of the more important results from these last two studies. We found that by swirling the combustion air, we could lower the pollutant concentration by a factor of three and get even better combustion of the coal. We also measured the rate at which the pollutant forms throughout the combustor, as shown in illustration 5. Notice how it forms early in the combustor and then declines toward the exit. And we published the results of our work in prominent technical journals.

This doesn't end the story. While we were making these measurements, we were also working on ways to model this pollutant formation process. It is presumed that if you can predict a natural occurrence, you may be able to use the predictive method to identify ways to control the event, or at least to accommodate it. Thus, scientists and engineers strive to predict big events, such as weather and earthquakes, as well as smaller events, such as an automotive crash or the combustion of coal.

Just how does one go about predicting a natural event? The key is that natural occurrences always take place according to the laws of nature. A model, then, is a mathematical solution of these laws, often simplified, which can be used to obtain information that wasn't known before. Let's look at a simple example. Suppose you wanted to determine the loss of weight that took place when you baked a cake. When the cake bakes, water in the cake mix is evaporated. Further, the baking soda (sodium bicarbonate) decomposes at high oven temperatures to release carbon dioxide which helps the cake to rise. Other losses may also occur. The cake is thus lighter than the weight of its ingredients, as shown in illustration 6. To determine the loss in weight, you would simply weigh the cake batter in the pan before you baked the cake, and then weigh the cake after baking. The difference is the loss of weight, as anyone can see.

In making this analysis, we have applied a basic physical law. In any natural process, matter (or more exactly, mass) is neither created or destroyed. We think conceptually of the "universe," which we divide into two parts: the system to be investigated, and the balance of the universe we call the surroundings. The system may be a cake, a furnace, a rocket engine, or the cylinder of an automobile engine. While the mass of a system can change, as shown in illustration 7, the mass of the "universe" must be constant. Thus, for the cake, the mathematical expression determining the weight of ingredients lost to the atmosphere is:

$$\text{weight loss on baking} = \text{weight of ingredients} - \text{weight of the baked cake.}$$

In a much more complex way, this is how we calculate the formulation of nitrogen oxide during coal combustion. Here we need several natural laws, including, among others:

