chlorine nitrate would temporarily remove them from the reaction chains. When Lazrus announced his mistaken results for hydrogen chloride, it was widely assumed that the missing chlorine had been incorporated into chlorine nitrate.

A closer investigation of the reaction rates involved indicates that chlorine nitrate is not as important a sink as halocarbon proponents had hoped, but the extent of its contribution to stratospheric chemistry is still in dispute. Rowland and Molina estimate that the formation of chlorine nitrate would reduce their original projections by about 30 percent. The NRC committee concluded that chlorine nitrate would reduce ozone damage by a factor of 1.85, and the figure of 7 percent reflects this reduction.

Unfortunately, the predicted concentration of chlorine nitrate in the stratosphere is lower than the sensitivity of measurements made so far. About all that can be said so far is that there is not much more there than is predicted by theory. But these measurements are interpreted by some investigators, such as Phillip Hanst of the Environmental Protection Agency, as indicating that chlorine nitrate is not important in stratospheric chemistry. In the unlikely event that this view should prove correct, the most probable reduction in ozone could be as high as 14 percent.

Because of all these uncertainties, it seems likely that the extent of the potential danger to the ozone layer will be the subject of dispute for many years. But there now seems little question that the theory is valid and that the danger exists, and it appears equally clear that the danger can be reduced only by eliminating unnecessary use of halocarbons.

—THOMAS H. MAUGH II

Coal Research (IV): Direct Combustion Lags Its Potential

Burning coal directly to generate electricity accounts for most of the energy now derived from this material—but contributes less than 15 percent of the U.S. energy supply. It is a use that could in theory be rapidly expanded to replace declining domestic supplies of oil and gas. In practice, means of burning coal cleanly are either not yet available or troublesome enough that environmental standards for sulfur dioxide emissions pose a considerable barrier to more widespread use. Two principal technologies are being developed to overcome this barrier: stack gas scrubbing, a technique for removing pollutants after combustion in conventional boilers, and fluidized bed combustion, a new and potentially cleaner method of burning coal and other fuels. In the past few years there has been considerable progress with both technologies in this country and elsewhere. Nonetheless, the U.S. R & D program on direct coal combustion is hindered by being split between two agencies with differing missions, by the resistance of the electric utility industry to coal clean-up efforts, and by what many observers believe to be unresolved technical problems in the experimental and demonstration equipment now being built. Overall, the impression is of a program given inadequate priority and of technologies lagging behind their potential to make a very substantial contribution to clean energy supplies far sooner than coal-based synthetic fuels.

The Environmental Protection Agency (EPA), for example, has been the principal supporter of research on stack gas scrubbers. Indeed, the Energy Research and Development Administration (ERDA) has been constrained, under the terms of an informal agreement extracted by Senator Edmund Muskie (D–Maine), from engaging in scrubber R & D. But the EPA is primarily a regulatory agency and its approach to scrubber development has been halfhearted. Having carried the work far enough to set sulfur dioxide emission standards and to establish to its own satisfaction that several different scrubber techniques are workable, the agency is phasing out its R & D support of this technology (the current budget is about $5 million). EPA spokesmen ascribe numerous failures in demonstration projects to lack of effort on the part of utility companies in making the equipment work, and the agency position is that further development of the technology is up to industry.

It is no secret that the power industry has, to varying degrees, been reluctant to adopt scrubbers. The equipment is expensive—$75 to $125 per kilowatt, a substantial fraction of the cost of the power station itself—and increases costs but not profits. Scrubbers also consume as much as 5 percent of the power output of a generating plant and introduce a whole new order of complexity, that of chemical processing, into its operation. Most of the scrubbers now planned or in operation on coal-fired boilers in the United States utilize an aqueous slurry of lime, $Ca(OH)_2$, or limestone, $CaCO_3$, as the scrubbing agent. Both are throwaway processes that consume hundreds of thousands of tons of the scrubbing reagent per power plant per year and produce even larger quantities of a wet sludge, principally calcium sulfate, which must be disposed of. Also under development are several processes in which the scrubbing agent can be regenerated and the sulfur recovered in the form of a useful by-product. The principal contenders here seem to be the Wellman-Lord, magnesium oxide, aqueous carbonate, and citrate processes.

