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VOLUME 9 NUMBER 3

REVIEW

OAK RIDGE NATIONAL LABORATORY · SUMMER 76

THE COVER: *Daphnia pulex*, the water flea that figures personally in Lee Smith's article on resource competition, is just one species of zooplankton whose eating habits have apparently been misunderstood for so long. The scientific paper on which his article is based has been characterized by ecologists as "of benchmark quality," and he has received over 200 requests for reprints. See page 13 for a very readable version.

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REVIEW

VOLUME 9, NUMBER 3 **SUMMER 1976**

FEATURES

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION • FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

W. N. Shipley

Art Fraas has a hand in several pieces of the energy research pie. The innovative engineer is currently responsible for a project involving the use of a fluidized-bed coal combustion chamber coupled to a closed-cycle gas turbine as well as for efforts in designing potassium vapor cycle plants using fossil fuel heat sources. Fraas also is assisting the Thermonuclear Division in the conceptual design of full-scale fusion reactor power plants.

Currently manager of High Temperature Systems in the Energy Division, Fraas came to ORNL in 1950 to work as principal design engineer in the Aircraft Nuclear Propulsion Project. Prior to that, Fraas worked for Wright Aeronautical Corporation and Packard Motor Car Company and taught engineering courses at a Brazilian institute, Case Institute of Technology in Cleveland, and New York University, from which he earned his M.S. in aeronautical engineering. Fraas, who holds a number of patents, is author of three books and associate editor of *Journal of the Franklin Institute*.

Bob Holcomb, a mechanical engineer who has been at ORNL 19 years, is a University of Arkansas graduate and former employee of Shell Chemical Corporation in Houston. He is coordinator of the fluidized-bed coal-burner-gas-turbine project for the Modular Integrated Utilities Systems (MIUS) program under HUD. Here Fraas (l.) and Holcomb discuss the mockup of a fluidized-bed coal burner shown behind them.

The Fluidized-Bed Coal Burner

. . . a new look

By CAROLYN KRAUSE

SCENARIO I: In an Appalachian city, a 700-unit apartment complex rises out of the coal dust not far from a strip mine. Environmentalists in the town are skeptical at first about the new housing project because the builders constructed for it a coal-burning power plant that is fueled with high-sulfur coal from nearby mines. Such a plant, they say, will add to the environmental insults inflicted by the presence of old strip mines, houses and small industries using coal-burning furnaces, and a local coal-fired steam power plant spewing forth sulfur dioxide and nitrogen oxides deemed hazardous to human health. But this plant has a fluidized-bed coal burner and gas turbine, making it environmentally attractive. Its stack gas emissions are nearly free of the noxious oxides, and thermal pollution is no problem because 85% of the energy produced by the system can be used for electrical and heating needs. The waste heat from the plant not only provides building heating, air conditioning, and hot water, but also speeds the digestion of sewage in the housing complex's sewage plant. Organic wastes from the apartments are incinerated along with the coal, thus saving fuel and alleviating the garbage disposal problem. To top it all, one of the combustion by-products could be a remedy for the acidic wasteland left by local strip mining.

SCENARIO II: Executives of a large chemical company in the Southwest, concerned about imminent shortages of natural gas, decide to switch from gas to coal to produce in-plant electricity and process heat. Abandoning several gas-fired boilers, company officials opt for a 600-MW power-generating central station using a fluidized-bed coal burner coupled to a potassium–steam binary vapor cycle (potassium turbine and steam turbine). Company executives explain their choice:

- Its stack gases meet the U.S. Environmental Protection Agency's standards for SO_2, NO_x, and ash emissions.
- It is less costly than a conventional coal-fired steam plant equipped with pollution control devices.
- Its efficiency in producing electricity is 50%, as compared with 35 to 40% for conventional steam plants, thus offering a reduction in fuel consumption of about 25% and in waste heat rejection of about 50%.
- Process heat can be drawn off the thermodynamic cycle at any given constant temperature up to 1500°F (about 815°C). (Using such heat from condensed potassium would reduce the efficiency of the plant's electricity production.)

Fluidized-bed coal burners coupled to air, helium, or potassium–steam cycles for generating electricity and usable heat for housing complexes and industry may reach fruition in the 1980s if the wrinkles in such systems are ironed out in the next several years by researchers at Oak Ridge National Laboratory and elsewhere. A fluidized-bed coal burner is a chamber in which a steady flow of heated air ignites particles of coal mixed with crushed limestone and ash. If the temperature range is right, the sulfur dioxide produced in the burning coal reacts with calcium oxide produced by heating the limestone to form calcium sulfate; the calcium oxide/calcium sulfate product is a soil enricher that can be used to neutralize acidic material found around deep mines and strip mines. Thus, while the coal burns, the sulfur is captured in the bed rather than being emitted in stack gases as sulfur dioxide.

Art Fraas, Bob Holcomb, Garland Samuels, and other Energy Division engineers have completed a detailed conceptual design for a 6-ft-square fluidized-bed coal combustion chamber coupled to a closed-cycle gas turbine, which will produce about 400 kW of electricity plus 800 kW of heat that can be used for a housing complex's space heating, absorption air conditioning, and domestic hot water. In such a system, 85 to 90% of the energy in the fuel would be available for use—about one third as electricity and the balance as heat in the form of 250°F (121°C) steam obtained from a waste heat boiler. Ideally, four to eight such systems would be built for a housing complex having 700 to 1000 units to assure reliability.

The ORNL design was done for ERDA and the U.S. Department of Housing and Urban Development (HUD), which has a program to develop Modular Integrated Utility Systems (MIUS). One MIUS program objective has been to develop energy-conserving systems that use waste heat from the power-generating cycle to heat and cool houses and to make domestic hot water. In 1972, impending shortages of natural gas and fuel oil prompted HUD to ask ORNL to study the possibility of developing a small total energy system that would operate with coal as fuel. ORNL engineers concluded in a 1974 report that the most promising system would be a fluidized-bed coal combustion system coupled to a closed-cycle gas turbine, largely because such a system could burn high-sulfur coal without polluting the air. As Fraas puts it: "Ninety percent of the coal deposits east of the Mississippi River are high in sulfur. The best way to utilize such deposits in this region from a combustion standpoint is to burn them in a fluidized bed."

In 1975, Fraas, Holcomb, and their associates developed a conceptual design and cost estimate for the construction of a fluidized-bed system for test and evaluation. This year materials are being procured, and construction is under way. The MIUS project, estimated to cost a total of $2.7 million, is expected to be built and operating for tests in FY 1977.

The ORNL prototype plant, the first to couple a fluidized-bed coal burner with a closed-cycle gas turbine to produce electricity, would yield 350 kW of power and 1100 kW of heat, Holcomb says. The plant, which will consume about 6 tons of coal a day, will be located in Building 9401 at the east end of the Y-12 Plant.

The design of the prototype is based on data from ORNL studies. ORNL has operated two cold flow models of fluidized-bed burners to investigate fuel loading and mixing of the coal with limestone. One is a 10-in.-square test model used in laboratory studies, whereas the larger is about two thirds the size of the equipment to be installed in the operating prototype.

Meanwhile, Fraas is also busily engaged in studies and tests on his pet energy project—potassium-steam binary vapor cycles—which provide a means of using extremely high-temperature heat from fossil fuel or nuclear burners to spin a potassium turbine, from which heat, rejected when the potassium vapor condenses, is used to make steam for driving a steam turbine.