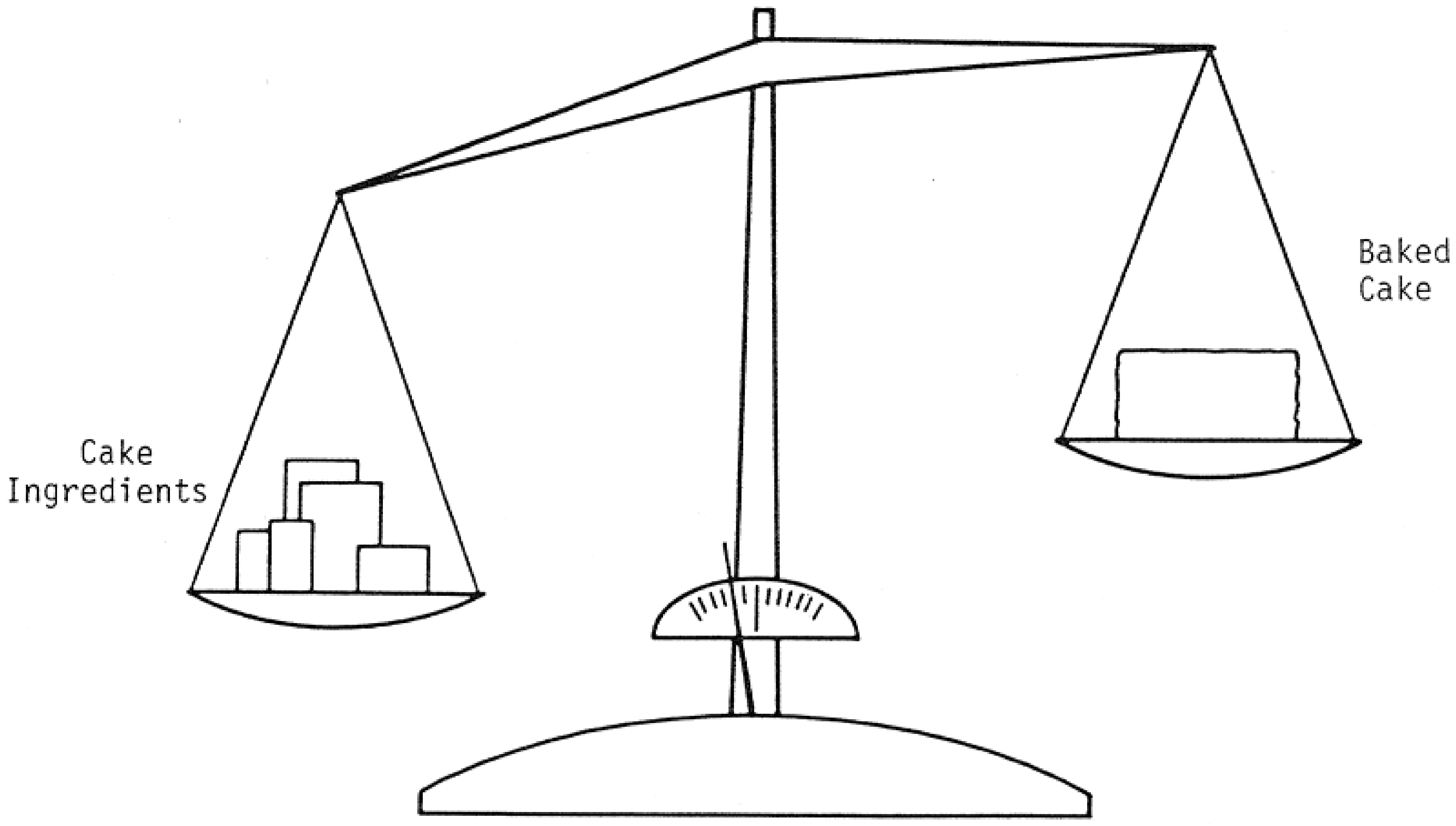


ILLUSTRATION 6. WEIGHT COMPARISON OF BAKED CAKE AND ITS INGREDIENTS

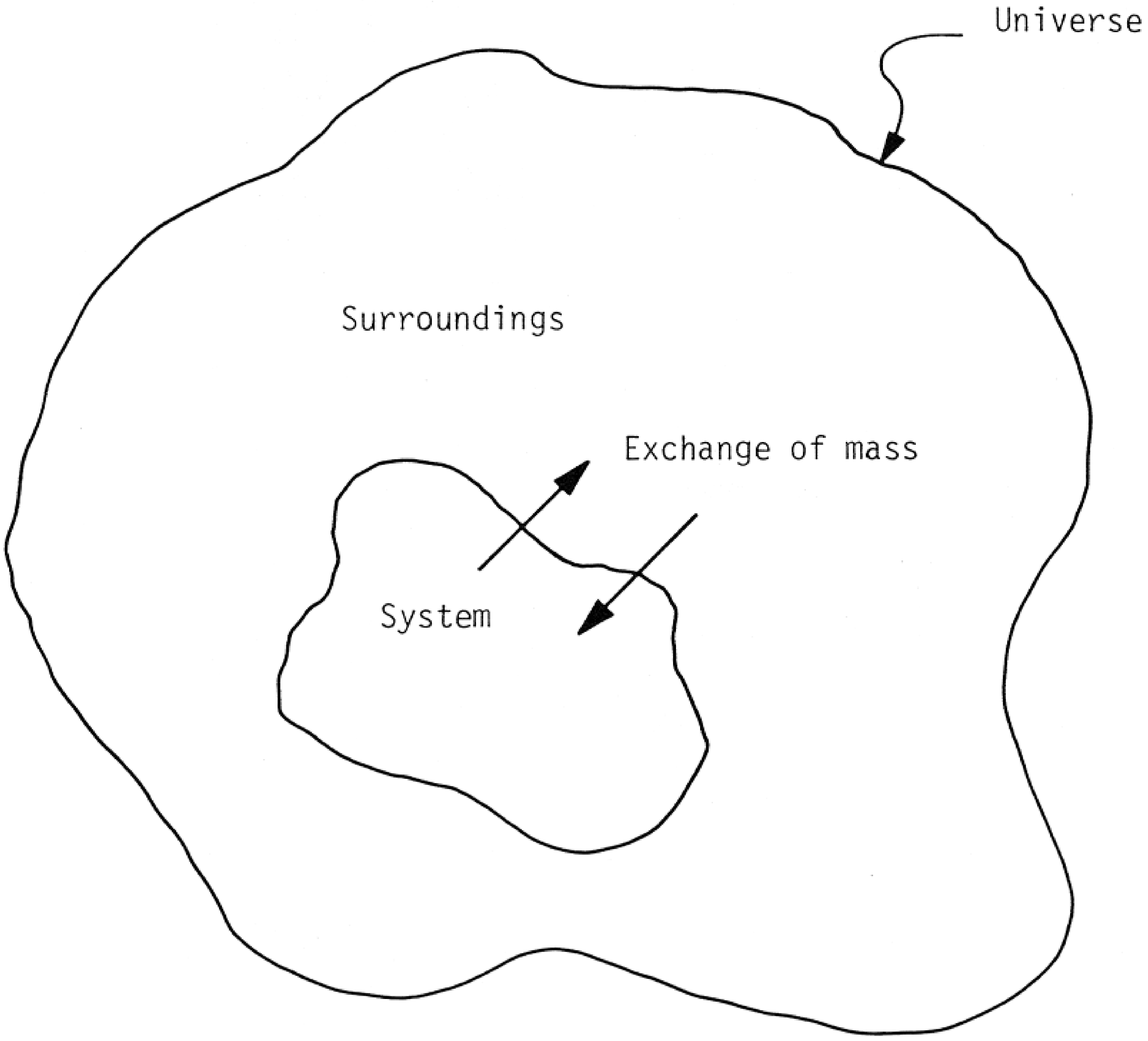


ILLUSTRATION 7. CONTROL VOLUME FOR A MASS BALANCE

1. Mass balances for each chemical element such as carbon, hydrogen, etc.
2. Energy balances for the gas and the coal.
3. Newton's laws of motion of the gas and the coal, sometimes called momentum balances.

These equations are written for each of the little rectangles of the coal reactor in illustration 8, just like the mass balance that was written for the cake. Illustration 9 shows some of the complex balance equations that must be solved. But these equations are not enough, because they contain too many quantities (that is, variables) that we don't know. A rule of mathematics is that you can only calculate one new quantity that you didn't already know from each equation. We used the cake weight balance equation to calculate loss of weight during baking. But to do so, we had to weigh the cake before and after. That's what we have to do with the coal furnace—not weigh it before and after, but make many basic measurements of quantities to be used in our equations. For example, we measure the rate at which small coal particles react in oxygen for various temperatures. We measure the fraction of the various elements contained in the coal before it is burned, such as carbon, hydrogen, and of course nitrogen. We measure the size of the furnace and the flow rates of coal and air into the furnace. We measure the size of the coal particles after they are finely ground. Some of the measurements are made in our laboratory and others are basic measurements made at other laboratories. Thus, a single calculation of nitrogen oxide formation is based on literally hundreds of measurements from laboratories throughout the world.

Taking this approach, we launched into our model development. But it wasn't a trivial exercise. In fact, we have spent a decade of time, consumed more than one million dollars in contract research funds, and graduated four Ph.D. students, all of whom made vital contributions to the effort.[18] After all of this, we now have a model, thought to be the first of its kind, which will calculate how nitrogen oxide pollutant forms during coal combustion. Now other questions arise. Does it predict what really happens? Will anyone else want to use it? Is the cost of a solution acceptable?