From the utility point of view, claims that scrubbing technology has been commercially demonstrated and its problems solved are greatly exaggerated. Part of the problem is the great variability of impurities in coal and water and of operating constraints across the United States. Most successful experience so far has been with low-sulfur coals found in the western United States. No commercial equipment has yet proved able to cope with typical high-sulfur, high-chlorine coal in the eastern United States without discharging large volumes of polluted waste water. Moreover, the first trouble-free commercial unit is not yet on line, according to Gerald Hollinden, head of scrubber R & D for the Tennessee Valley Authority (TVA), a utility that has co-operated with EPA in developing scrubber technology. Designs for scrubbing equipment are still in flux, and Kurt Yeager of the Electric Power Research Institute (EPRI) says that any given unit must still be considered a prototype.

The problems encountered with lime and limestone scrubbers illustrate the complexity of the stack gas cleaning process. Combustion gases from a boiler are piped to a reactor vessel where most of the sulfur dioxide is removed. In one configuration, for example, lime or limestone slurry is sprayed from the top of the vessel while the gases enter from the bottom, to afford maximum opportunity for the absorbent liquid to react with the SO_2. The liquid is drained off to a holding tank, where more lime or limestone is added to precipitate the sludge. If the operating conditions are not held within narrow bounds, however, solids are are deposited within the scrubber vessel, eventually plugging it.

From the scrubbing vessel, the stack gas is passed through equipment known as mist eliminators, where moisture and often solids that remain in the gas stream are precipitated and recovered. Formation of scale deposits and plugging are often a problem here too, and for that reason many of the scrubbers now in use do not recover all of the moisture—a mode of operation that consumes large quantities of water. A small unit at EPA's Shawnee test facility near Paducah, Kentucky, has recently been operated in such a way as to recover most of the water without plugging and scaling, but the procedures have not been proved on commercial equipment.

After passing through the mist eliminators, the now relatively cool gas must be reheated to about 175°F. Reheating is necessary to get the exhaust plume high enough in the air to prevent fogging on the ground and to protect downstream equipment from the sulfur remaining in the gas, which, at temperatures low enough for moisture to condense, would form some sulfuric acid. Some scrubber units now reheat by burning oil or natural gas, exacerbating the shortage of these fuels; eventually a portion of the steam produced in the boiler is expected to provide the energy source for reheating, but the means to do this are not yet fully worked out.

Finally, there is what many observers believe to be the most difficult problem associated with lime and limestone scrubbers—sludge disposal. Not only is the volume enormous, 8 or 9 cubic feet per ton of coal burned or about 80,000 cubic feet per day for a 1000-megawatt power plant burning high-sulfur coal, but the sludge must be disposed of in a pond lined to prevent it from seeping into the groundwater or chemically treated to stabilize it as landfill. The scale of the problem is illustrated by the disposal plans for a new power station at Shippingport, Pennsylvania, where a valley is being dammed and will, over the next 25 years, be filled to a depth of 400 feet with sludge pumped through a special 7-mile-long pipeline (see Fig. 1). There is as yet very little experience to indicate the long-term reliability and acceptability of any of the proposed disposal techniques—such as whether the sludge will be resistant to bacterial attack that might release hydrogen sulfide.

In any case, the sludge disposal problem would seem to provide a strong incentive to develop regenerable scrubbing processes that do not produce sludge. One such process, the Wellman-Lord, absorbs SO_2 with a solution of sodium sulfite (Na_2SO_3), converting the sulfite to sodium bisulfite ($NaHSO_3$). The spent absorbent is then evaporated in a separate vessel to regenerate the sodium sulfite and the SO_2. The dilute SO_2 gas thus obtained can be used as feed to a sulfuric acid plant. Small quantities of sodium sulfate (Na_2SO_4), a potentially salable waste product, are also produced, but except for this the process operates as a closed cycle. To obtain the benefits of the Wellman-Lord process, however, a power company must either go into the sulfuric acid business by building its own acid plant or be located near one. The equipment for the process is also considered to be more expensive to install than a lime or limestone scrubber.

Fig. 1. Earth-fill dam being constructed across the mouth of Little Blue Run Valley, near Shippingport, Pennsylvania, to hold sludge that will be generated by lime scrubbers at the Bruce Mansfield Power Station. The completed dam will be an additional 150 feet in height and the valley will eventually be filled in with sludge to a length of more than 5 miles. [Source: Pennsylvania Power Co.]

A number of Wellman-Lord units have operated successfully on oil-fired boilers in Japan. The first coal-fired demonstration unit, being built by the Northern Indiana Public Service Company near Gary, Indiana, with support from EPA, is nearing completion. But EPA does not intend to fund any additional development work or demonstrations of this process should they prove necessary.