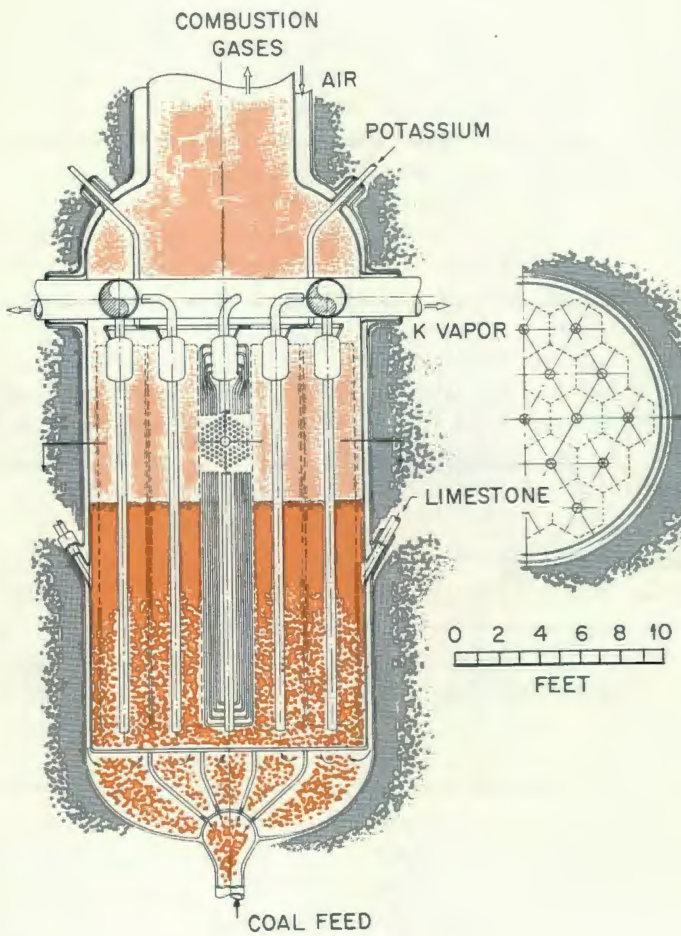
Fraas has been interested in potassium vapor cycles since 1958 when ORNL began work on nuclear electric systems for outer space. At that time the possibility of coupling a small nuclear reactor to potassium-steam cycles looked attractive. In 1959, Fraas proposed studying the possibility of coupling a potassium-steam cycle to a coal-burning plant, but Alvin Weinberg, then ORNL director, questioned the idea because of the sulfur emission problem. In the 1960s, Fraas examined the possibilities of coupling potassium vapor cycles to molten salt reactors, thermonuclear fusion reactors, and liquid metal fast breeder reactors. Then, in 1970, he proposed a gas-fired potassium boiler and received funding for the project from the National Science Foundation. The boiler has been built, and after water shakedown tests are completed, the system will be converted to operate with potassium. Fraas and his associates have requested funds to complete tests of the gas-fired potassium boilers, which should be ready for test operation in FY 1978. R. E. MacPherson, David Lloyd, and Ralph Guymon of the Reactor Division are working on the construction and testing of the gas-fired potassium boiler.

Commercialization of a gas-fired potassium boiler seems unlikely, however, because of impending shortages of natural gas and the time lag in building coal conversion plants to produce large quantities of synthetic fuel gas. "With this in mind," Fraas said, "Neal Cochran of the U.S. Office of Coal Research (now part of ERDA) and Arthur Squires, well-known coal expert and Distinguished University Professor of Chemical Engineering at the City College of the City University of New York, independently encouraged me to look at fluidized-bed coal combustion systems coupled to potassium vapor cycles." Fraas talked with fossil energy officials in ERDA about the fluidized coal bed-potassium vapor cycle concept and found willing ears. "We expect funding soon," said Fraas, adding that most of the work on the gas-fired potassium boiler should be applicable to a fluidized-bed potassium boiler. Project design coordinator for the fluidized-bed potassium boiler is Garland Samuels.

Fluidized Beds in Use

For more than 20 years, the performance of fluidized-bed burners has been under investigation in Great Britain and the United States. More than 200 fluidized-bed combustion systems for roasting pyrite ores are operating in the United States, and another 100 fluidized-bed combustion systems are in use for incinerating industrial wastes and sludge from domestic sewage plants. There are also a number of designs for fluidized-bed systems for industrial processes, particularly the catalytic cracking and reforming of gasoline. No commercial fluidized-bed coal burners exist in the United States, but there has been substantial experience in operating experimental fluidized-bed coal combustion systems coupled to steam boilers. Just such a system, designed by Michael Pope, a New York consulting engineer, will soon be tested by ERDA at a power plant in Rivesville, West Virginia. The problem with coupling such coal burners to steam boilers is that the heat transfer from the hot coal bed to the water in immersed tubes can be so great that the temperature in the bed could be reduced considerably. This effect could lead to quenching—and thus incomplete combustion of coal and more sulfur emissions. However, quenching is not a serious control problem in fluidized coal beds coupled to gas or potassium turbines, according to Holcomb.

In the novel design developed by Fraas, Holcomb, Samuels, and their colleagues, the fluidized-bed coal combustion system would be coupled to a closed-cycle gas turbine using heated



In this fluidized-bed combustion chamber and potassium boiler, the liquid potassium circulates in vertical, 1-in. tubes, which connect at the top with vapor separators, from which the vapor heads horizontally toward the turbine. Condensed potassium and the separated-out liquid potassium are sent to the bottom of the hot bed of coal and limestone via the 4-in. downcomer tubes.

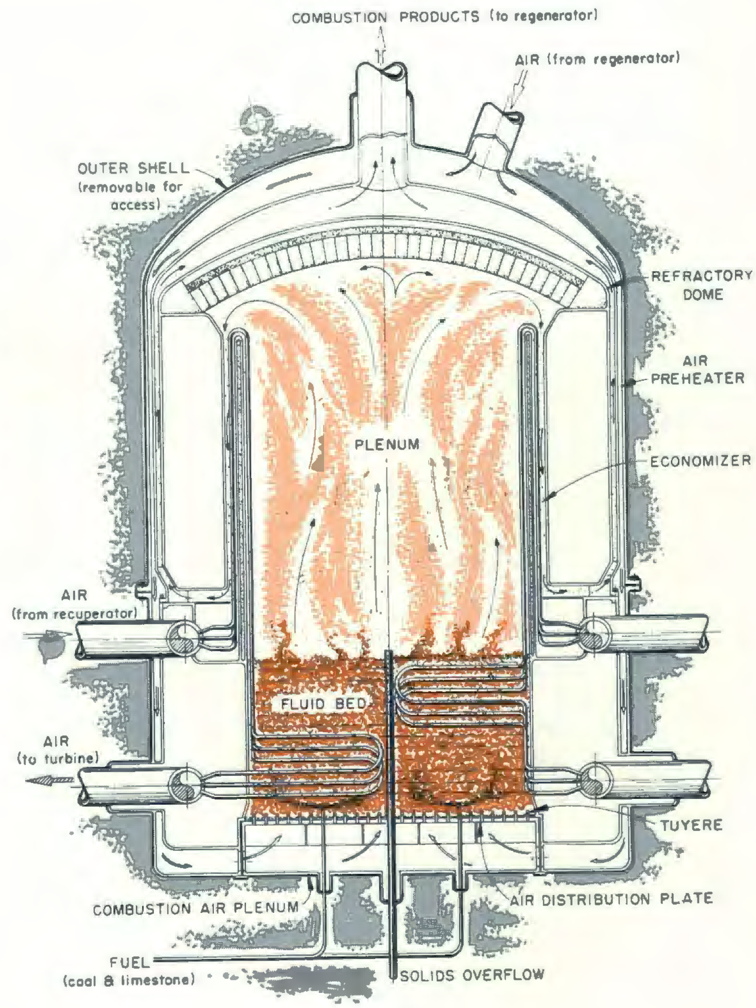
air as the working fluid. According to a recent article coauthored by Fraas, Holcomb, M. E. Lackey, and J. J. Tudor, "The special requirements of the gas turbine application present many unusual problems and lead to a design substantially different from that for any other fluidized-bed system that has been built in the past."

In ORNL's fluidized-bed-gas-turbine concept developed for the MIUS program, a bank of hairpin-shaped tubes comprising the heat transfer matrix is immersed in the combustion chamber so that the air (or some other gas in the tubes such as helium) will pick up the heat and transmit the energy to spin a turbine for generating electricity. The heat transfer matrix not only provides a means to drive a turbine, but also keeps the temperature range in the bed at 1500 to 1700°F (815 to 926°C), thus facilitating good conversion of sulfur into calcium sulfate to minimize sulfur emissions. According to Fraas: "At lower temperatures reactions between the sulfur and the lime do not proceed rapidly enough to keep the SO_2 concentration in the exhaust gas to as low a level as desired, whereas at temperatures above 1700°F (926°C), the calcium sulfate formed tends to break down, and again the SO_2 content of the exhaust gas begins to rise." This desirable temperature range also limits formation of nitric oxides from nitrogen in the combustion air and prevents the fusion of ash into glassy cinders. Because the coal bed designed at ORNL does not have to be deeper than 2 ft to give good performance, the heat transfer tubes for the gas cycle are horizontal.