We have used this model now for hundreds of predictions, but I'll refer to only two. Illustrations 4 and 5 show comparisons of predicted measured nitrogen oxide in a coal reactor. The model predicts the magnitude and the trends observed in the measurement. In fact, given the complexity of this entire process, the agreement was quite satisfying and, admittedly, surprising to us. This same type of agreement has been observed in many other cases.[19] To our knowledge, this is the only such method available for predicting nitrogen oxide formation during coal combustion, and we think of this as a significant contribution.

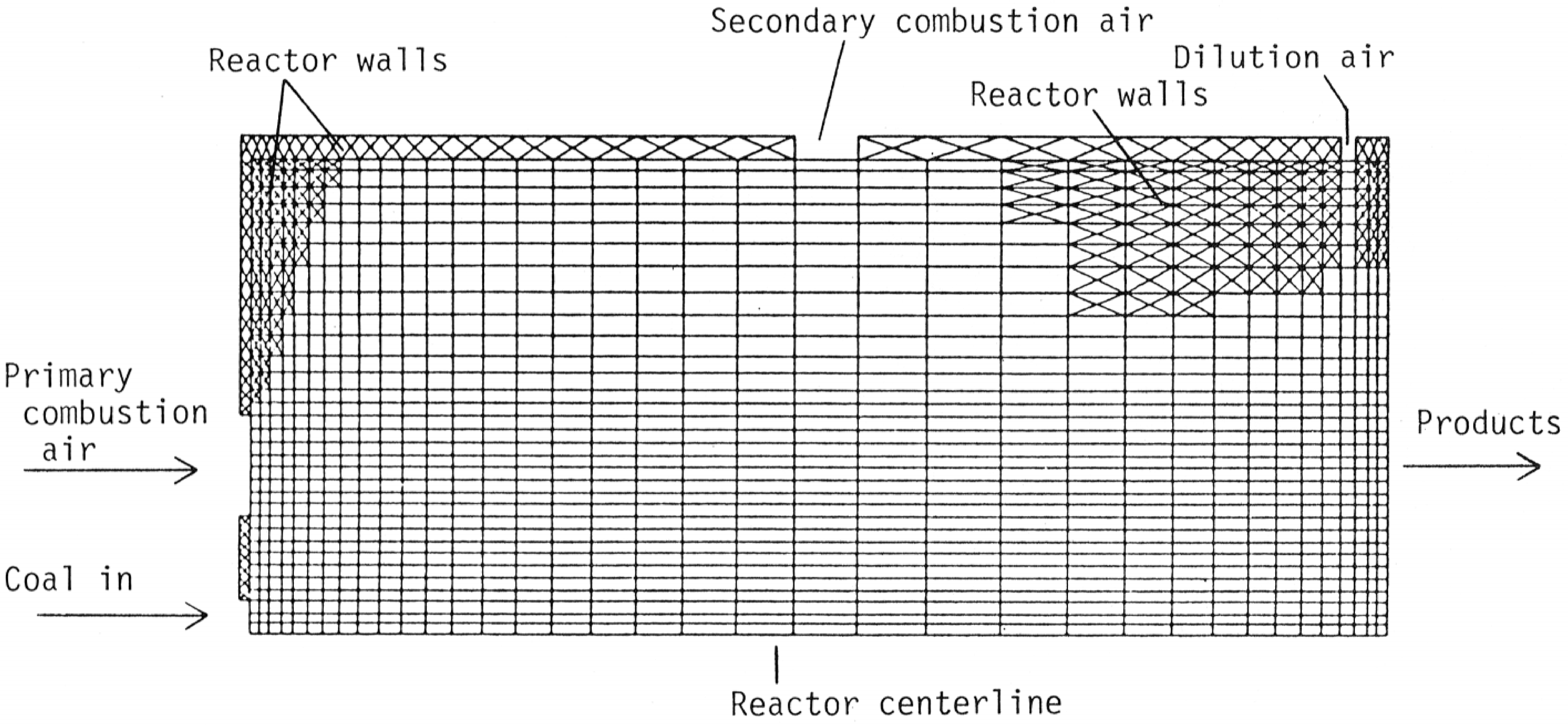


ILLUSTRATION 8. CONTROL VOLUME AND FINITE NUMERICAL ZONES FOR A TYPICAL SMALL COAL REACTOR
(40 cm long × 11 cm radius)
Illustration courtesy of Philip J. Smith.

A. GENERAL EQUATION FORM

$$\frac{\partial}{\partial x}(\overline{\rho u \phi}) + \frac{1\partial}{r\partial r}(\overline{r\rho v\phi}) - \frac{\partial}{\partial x}\left(\Gamma_\phi \frac{\partial\phi}{\partial x}\right) - \frac{1\partial}{r\partial r}\left(r\Gamma_\phi \frac{\partial\phi}{\partial r}\right) = S_\phi$$

B. SPECIFIC EQUATIONS

ϕ	Γ_ϕ	S_ϕ	Type
$\bar{u}$	μ_e	$-\frac{\partial\bar{p}}{\partial x} + \frac{\partial}{\partial x}\left(\mu_e \frac{\partial\bar{u}}{\partial x}\right) + \frac{1\partial}{r\partial r}\left(r\mu_e \frac{\partial\bar{v}}{\partial x}\right) + S_p^u + \bar{u}S_p^m$	Momentum
$\bar{v}$	μ_e	$-\frac{\partial\bar{p}}{\partial r} + \frac{\partial}{\partial x}\left(\mu_e \frac{\partial\bar{u}}{\partial r}\right) + \frac{1\partial}{r\partial r}\left(r\mu_e \frac{\partial\bar{v}}{\partial r}\right) - 2\mu_e \bar{v}/r^2 + S_p^v + \bar{v}S_p^m$	Momentum