A second regenerable process employs magnesium oxide as the reagent to capture SO_2, converting it to magnesium sulfite ($MgSO_3$). The $MgSO_3$ is removed from the scrubber effluent by centrifugation and dried, and it can then be heated to regenerate the magnesium oxide and SO_2 for conversion to sulfuric acid. One advantage is that the dried $MgSO_3$ can be readily shipped, so the sulfuric acid plant need not be located near the power station. The process is also considered to be potentially comparable in cost to lime and limestone scrubbers.

What were once high hopes for this technique have been somewhat diminished, however, by problems with two demonstration units. One, an EPA sponsored test at the Potomac Electric Power Company's Dickerson station near Washington, D.C., experienced a multitude of mechanical problems and has, in effect, been abandoned. EPA officials fault the utility, but other observers believe the failure was at least in part attributable to EPA management of the program—no money was provided for contingencies, for example. A second demonstration unit built by Philadelphia Electric for their Eddystone station, was forced to suspend operations when the sulfuric acid plant contracted to regenerate the magnesium oxide was shut down by the regulatory branch of EPA for other reasons. Another plant is being sought. No further demonstrations of the process are now planned.

Two additional regenerable scrubbing processes are of interest because they produce elemental sulfur, which can be easily stored or sold, as the principal product. One is known as the citrate process because citrate ion is used to control the pH of the scrubbing solution. The other, the aqueous carbonate process, incorporates a one-step regeneration process that consumes relatively little energy. Neither is as far along as the Wellman-Lord and magnesium oxide techniques, although EPA has anounced a small-scale demonstration of the citrate process in cooperation with the Bureau of Mines, which developed the process, and recently announced a larger (100 megawatt) demonstration of the aqueous carbonate process. Still other regenerable and throwaway processes have been proposed or tested on a small scale, and the situation is far from static, although it does not appear likely that EPA will fund much additional work.

Despite the unresolved problems, stack gas scrubbing has much to recommend it—not least that it now appears to be a far cheaper way of cleaning up coal for power generation than conversion of the coal to a synthetic fuel. The electric utility industry also seems to be beginning to moderate its opposition to the technology, in part because the amount of money invested in scrubbers is becoming so large that companies cannot afford not to have them work. But there is nearly unanimous opinion among technical observers within and without the utility industry that the EPA R & D program has not resulted in a working technology, partly because, as one engineer put it, the program tended to "assume success rather than produce it." The agency, another says, too often carried processes "right to the point where they need more R & D, and then quit." Still others point out that EPA—much like the old Atomic Energy Commission—suffers from an inherent conflict in being both the promot-

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er and the regulator of scrubbers, a conflict that has severely hampered the agency's research staff. Hollinden believes that "there is an important role for ERDA, not EPA, in sponsoring further federal research on regenerable scrubbers."

At present, however, ERDA does not support scrubber R & D. Instead, its main emphasis in the area of direct combustion of coal is on fluidized bed boilers—the main alternative to scrubbers, but a technology that is not as close to commercial use. Fluidized bed boilers—a name that derives from the flow of air up through the boiler at a rate sufficient to suspend and "fluidize" a bed of particles, normally coal and limestone—offer a number of potential advantages, in particular that they might eventually be cheaper, more efficient, and more versatile than the combination of conventional boiler and scrubber.

Conventional boilers, for example, are designed for particular coals, but fluidized bed boilers can be designed relatively independent of the type of coal or other fuel they are to burn, because they operate at temperatures below the melting point of coal ash. Temperature is controlled by a series of tubes within the bed through which water is pumped to remove heat and generate steam. These tubes, which are in direct contact with the solid particles of the bed, permit a rate of heat transfer several times that of a conventional boiler. As a result, fluidized beds are expected to be more compact, of standardized designs, and possibly able to be fabricated in the shop rather than in the field.

Sulfur dioxide evolved during combustion in absorbed within the bed by limestone particles and removed as calcium sulfate in the form of a dry solid. Although the process consumes as much limestone as a scrubber, the waste material is more easily disposed of than sludge, and there have been preliminary experiments with regenerable absorbents such as magnesium oxide. However, fluidized beds do not appear capable of removing more than about 90 percent of the sulfur in coal (scrubbers do not seem to be similarly limited), and their ability to control emission of small particulates is still uncertain.