Potassium Cycle Concept

In the fluidized-bed-potassium-cycle concept under development at ORNL, the bed would be

This shows a fluidized-bed coal combustion system designed as the heat source for a closed-cycle gas turbine. Heated air blown up through the bed agitates coal and limestone particles and ignites the coal. Sulfur from the coal is captured in the bed by reaction with the limestone, and heat from the coal is transferred to the hairpin tubes containing air used to drive a turbine. Heat from the combustion gases passing through the upper plenum is picked up by air in the vertical tube sections.*



designed to be about 10 to 15 ft deep to accommodate vertical tubes for the potassium coolant. The tubes would be vertical to take advantage of the natural thermal convection recirculation of the boiling potassium. As the boiling liquid moves upward during the process of turning to vapor, it would enter a vapor separator at the top of bundles of long, 1-in.-diam tubes. There the separated vapor would flow upward and out to the turbine while the liquid would join condensed potassium from the turbine and return downward through the expansion tank to the downcomer, a 4-in.-diam tube that runs down through the middle of the tube bundle module to which it connects at the bottom. The potassium that goes to the turbine must be at least 99% pure vapor since the presence of more than 1% liquid potassium erodes turbine blades. After the potassium vapor has done its work in spinning the turbine, it is condensed by transferring its heat energy to water in a boiler; the resulting steam spins another turbine, which means that half of the heat produced by the coal burner is converted to electrical energy.

The potassium vapor topping cycle would increase the thermal efficiency of a coal-fired power plant by 10 to 15% because this working fluid allows the peak temperature of the thermodynamic cycle to rise as high as 1540°F (about 838°C). As is well-known, the Carnot efficiency of any heat engine improves as the peak temperature rises. Fraas says that, if the peak temperature of steam exceeds about 1000°F (538°C), serious materials problems arise. Above this temperature, the water dissociates into its elements: The hydrogen diffuses through boiler tube walls and the oxygen attacks the steel surfaces. Because the fluidized-bed coal burner operates best at 1500 to 1700°F (815 to 926°C), it would be desirable to use this high-temperature heat for a potassium topping cycle, which would be superimposed on a conventional steam cycle with a turbine inlet temperature of 1050°F (566°C) (the temperature at which potassium vapor condenses). About 180 thousand hr of boiling potassium system operation were achieved at ORNL under the nuclear electric space power program in the 1960s. On the basis of this experience, ORNL engineers are familiar with the degree of compatibility between potassium and the boiler structural material, allowing them to design large potassium boiler and steam generator systems, Fraas said.

The MIUS System

The fluidized-bed coal-burner–gas-cycle system, as designed by ORNL engineers, would work this way. For startup, air preheated to 1000°F (538°C) by an oil- or gas-fired burner is blown from below a plenum chamber up through tuyeres or nozzles in a porous grid plate on which the 2-ft-deep bed of limestone and ash rests. Coal particles introduced through four feed ports are ignited by the steady flow of combustion air, which agitates the coal and limestone particles sufficiently to lift or float portions of the bed. Some of the particles rise into the 8-ft-high upper plenum chamber and fall back into the bed. The selection of the particle size (1/16-in. diam and smaller) and combustion air velocity (2 fps) is such that the air will float the particles but blow only the finer particles of ash and calcium sulfate out with the stack gases. The turbulence caused by the airflow results in good mixing of the coal and limestone particles so that calcium sulfate is formed and ensures good heat transfer as the different sets of hot coal particles are constantly tumbled over the hairpin-shaped turbine air tubes. (By contrast, in a fixed coal bed, the tubes are heated by rising gases, resulting in one tenth of the heat transfer that is characteristic of a fluidized bed.)

The larger particles of calcium sulfate and ash are continuously removed through an overflow line to the ash-removal system. The limestone and coal removed by this process and the fine particles blown out with the flue gas must be replenished so that they are continuously fed into the bed according to a ratio that is dependent on the sulfur content of the coal. For example, Holcomb explains, 30 lb of limestone is fed in for every 100 lb of coal with a 3% sulfur content added to the bed.

The burning coal raises the temperature of the bed to about 1650°F (899°C). The hot combustion gases generated from the burning coal rise through the upper plenum into the economizer region, where they give up much of the heat to the turbine air entering the heater via long, straight tubes that connect below with the hairpin tubes immersed in the bed.

The pressurized air in the heat transfer matrix enters the turbine at 1500°F (815°C). Heat energy (1100°F, or 593°C) from the stack gases leaving the economizer is picked up by a regenerator and used to keep the combustion air entering the coal burner heated to a temperature of 1000°F (538°C). Heat energy from the exhaust air that has passed through the turbine is recovered by a recuperator, which introduces this heat back into the high-pressure air after it leaves the compressor. The recuperator raises the temperature of the compression air from 355 to 967°F (179 to 519°C); this pressurized air then picks up even more heat energy on its way back to the turbine as it passes through the economizer and into the fluidized-bed burner.

Some of the heat (466°F, or 241°C) from the exhaust turbine air is passed into a waste heat recovery system, which provides 250°F (121°C) steam for the heating and air conditioning system and 300°F (149°C) heat for the domestic hot water heater in the MIUS system.

Engineering Problems

Fraas, Holcomb, Samuels, and their associates had to consider a number of problems in doing their design study for a coal-fueled closed-cycle gas turbine system for MIUS applications. Among the challenges are difficulties that have been encountered in operating fluidized coal beds experimentally. The major problems that have arisen in the development work done by others, according to Fraas, "have been with the feed of the coal and limestone into the bed; blowthrough of fines and separation of these fines from the gases leaving the bed; and utilization of the $CaSO_4$, either its regeneration to calcium oxide or finding a commercial use for it in its ash mixture state.

"Relatively little difficulty has been experienced in getting good combustion in the bed, the principal problem being the avoidance of excessive burning rates and hot spots at the points where the coal is introduced into the bed. Note that the bulk of the work carried out to date has been with small beds where agitation of the bed is reasonably effective in distributing the coal.

"However," Fraas continues, "if one goes to a 6-ft-square bed, as envisioned in this study, scale-up uncertainties include problems associated with devising provisions for a large number of coal feed ports across the base of the bed, distribution of coal and limestone across the bed, upper limits of gas velocity and bed depth, size and spacing of heat transfer tubes, control of the power level, and decrepitation rates and reactivities of various limestones after recycling."

In designing the fluidized bed, the ORNL engineers considered these precepts:

- The bed depth should be shallow enough to keep the pumping power for the combustion air at a reasonable value, but deep enough to allow time for fine coal particles to burn so as to minimize the amount of unburned carbon in the fines blown out of the bed.

- The number, shape, and spacing of the coal feed ports and air tuyeres should yield a high level of turbulence and excellent mixing of the coal particles just above the tuyeres.

- The bed design should include provisions for injecting up to 10% of the fuel in the form of organic material separated from solid wastes.

- Startup from cold conditions to at least 25% power in 30 min should be made possible.

- The startup operation and control functions should be simple, and the components should be reliable so that an operator need visit the installation only once or twice a day for an hour or two.

- The operating range should be free of any objectionable bed pulsations or tube vibration.

- Adequate heat-transfer area should be provided in the fluidized bed to meet heat balance requirements.