k	μ_e/σ_k	$\Phi - \bar{\rho}\varepsilon$	Turbulence
ε	μ_e/σ_ε	$(\varepsilon/k)[C_1\Phi - C_2\bar{\rho}\varepsilon]$	Turbulence
$\bar{f}$	μ_e/σ_f	0	Mass
g_f	μ_e/σ_g	$C_{g1}\mu_e\left[\left(\frac{\partial\bar{f}}{\partial x}\right)^2 + \left(\frac{\partial\bar{f}}{\partial r}\right)^2\right] - C_{g2}\bar{\rho}\varepsilon g_f/k$	Mass
$\bar{\eta}$	μ_e/σ_η	S_p^m	Mass
g_η	μ_e/σ_g	$C_{g1}\mu_e\left[\left(\frac{\partial\bar{\eta}}{\partial x}\right)^2 + \left(\frac{\partial\bar{\eta}}{\partial r}\right)^2\right] - C_{g2}\bar{\rho}\varepsilon g_\eta/k$	Mass
$\bar{h}$	μ_e/σ_h	$q'_{rg} + \bar{u}\frac{\partial\bar{p}}{\partial x} + \bar{v}\frac{\partial\bar{p}}{\partial r} + S_p^h + hS_p^m$	Energy

ILLUSTRATION 9. SOME OF THE MODEL EQUATIONS USED TO DESCRIBE THE STRUCTURE OF A TURBULENT, COMBUSTING PARTICLE-LADEN SYSTEM[9]

With this success, it would be natural to wonder now whether our findings and methods have been used to reduce the level of nitrogen oxide in large industrial systems. Today's answer is "most likely not yet." But the computer program of our mathematical model has been obtained by about twenty-five organizations in the United States, Europe, and Japan. It's not a tool that you can just enter into the computer and let the answers start printing out. It may take a qualified professional a year or so to become really familiar with the method. Then, you may wonder, will these methods ever be used to help provide us clean power? I hope so. That's what we want to occur. That's why we offer a summer course to teach these methods. That's why we've written two books on coal combustion. But it takes time to transfer new ideas and technology to industrial use. We just reached this state of development a couple of years ago.