The advantages of fluidized bed boilers for power generation are still to be demonstrated, however. Initial development of the technology with small units in the United States and in Great Britain nearly came to a standstill in the late 1960's when the Office of Coal Research (OCR), the main supporter of the

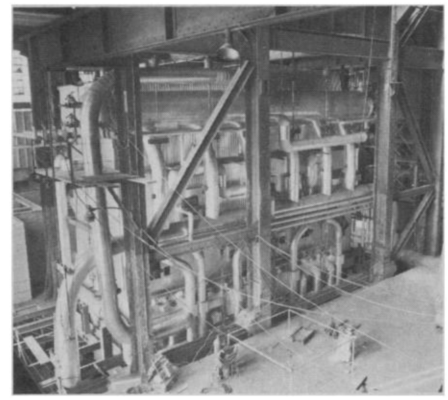

Fig. 2. One cell of a fluidized bed boiler at Rivesville, West Virginia. The experimental unit is the largest yet built and is now beginning shakedown operations. [Source: Pope, Evans, and Robbins, Inc.]

concept, ran out of money. The project was kept alive for some years with support from EPA, but larger units were not begun until 1973, when OCR (now ERDA) contracted for a 30-megawatt plant to be built in Rivesville, West Virginia, by Pope, Evans, and Robbins, Inc. That facility (Fig. 2) has only recently been completed and is beginning test operations this month.

The Rivesville plant represents a substantial jump in size from the original pilot plans—too large, in the opinion of some engineers, who believe that experience with intermediate-size units would have been desirable. Indeed, EPRI has contracted with Babcock and Wilcox, a major boiler manufacturer, to build an intermediate-size boiler. The Rivesville plant is also of a novel, modular design, consisting of three identical combustion cells and a fourth cell to burn fine coal particles that escape from the other three. According to John Mesko of Pope, Evans, and Robbins, the modular design makes it easier to control the steam output of the boiler over a wide range, and also facilitates rapid construction. He is optimistic that the boiler will operate successfully. Other observers are hopeful, but less certain. Shelton Ehrlich of EPRI, who earlier helped to develop the fluidized bed concept for Pope, Evans, and Robbins, says that it "represents something of a gamble." Bruce Henschel of the EPA's Research Triangle Park laboratory in North Carolina describes it as a "very visible project whose failure would have a dampening effect" on the utility industry's confidence in the technology.

If the Rivesville unit does work well, the technology may find rapid commercial use. Foster-Wheeler, a boiler manufacturer that is supplying part of the Rivesville plant, has announced plans to offer warranties on units of comparable size, which are suitable for steam and on-site power generation for industry, as soon as 6 months of successful operation have been completed. ERDA is considering a larger demonstration unit, probably 200 megawatts, for power industry use. TVA recently announced plans to develop and build a 200-megawatt unit, with or without ERDA's help. Development of fluidized bed technology has also been proceeding rapidly in Europe in recent years. A 25-megawatt unit based on Norwegian designs is now under construction in Enkoeping, Sweden, to supply hot water for that city's district heating system.

Most likely, both fluidized beds and scrubbers will be needed in the 1980's and succeeding decades. But beyond their present problems, these technologies may face new obstacles: evolving environmental standards that would require the control of additional pollutants could alter their relative economic attractiveness, and new information about the atmospheric chemistry and health effects of sulfur compounds and other pollutants, now poorly understood, might obviate the need for or considerably modify the application of these devices.

Oxides of nitrogen, for example, are not now controlled at all, and their output is growing exponentially. Were standards to be imposed, they could be readily met with fluidized bed boilers because of the low temperatures at which they operate but would require additional scrubbing equipment on conventional boilers. For sulfur emissions, there is now substantial evidence that suggests the health hazard is due to sulfuric acid and sulfate particulates, not the sulfur dioxide that has been the main target of the sulfur control effort. But the origins of the acid rainfall that occurs in the northeastern United States and the high sulfate particulate concentrations found in many cities are not agreed on. If they are somehow formed from the sulfur dioxide released at power plants, still tighter sulfur controls might be needed; if, on the other hand, they have a different origin altogether, sulfur dioxide controls might conceivably be relaxed enough that cleaning coal before it is burned would suffice. The existing information appears to be inadequate to resolve the issue.

Despite the uncertainties, both scrubbers and fluidized bed boilers should benefit from additional R & D, and both deserve to be considered together as the most promising candidates for increasing the contribution of coal to the U.S. energy supply, at least until synthetic fuels are more economically viable.

—Allen L. Hammond