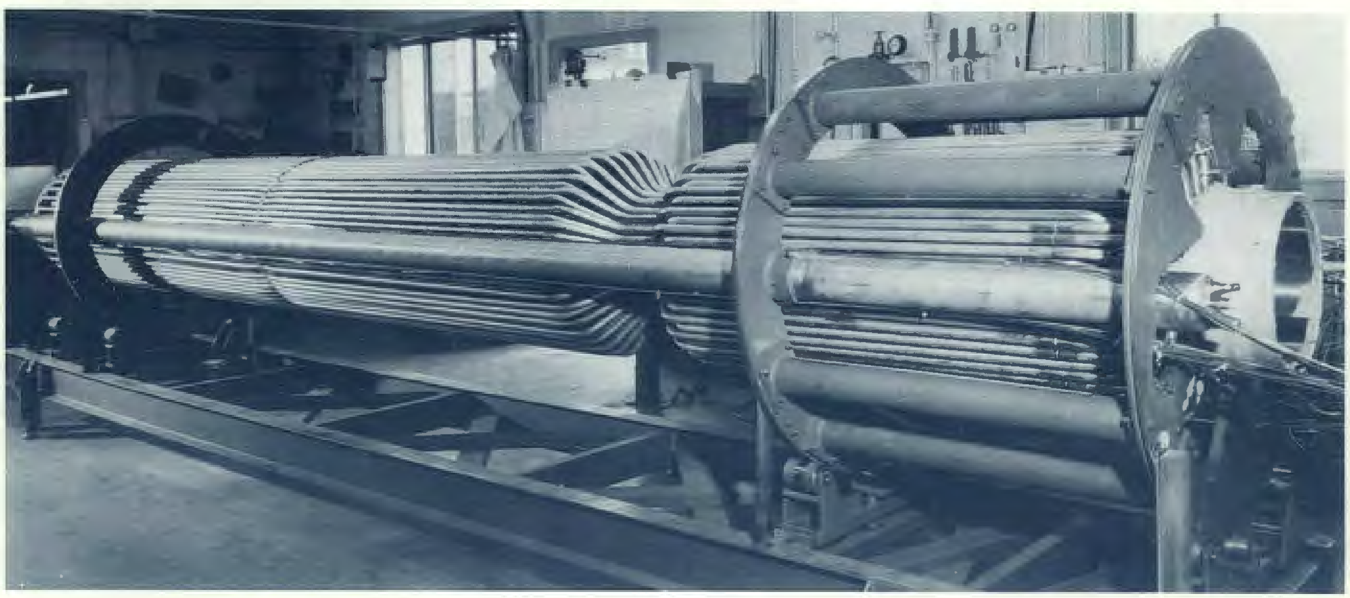
- The fluidized-bed design should permit turndown from the design operating limit to at least 50% power (half the maximum heat output), and preferably, to 25% power. This should be accomplished with no more than doubling of the amount of excess air and without quenching in the bed.

- Differential expansion between the tubes carrying the turbine air and the support structure should be accommodated elastically.

- There should be no severe thermal stresses in the furnace structure, and there should be no severe local overheating or thermal stress resulting from an abrupt stoppage of air and coal flow at design point or at any reduced power.

Experimental operation of the fluidized-bed prototype system in FY 1977 should prove a stern test of how well the ORNL design accommodates these particular conditions.

This gas-fired potassium boiler test module will be undergoing tests this summer.



Curtis Boles

Conclusion

One of the messages we get from Art Fraas is that the thermal efficiency of coal-fired steam plants has not improved any since 1950—a significant fact in an age of energy shortages. Between 1880 and 1950, Fraas says, thermal efficiencies at steam plants increased by a factor of 10, thus keeping the nation's appetite for coal from becoming excessively voracious. But the average thermal efficiency has remained on a plateau of 35 to 40% for 25 years because coal plants have reached the upper practicable limit for the steam cycle—1000°F (538°C).

To get thermal efficiencies to climb higher than 50%, Fraas recommends using other working fluids so that coal plants can be operated at higher temperatures. Thus, he favors coupling the fluidized-bed coal combustion system to either gas turbines running on air or helium or to potassium (or cesium) vapor topping cycles superimposed on a conventional steam cycle. This would mean that such a coal plant could operate at a peak temperature range of 1600 to 1700°F (871 to 926°C)—a range that is high enough to allow sulfur capture in the bed, but just low enough to avoid serious corrosion and sudden weakening of structural materials. In short, these concepts employing fluidized-bed coal burners may be a step in the right direction for engineers in quest of one of today's technological Holy Grails—economic energy-producing systems that consume abundant fuel while minimizing pollution and energy wastage.

Staff quote:

Recycling uranium and plutonium to the present generation of light water reactors (LWRs) is important to the nuclear economy because it can reduce the demand for natural uranium. When fuel reprocessing plants begin to recover uranium and plutonium from spent fuel at about the rate at which it is leaving the reactors, a significant amount of the fuel needed to sustain those reactors may be fabricated from this recovered fuel, or its equivalent. While this recycling is important to the LWR fuel cycle, it is essential to the fast breeder reactor (FBR) fuel cycle.

The first FBRs will be fueled with plutonium from LWRs, but eventually the plutonium must come from the FBRs themselves. The doubling time of the FBRs must be kept low to provide plutonium at the desired rate. This can be accomplished both by building reactors and fabricating fuels with high breeding ratios and by minimizing the time required for fuel recycle operations. Reducing the time required for fuel recycle appears both to be a promising way to reduce doubling time and to be feasible. Further, from the point of view of safeguards it is important to minimize both the time plutonium is in a purified form and the time it is outside a secure area. For these and other reasons I suggest that the IAEA sponsor studies on the close coupling of fuel reprocessing and refabrication using processes (e.g., sol-gel processes) which obviate the need to produce PuO_2 in a purified and separated form. Such processes hold promise of reducing the amount of scrap plutonium recycle, both as PuO_2 and as mixed UO_2-PuO_2. This would reduce both the Pu in-process inventory and the fuel recycle time, and thus decrease the doubling time. Further, problems attending production of PuO_2 dust, which may exist as effluent release control problems, or as problems of PuO_2 recovery from filters, equipment, and glove boxes or cells, may be obviated or at least reduced if PuO_2 powder itself is not produced.—R. G. Wymer, discussing possible future activities for IAEA.

Letter to the *Review*:

Your article on the "Thermochemical Production of H_2" arouses my curiosity. I am an inorganic chemist and have had a casual interest in such cycles as you describe for about 20 years. Several of the statements in the article surprise me: (1) "The Sr-Cr cycle reactants are less corrosive than are those of the Ba-Cr cycle;" (2) "the Sr-Cr cycle requires steam" (the presumption being that the Ba-Cr cycle does not); (3) "$BaCrO_4$ is insoluble whereas $SrCrO_4$ is soluble." It is a fact that $BaCrO_4$ is less soluble than $SrCrO_4$, but the difference is most certainly not great. Also, a large difference between the dissociation pressures of H_2O over $Ba(OH)_2$ and $Sr(OH)_2$ would be most surprising to me.

Please accept my compliments on a well-written article. I read the ORNL **Review** *almost in its entirety every issue.*

Prof. S. Y. Tyree, Jr.
Department of Chemistry
The College of William and Mary in Virginia
Williamsburg, Virginia

C. E. Bamberger replies:

I will attempt to clarify the statements that surprise Prof. Tyree, and I would like to point out that those statements are based on our numerous experimental observations. Because we have found in many instances that the data in the literature are wrong, we have been forced to rely, to a large extent, on new experimental results.

(1) We have indeed found that molten $Sr(OH)_2$ is less corrosive than molten $Ba(OH)_2$ toward some common metals; we believe that this is caused by the larger stability of barium metallates, which may be explained by the larger size of the Ba^{2+}.

(2) The Sr-Cr cycle requires the presence of steam to stabilize the $Sr(OH)_2$; otherwise, in a dynamic system such as ours, at 700° C or more, we would convert it to SrO and thus lose our ability to produce hydrogen. This, however, does not occur with $Ba(OH)_2$, despite the published information, and we have been able to generate stoichiometric yields of hydrogen at temperatures higher than those suggested in the literature.

(3) With respect to the difference in solubilities between $BaCrO_4$ and $SrCrO_4$ in water, the literature indicates that the latter is about 400 times as soluble (in mole units). This difference is somewhat decreased by the presence of the respective alkaline earth hydroxides, $Sr(OH)_2$ being more soluble and thus having a larger common ion effect on the solubility of $SrCrO_4$. I concede that, since the solubility of $BaCrO_4$ is extremely low, changing to $SrCrO_4$ does not appear to be a great gain. However, our results from hydrolytic disproportionations of barium and strontium chromates (IV) and (V) have shown unequivocally that the former yield the appropriate stoichiometric mixtures of Cr_2O_3 (hydrated) and $BaCrO_4$, whereas the latter yield only pure Cr_2O_3 (hydrated) on the filter of a Soxhlet extractor. The hydrolysis step worries us because large amounts of water have to be managed in dissolving and later drying the compounds. Although we have not yet performed any calculations on this, we think that it is not an insurmountable obstacle because the heat required for those operations would be of low grade.