Maybe this will give you some idea of what we work on and how we do it. I've told you about one problem that interests us. We are also working on several other combustion problems. For example, we are studying the basic combustion processes of mixtures of pulverized coal and water. A coal–water mixture forms a thick, liquidlike, pumpable fuel that might be used to replace oil in some important applications. One promising potential use would be to burn the slurry in existing electricity-generating furnaces that were designed for oil. We, and other researchers in the United States, have shown that such mixtures can be burned quite efficiently. But much is yet to be learned about the use of coal in this manner.

We are continuing our work on combustion in dusty atmospheres. Explosions of coal dust or grain dust or a host of other finely divided substances occur far too commonly in our society. We think that a detailed understanding of the mechanisms governing these explosions will be very important in achieving greater safety for the miners and workers. Our research has already led to a significantly improved knowledge of slowly moving (laminar) dust–air flames. We want to work more on fast-moving (turbulent) flames in the future.

Our research on the gasification of coal is also adding new understanding on this important process. Coal can be partially burned to produce fuel-rich gases, particularly carbon monoxide and hydrogen, which have a variety of uses. For example, these gases can be converted to a substitute for natural gas for use in heating our homes. We have been characterizing the basic reaction processes during coal gasification at high temperature and high pressure. We think that the detailed data from our laboratory gasifier are the only such data available. In all of these studies, which involve graduate students and faculty, we try to make basic measurements and describe the processes mathematically, so we can understand what happens and with this understanding obtain some control over the result.

EXTINGUISHMENT—WILL THE FLAME GO OUT?

It depends on which flame we refer to! How about the flame of the Combustion Laboratory? It burns as brightly today as ever. And candle wax still remains. We are just concluding negotiations for our largest research grant ever—about $1.2 million over four years. We will develop a new model for application to full-scale furnaces, like that shown in illustration 10. And maybe, after that, what we've done will have helped.

We won't always work on fossil fuels. But there will always be important combustion problems to be solved. Young, outstanding faculty in our group are finding ways to mold their own candles, and, before my candle flickers, maybe I will have helped to light theirs.

How about the flame of the university? Present and past prophets have spoken about this. In fact, the last six presidents of the Church have been quoted, in one direct way or another, regarding this matter. President David O. McKay said:

> Because of its combination of revealed and secular learning, Brigham Young University is destined to become, if not the largest, at least the most proficient institution of learning in the world, producing scholars, with testimonies of the truth who will become leaders in science, industry, art, education, letters and government.[20]

President Kimball told us:

> I am both hopeful and expectant that out of this University and the Church's Educational System there will rise brilliant stars in drama, literature, music, sculpture, painting, science, and in all the scholarly graces. This University can be the refining host for many such individuals who will touch men and women the world over long after they have left this campus.[21]

We have been warmed by these promises of prophecy. The university candle is lit, and its flame will surely burn more brightly, and each of us can brighten that flame.

To complete the candlestick analogy from Matthew cited at the beginning, we read further: ''Let your light so shine before men, that they may see your good works, and glorify your Father which is in heaven'' (Matt. 5:16). Then, how about the flame of life itself? Pindar, the ancient Greek poet, reportedly said it this way: ''The loss of flame brings darkness but His glory burns brightly forever.'' Or from the Master himself we learn: ''And that which is of God is light; and he that receiveth light, and continueth in God, receiveth more light; and that light groweth brighter and brighter until the perfect day'' (D&C 50:24).