C. E. Bamberger
Chemistry Division

Editorial

NATIONAL LABORATORIES ARE ERDA'S PRIME RESOURCE

The question is now sharply put: Are the national laboratories to play a major role in nonnuclear energy research and development? There is a significant segment of people in government and industry whose answer is No. They contend that, although national laboratories must continue to back the national effort with long-range research, the development and demonstration function belongs solely to industry. They cite the advantages: Industrial R&D is closely coupled to the product; it keeps the customer in mind; and the profit motive operates to shorten the time between conception of an idea and marketing of a system. They cite the record: American industry has, frequently with government support, developed remarkable products that dominate world trade in communication equipment, computers, aircraft, etc. Why, then, should ERDA not put all its R&D money into industry, where it can expect a fast payoff and rapid amelioration of the energy problem?

We disagree with this view.

Energy technology is different from defense or space technology, areas in which government-industry combinations have proved successful, although not always at bargain prices. Energy technology affects national life through its economic, societal, health, and environmental effects. We cannot put fences around it. In the case of energy, there is little choice. All of us use energy; all of us profit when it is cheaply available; all of us are subject to its potentially harmful impact. The alternative to sufficient energy is economic ruin, and worse. The apparent advantages of a purely industry-centered R&D program are bought at a dear price. Industry, with its eye on the product and the customer, takes too narrow a view of environment, health, and safety. In spite of pious promises, the record speaks clearly: The cases in which industry has voluntarily included these diseconomies are rare indeed. In nuclear energy, we have learned with great pain that a technologically sound package is not enough—that environment, health, and safety are the prime constraints on public acceptance. (Let us not repeat history in coal, oil, solar, and geothermal technology.) The ERDA officials know this. By its very structure, ERDA mirrors the broad concerns of the enabling legislation for the consequences of energy technologies, for their pervasiveness, and for their very long-range impact. National laboratories, in turn, reflect this in their technical and scientific breadth, in their reach from social science, physical research, biological and environmental science, and materials development to the hardheaded practical engineering realities that demand a cheap and reliable product developed on time and within cost limits.

Even as ERDA identifies the main technological ventures to be developed and brought to the demonstration stage, it behooves us to be prudent, to carry along alternatives in case the main effort fails or falls short for technical, economic, environmental, or health reasons. National laboratories are proper homes where these parallel technologies can be nutured until a decision is reached to turn them off or to carry them on to commercialization.

Some of the broadly based R&D practices of national laboratories may appear wasteful because the product and the customer are not the twin godheads. Now entirely different economies appear. National laboratories carry the advanced research programs. Because these reside in the same place as the R&D effort, the transfer of new scientific developments to energy technology is enhanced and, as the record shows, results in inventions and developments that alter the economics of a technology by hundreds of millions of dollars.

Energy R&D is the most difficult technological task on which a people can embark. One need only contemplate the enormous complexity of a commercial-size controlled thermonuclear power reactor, where the magnetic coils, for example, are at 4°K and the plasma at 50 million degrees. Or consider the magnitude of the industrial complex required to produce 5 million barrels of oil a day from coal or shale. Picture plants of 100,000-bbl/day capacity, each having ten to thirty 10-ft-diam steel pressure vessels with 1-ft-thick walls, operating at 500° C and 3000 psi, handling a bubbling, corrosive, and toxic three-phase slurry. The variety of problems and the difficulty and subtlety of each are without precedent. To solve them, the national laboratories provide technical strength over the entire spectrum of R&D: heat transfer in entirely new regimes; new alloys, composites, molten salts, and ceramics; materials that can withstand extremes of temperature, pressure, and radiation; the effects of corrosion and erosion; multiphase mass flow; effluent control; superconductivity; power engineering; magnet technology; ecological dynamics; and on without end. What other existing institutions have such a broad reach and at the same time have a proved record of accomplishment, in the mega- to gigadollar range, in developing devices, processes, and entire technologies ready for industry, ready for the market? This country will not reach its stated energy goals by the most subtle analysis, by modeling innovative management, or by simplistic extrapolation of industrial practices. The salient characteristics of our future energy technologies are their unprecedented technical complexity and difficulty, and the care with which we must proceed to make energy safely available.

The framers of the Energy Reorganization Act of 1974 knew this; a principal motivation in converting the AEC to ERDA, rather than starting afresh, was to keep the superb technically strong Washington staff and to engage the powerful multidisciplinary resources of the national laboratories. The task is technically difficult, heavy with societal consequences, while the financial rewards are as yet distant and dim. Because these are the precise conditions for which national laboratories were originally created, they can once again prove their worth. Their deep and meaningful involvement is, we believe, essential to the success of the entire nonnuclear energy R&D mission.—A. Z.

BOOKS

"Thermodynamics for Chemical Engineers," by K. E. Bett, J. S. Rowlinson, and G. Saville.

The MIT Press, Cambridge (1975), 505 + xii pages. Evaluated by J. Braunstein.

THIS UNDERGRADUATE TEXTBOOK covers the principles of thermodynamics and their traditional applications in chemical engineering; it includes a brief working introduction to statistical thermodynamics and emphasis on corresponding states correlations, in the authoritative and lucid manner one expects of Prof. Rowlinson and his associates. Although written for the undergraduate, this book would serve very well as an introduction to thermodynamics for one who is in another field.

"Resource Materials for Environmental Management and Education," by W. H. Matthews, J. C. Perkowski, S. K. So, F. A. Curtis, and W. F. Martin.

The MIT Press, Cambridge (1975) 259 pages, $8.95. Evaluated by Helen Pfuderer.

THIS IS A COMPILATION of outlines and bibliographies for use by anyone concerned with environmental management. Some of the subjects covered are values and perceptions, ecology, environmental effects and indicators, modeling, monitoring, economics of externalities, law, and actor-role interactions. Extensive as it is, the book is still not complete; conspicuous by their absence are many ORNL titles, quite a few of which are pivotal in their contribution: "Cadmium, the Dissipative Element," for instance; and the EIS series, "Mercury in the Environment," "Arsenic in the Environment," "Transport of Hazardous Substances through Soil Processes," etc. Although some bibliographic collections are included, missing is "Biological Effects of Ionizing Radiation," the definitive compilation by Ingram of the University of Rochester. The subject, however, may be too large to cover in one book, even a bibliography. Nonetheless, the book is a step in the process of environmental impact assessment and will be of value to those engaged in that activity. It has the additional feature of summarizing actions to be taken toward meeting the necessary goals of professional education in the field of environmental management.

Special Fall Issue

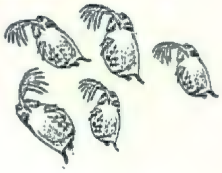
*The Fall issue of the ORNL **Review** will depart from the customary format in observance of the Bicentennial Year. Instead of the usual contemporary articles and departments, the issue will feature personal accounts of historical incidents from the early days of the Laboratory. These will be related by staff members, past and present, in varying degrees of length, technical detail, editorializing, and gravity.*

Lee Smith, a research physicist whose doctorate was earned at the University of Missouri, spent 11 years in the Reactor Division (his name is on a patent covering the Single-Fluid Molten Salt Breeder Reactor) before transferring to Instrumentation and Controls, where he is now involved in theoretical ecosystem analysis. The paper from which the following article was drawn was based on work supported by the Environmental Sciences Division, of which two of its coauthors, Shugart and O'Neill, are members. In a letter accepting the paper for publication, the editor of *The American Naturalist* wrote, "I . . . suspect that it may turn out to be one of the more important contributions on the subject of competition." That the paper has created a stir there is no doubt. Read Lee's account of it for a personable version.

Charles Tucker

Resource Competition:

an analytical model of zooplankton feeding on phytoplankton— So What?



By O. L. SMITH

RECENTLY HANK SHUGART, Bob O'Neill, Ray Booth, and I wrote a paper on resource competition, in which we developed an analytical model of plankton population dynamics—on the face of it a fairly esoteric-sounding subject. Since its publication in the September-October 1975 issue of *The American Naturalist,* more than 200 requests for reprints have come in from throughout the United States and some 20 foreign countries, with still more arriving daily. The question naturally arises: How can a paper on such a technical subject arouse so much interest?

For starters, it has something to do with the day two college friends and I had *Daphnia pulex* for supper. That happened one summer, years ago, while we were canoeing through the Ontario wilderness. Our first camp was somewhere on the remote north shore of 100-mile-long Lac Seul, and night was upon us when we lifted our paddles from the water. While my friends grappled with our tent in the darkness, I pulled a bucket of water from the lake and fixed supper, which included mixing up a package of dehydrated mashed potatoes.

Halfway through the meal, I snapped on a flashlight to look for the saltshaker that had slipped down between some rocks. The light beam skimmed over our plates, and it was then that I discovered hordes of little grayish things the size of pinheads thoroughly mixed into our half-eaten potatoes. They were either dead or in a mashed-potato stupor, but others were still wildly jumping around in the water in our half-empty drinking cups. I suddenly felt green.

Any aquatic biologist could have told us we were dining on *Daphnia pulex*—which only sounds fatal. All we had done was to inadvertently short-circuit one of nature's most fundamental food chains. *Daphnia pulex*, commonly known as the water flea, is one of dozens of species of tiny aquatic animals (zooplankton) that are usually a basic food source for forage fish (such as shad), which in turn are the basic food for most game fish.

Zooplankton feed on and compete for microscopic plants (phytoplankton), blue-green algae being a common example. Phytoplankton derive their energy photosynthetically from the sun. Collectively, the two types of plankton make up the foundation of lake, ocean, and many river ecosystems. The complete food chain is: Man eats game fish eats forage fish eats zooplankton eats phytoplankton "eats" sunlight. That evening in Ontario my friends and I had simply cut out the middlemen (middle fish?).

Plankton Research

A broad spectrum of research going on throughout the world is aimed at understanding just what makes plankton-based ecosystems function or, more and more frequently with the encroachment of man and technology, malfunction. Many of the requests for reprints of the paper described here came from Canada, where there is major interest in freshwater ecosystems; from Europe, Scandinavia, Japan, and Australia, where vast coastal areas foster interest in saltwater ecosystems; and from the west coast states of Central and South America, where both the Pacific Ocean and the high lakes of the Andes are of vital concern.

Biologists have long sought to unravel the mysteries of pristine aquatic ecosystems. Now, even before those matters are fully resolved, it is becoming increasingly important to understand exactly what makes these delicate systems break down under the mounting stresses of civilization. The tragedy of Lake Erie is perhaps the most famous example in this country.

Municipal and industrial wastes from Detroit, Toledo, Buffalo, and other cities have overloaded Lake Erie with nutrient-rich chemicals, particularly phosphates. The lake's algal populations, normally restricted by natural phosphate levels, have run amuck, increasing beyond all hope of being held in balance by zooplankton feeding and other natural processes. Decomposition of great masses of dead algae has robbed the water of oxygen, and many aquatic species have suffocated.

At Lake Erie State Park, bathers now go to the end of a long concrete pier before entering the water, trying to avoid the foul slimes of decomposing algae that contaminate the shore. Many of the beaches are posted as unsafe for swimming although some people accept the risk. Unfortunately, Lake Erie is not unique. It has numerous counterparts elsewhere in the world, such as the Bodensee of highly industrialized Europe. Eutrophication, meaning enrichment, used to be a good word, but is becoming a bad word for a dirty process.

Old vs New Models

It was against this background that the work described here was undertaken. Our goal was one of basic research—to try to learn more about the fundamental processes of plankton population dynamics. Theoretical studies on population dynamics usually proceed by accepting Volterra's famous mathematical model as a reasonable approximation of nature. However, there have been discussions in the literature of possible shortcomings of the Volterra model on both theoretical and experimental grounds. The new model discussed here attempts to overcome some of the shortcomings.

Previous workers have tended to use an overly empirical approach to modeling population dynamics. For example, if a certain behavior pattern looked "essentially exponential," it simply was approximated by an exponential term, glossing over the fact that the relatively simple-looking behavior was the net result of several more fundamental processes. Clearly, what has been sacrificed by such an approach is any hope of learning something about the more fundamental processes.

We have attempted to build the new model more rigorously, starting with a few basic premises extracted from analysis of existing data and deriving system equations from these premises, analogous to the way in which the theorems of geometry are derived from a few key postulates.

There are some basic observable facts. Close up, *Daphnia pulex* looks somewhat like a fat bird poised on a stubby tail. Movable appendages project from its head, allowing it to hop flealike through the water, filtering out phytoplankton as it goes. At low to moderate phytoplankton concentration, the gluttonous little animal continuously shovels in food at a rate directly proportional to food concentration. At high concentration, the feeding rate finally levels off. At very high concentration, the feeding rate declines, perhaps because the dense algae agglomerate and literally stick in the animal's gullet; or possibly the algae excrete minute amounts of toxic substances, which in sufficient quantity act like diet pills for zooplankton.

Another key observable is the so-called system carrying capacity. Available space and food limit the total biomass that a given habitat can support. Death rates accelerate drastically when the carrying capacity is approached. Phytoplankton carrying capacity is set largely by available light and inorganic nutrients. There is some evidence that various phytoplankton species poison each other. When crowded, zooplankton become nervous and their metabolic rate increases sharply. Like people, they drive each other crazy; and they die sooner.

These, then, are the main observable "premises" of the model. From them a set of system equations was derived which allowed interaction among an arbitrary number of zooplankton and phytoplankton species. In typical habitats such as the reservoirs of the Tennessee Valley or the Finger Lakes of New York, the number of plankton species ranges from a few to a few dozen. Because of seasonal variation of light, temperature, and nutrient availability, phytoplankton exhibit pronounced "blooms" in the spring and fall. The consumer zooplankton show a related variation.

Insights from ORNL Model

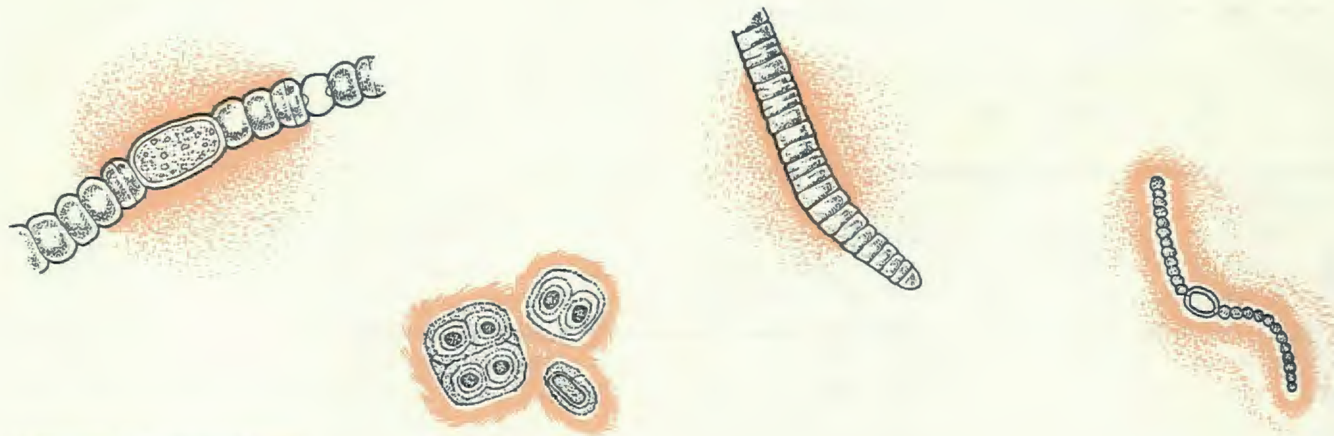
The most direct use of the model is to simulate this time-dependent behavior; but it is far more instructive to subject the equations to mathematical analysis to extract basic insights into population behavior. Three such insights are worth mentioning here.