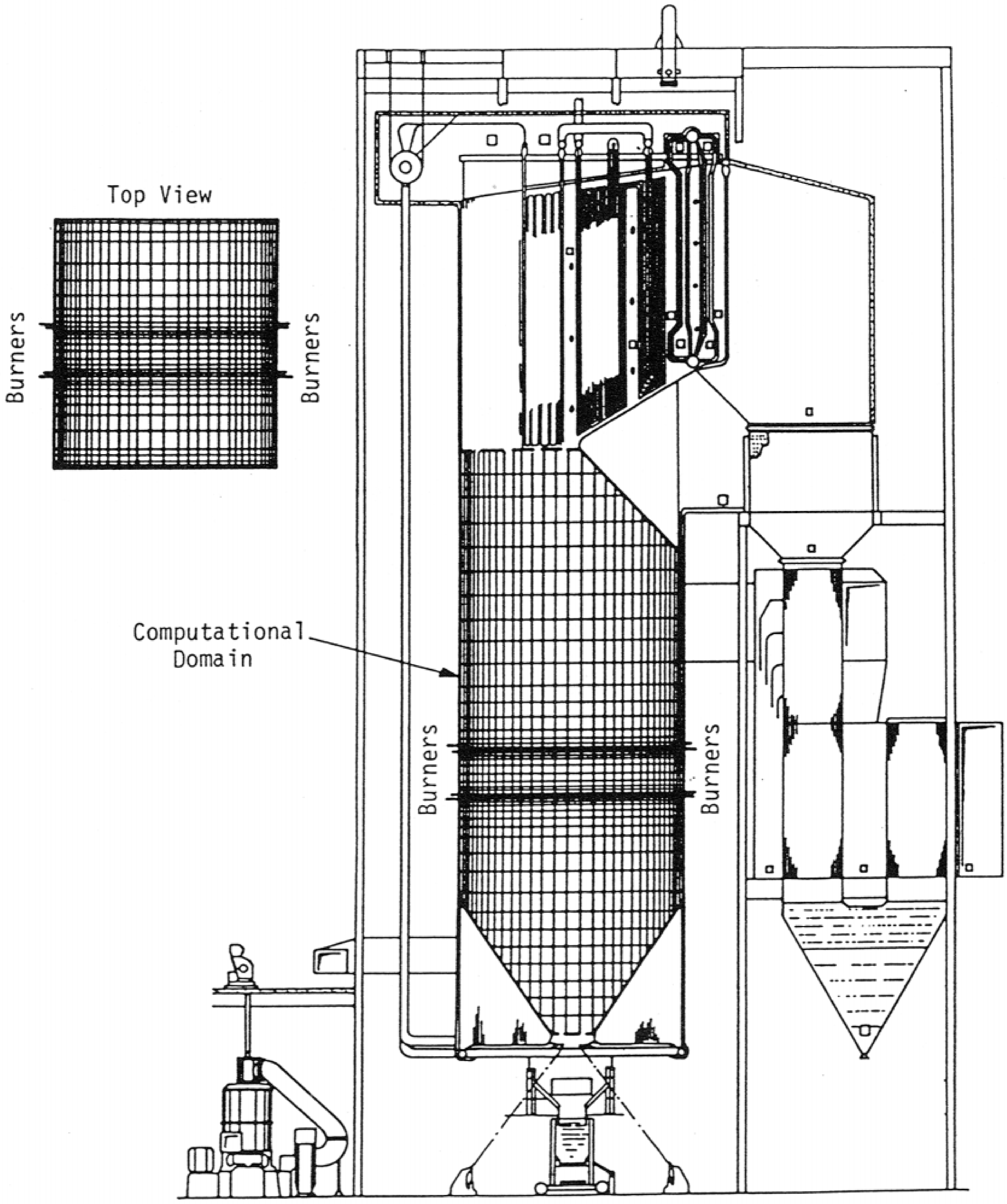


ILLUSTRATION 10. LARGE SCALE FURNACE FOR GENERATION OF POWER THROUGH COMUBSTION OF COAL
Illustration courtesy of Phillip J. Smith.

NOTES

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[13] Ibid., 20.

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