The first has to do with the famous "competitive exclusion principle," a classic concept of population behavior put forth by G. F. Gause in 1934 (discussed here only with regard to plankton populations). According to this principle, two (or more) species cannot occupy the same ecological niche. Specifically, two zooplankton species cannot compete for identically the same food: One species will be inherently stronger and drive the other into extinction.

The new model shows that the competitive exclusion principle is, in general, not valid for the following reason. Suppose A and B are two zooplankton species competing for a single food source such as one of the blue-green algae. Further, d_A and e_A are the death rate and efficiency of food utilization, respectively, of species A, and d_B and e_B are those of species B. If A's efficiency is higher than B's while its death rate is lower, the competitive exclusion principle says that A will win the struggle for survival because of its obvious superiority.

However, as population A increases, the competitive exclusion principle fails to properly acknowledge an important phenomenon—intraspecific competition. The members of A begin to compete vigorously with each other for the food. The result of this competition, shown clearly by analysis of the model equations, is that A's death rate increases, and at a certain population level the ratio of death rates d_A/d_B becomes identical with the ratio of efficiencies e_B/e_A. Species A then loses its inherent advantage, and A and B coexist as equal members of society.

A second conclusion that may be drawn from the model is that complex communities are not always as complex as they may look. If there are J zooplankton species and K phytoplankton species in a community, the population densities are described in full by $J + K$ system equations. The model shows that, in many common cases, the set of equations can be reduced to a single pair of equations with well-defined average parameters. The complex system has the dynamic behavior of a single, mathematically equivalent zooplankton species and a single-equivalent food species. Both species are fictitious, of course, but if one is primarily interested in basic biodynamics, almost as much can be learned, and far more easily, from



Algae come in many shapes.

the pair of equations as from all $J + K$ equations. This mathematical simplification is analogous to replacing a network of resistors with a single equivalent resistor for purposes of analyzing an electric circuit.

This point brought to light a mild dichotomy among some biologists. "New biologists" usually nod in agreement with the idea, whereas certain "old biologists," having less enthusiasm for recent "inorganic" approaches to biology, shake their heads and grumble, "What do you mean, mathematically equivalent species? A water flea is a water flea is a water flea."

A third conclusion drawn from the model has to do with the well-known competition coefficient, C, which has been used for decades as an index of the strength of interaction between competing species. The defining equation for this index is $C = \Delta A/\Delta B$, where ΔA is the change in population A when population B changes for some reason by ΔB. The model shows clearly that the conventional method that has been used to calculate C is fallacious and can lead to absurd conclusions. The basic problem is that the conventional method overlooks system nonlinearities. We proposed a new method based on partial derivatives, which eliminates the difficulties.

Using the conventional method, previous workers concluded that the addition of more and more food species to an ecosystem would eliminate competition; that is, the competition coefficients between all pairs of zooplankton species would go to zero. We found this conclusion to be incorrect. When using the new method to calculate C, addition of food species equalizes rather than eliminates competition; that is, the competition coefficients between pairs of species tend to converge rather than go to zero. Competition can, in fact, be eliminated only if the species feed on different foods; the equations are thus uncoupled.

Relevance of ORNL Model

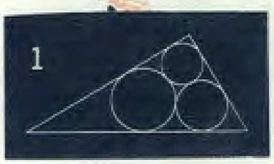
But what do competition coefficients, mathematically equivalent species, and the competitive exclusion principle have to do with really practical things like the energy crunch and the quality of our own lives? We've already mentioned worldwide concern over the insidious problem of eutrophication. Additionally, among the requests we received for reprints of our paper were those from the Duke Power Company of North Carolina, from Sargent and Lundy Engineers of Chicago, from the Bechtel Corporation of California, and from the Environmental Protection Agency's National Water Quality Laboratory.

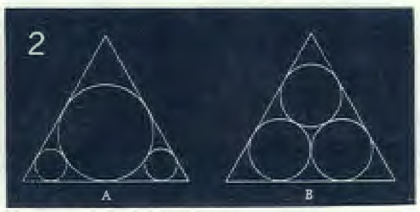
Organizations such as these are concerned with the impact of power plant thermal pollution on temperature-sensitive plankton populations, with plankton entrainment in reactor condenser water, which can be harmful to both condenser and plankton, and with the objectionable taste and smell algae can impart to municipal drinking water supplies. The list could go on.

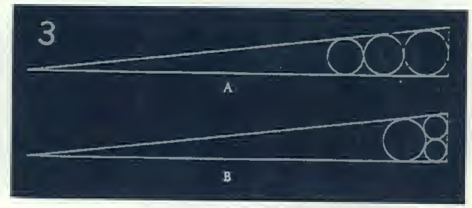
If our mail is any indication, it is clear that "resource competition and an analytical model of zooplankton feeding on phytoplankton," has something to do with a lot of things. Checking the mail is always an adventure. Today we received a card from the Food and Drug Administration. I wonder why plankton is of interest to them. Could it have anything to do with *Daphnia pulex* for supper?

Take A Number.....

BY V. R. R. UPPULURI







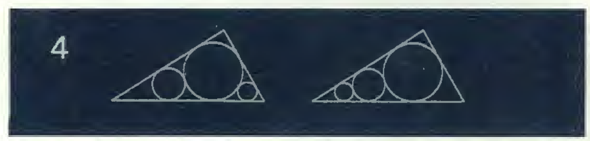
MALFATTI'S PROBLEM

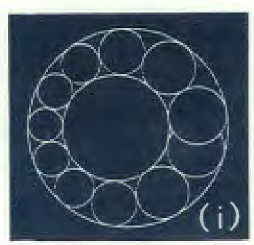
In 1803, Gianfrancesco Malfatti, Italian mathematician, stated the following problem: Given a piece of marble in the form of a right triangular prism, how can one cut three cylindrical columns from it so as to waste the least possible amount of marble? This problem is equivalent to inscribing three circles in a triangle so that the sum of their areas is a maximum.

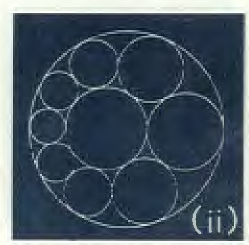
Malfatti and several others assumed that the circles should be mutually tangent and each tangent to two sides of the triangle as in Fig. 1. The problem was considered solved and put on the shelf.

After more than a hundred years, it was observed that, in the case of an equilateral triangle, the circles of Fig. 2*a* have a total area greater than those of Fig. 2*b*. In 1965, Howard Eves pointed out that, if the triangle is long and thin, the circles of Fig. 3*a* have a combined area greater than those of Fig. 3*b*, the classical solution.

In 1967, Michael Goldberg announced that the Malfatti Configuration is never the solution, no matter what the shape of the triangle is! Goldberg showed that the best arrangement is Fig. 2*a*, 3*a*, or 4; his conclusions are based on calculations and graphs. There is no mathematical proof available.







STEINER CHAIN OF CIRCLES

Suppose we are given two circles, one inside the other. We can insert a chain of circles tangent to both these circles and each tangent to its two neighbors. In general, the inserted chain will not "come out even," but will look something like Fig. (i); but, if various conditions of size and spacing happen to be just right, the chain may close as in Fig. (ii).

Suppose we find a pair of "given" circles with the closed chain. The nineteenth-century geometer, Steiner, showed that, if a closed chain is possible, then a chain started from any position will close.

Charles Tucker

Uranium Tailings in the Public Eye

By BARBARA LYON

ONE AFTERNOON in the fall of 1973, Fred Haywood, called to the phone at his desk at the Health Physics Research Reactor facility, found himself talking to his old friend, L. Joe Deal, Assistant Director for Health Protection in ERDA's (then AEC) Division of Operational Safety. Deal's call had been occasioned by some of the findings of extensive studies in several residences and at least one school in Grand Junction, Colorado. These buildings were either sitting on landfill consisting almost entirely of uranium mill tailings—a fine, granular earth containing approximately 0.03% natural uranium that is a waste product of the mills that process uranium ore—or otherwise had tailings in intimate contact with the structure, such as in mortar, concrete, or backfill around basement walls. What Deal wanted was a detailed

The material for this article came from Fred Haywood and Phil Perdue, members of the Health Physics Division who, with Bill Goldsmith, have taken key roles in the ORNL contribution to the work described. Fred, who has supervised the Lab effort, has his M.S. from Vanderbilt in physics and has been in the Division for 17 years; for three of these years, Fred served as head of Radiation Research and Development Section (now called Assessment Technology) at the Health Physics Research Reactor site in the 7700 area, popularly known as DOSAR. Phil, an electronics engineer, has been at the Laboratory for 22 years, half of which have been in the Health Physics Division. His activities on this mission have been as a troubleshooter for the high-class equipment that has gone out on the punishing field trips. High winds, rough roads, hot sun, and accompanying dust storms of a ferocity that required the use of masks and goggles—all have kept him busy maintaining the instruments at their necessary precision. Bill Goldsmith, whose doctorate is in environmental engineering from the University of Florida, came here a year ago from Los Alamos to perform the calculations on the analyses that are needed to answer some of the questions being asked of the scientists. The principals in the team are shown here outside their laboratories at ORNL, going over some samples of tailings. Seated at left is Goldsmith, with Perdue and Haywood standing, and Bill Shinpaugh, senior health physics technician and veteran of at least six of the western field trips, seated on the right.

characterization of the radioactivity that was coming through the floors and walls of the affected buildings. After it was found that tailings from the old Climax Mill in Grand Junction had been taken for private use, the Environmental Protection Agency (EPA) made an initial survey to determine what sites had been thus affected. Later, as a result of hearings in Congress, the AEC and the State of Colorado undertook a cooperative program of remedial action, which consisted of taking careful measurements at each suspected site to pinpoint the location of tailings. The need for this action was based on the concentration of radon and its radioactive daughters as well as the gamma radiation levels inside the affected structures. Knowledge of the diurnal variation of radon and its progeny is important in determining potential lung exposure to individuals living in contaminated structures. This is where the ORNL health physicists came in. The ORNL radon progeny monitoring system, based on an alpha spectroscopy technique, can measure the magnitude of daily fluctuations in the concentration of radon daughters. Deal asked Fred to go to Grand Junction to make a series of measurements in several structures that had been selected for remedial action.

Field Trips Begin

Armed with some of the Laboratory's state-of-the-art dosimetry equipment, including an alpha spectrometer developed by John Auxier and others in the division, and recently patented by ERDA, Fred set out on the 1700-mile trip with health physicists George Kerr, Phil Perdue, and Bill Fox.

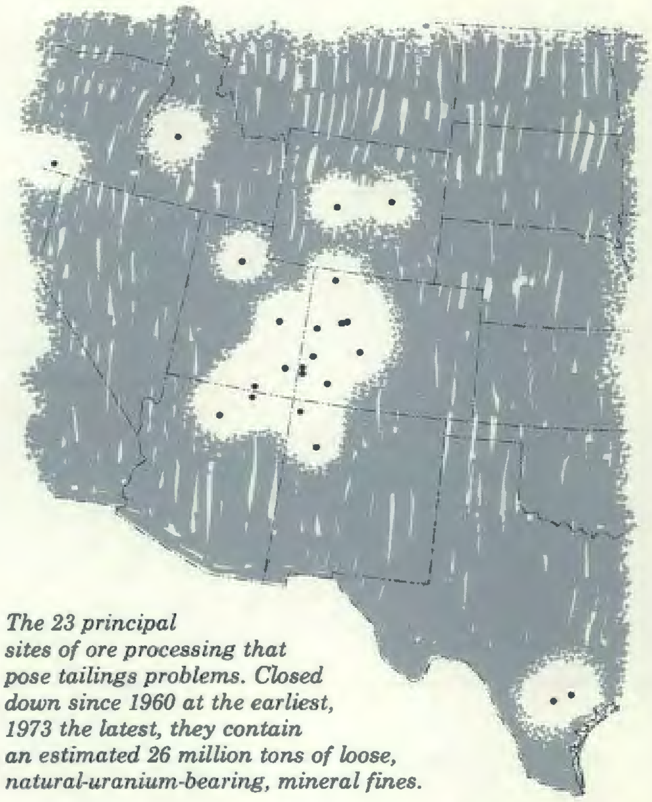
Once at Grand Junction, Fred and his team found that the radon daughter concentrations in the basements of houses resting on radioactive fill ranged up to five times the occupational level permitted for uranium miners. To date, ERDA and the State of Colorado have performed extensive reparation in the form of excavation and replacement of foundation materials, backfill, and some material in walls and chimneys. Generally, residents were relocated during this period of renovation. This activity focused attention on the tailings of the rest of the mills in the country and sparked an in-depth study of the situation.

For over a year now, a team of ORNL health physicists has been assessing the potential health hazards imposed on the surrounding populace by abandoned uranium mills in several western states. The work has been in response to a request by ERDA and EPA, who, with the involved states, have undertaken to do what is necessary to the naturally radioactive material to render it environmentally acceptable.

There are 23 of these mills, most of them in the sparsely populated sections of the country where the mines are located. Some, however, are close to populous areas, and one is within 3 miles of downtown Salt Lake City. At each mill, there is a large pile of mill tailings, the fine sandy substance that remains after the ore has been crushed and the uranium leached out. This dusty sand, left unattended and in the open, is subject to scattering and wide dispersal by both wind and water. In the past it was available to people who took it for their own use, either as fill or for construction. All this presents a possible exposure hazard to the public. The principal pathways by which radioactive materials from tailings piles are transferred to man are (1) radon emanation from the radium in the pile and diffusion through the atmosphere to populated areas; (2) resuspension of radioactive particles into the air by winds and subsequent inhalation or ingestion of these by individuals; (3) uptake of radioactive material deposited on the ground, either through uptake in food crops or animal grazing; and (4) ingestion of contaminated water or uptake of contaminated water in food crops through irrigation.

All in the Family

As is well known, uranium-238 is not very radioactive. It is a pure alpha emitter with a very long half-life (4.5×10^9 years). Although there is some spontaneous fission, the uranium decay cannot be detected with the Geiger counter. As uranium decays, however, its daughter radionuclides—isotopes of thorium, radium, radon, and the radon daughters—make themselves known loud and clear. About 85% of the natural radioactivity remains in the tailings after the ore has been processed. All the above nuclides are present in nature, to be sure, but their concentrations are several orders of magnitude greater in the tailings than elsewhere. Moreover, in the exposed state, they are more available to man; they are considered to be unstabilized. Permanent measures for their stabilization or long-term storage are now the object of the ORNL health physicists' work.



The 23 principal sites of ore processing that pose tailings problems. Closed down since 1960 at the earliest, 1973 the latest, they contain an estimated 26 million tons of loose, natural-uranium-bearing, mineral fines.

Knowledge of the tailings piles as potential hazards is nothing new; they have been the subject of radiation surveys for well over ten years. Most of these projects have been short-term and have largely concentrated on measurements of airborne activity or on the gamma radiation coming directly from the pile. In the early 1970s, the picture began to unfold as to the significant amount of this material that had been taken from some of the piles for use in the building of roadbeds, as backfill around houses and other buildings, in concrete and mortar, and even for use in driveways and in gardens and flower beds.

In other communities, demands have been vocal that these large, in-situ sources of natural radioactivity be removed to an area where long-term management is practical and where the radiological impact on man and his environment is minimized. Mingled with the objections posed by well-informed citizens are the shriller voices of those who warn that these piles will be responsible for the deaths of millions before the nuclides become harmless through radioactive decay. Considering the issues and the current climate of public feeling on this and related subjects, even more caution and study may be called for than would seem to be warranted by the hazards imposed. If, for instance, the final decision is to

ORNL's mobile laboratory van is parked by a partially dismantled process building at a uranium mill near Tuba City, Arizona. This photograph was taken from a uranium tailings pile, part of which can be seen in the foreground.

F. F. Haywood

Holding a uranium tailings sample, Phil Perdue stands atop a 250-ft.-deep tailings pile overlooking Durango, Colorado.

F. F. Haywood

remove the piles, there is still the problem of how, where, and by what routes they should be moved. An environmental impact statement will be required prior to performing remedial action at each site.

JCAE Takes Hold

In March of 1974, hearings were held by the Subcommittee on Raw Materials of the Joint Committee on Atomic Energy (JCAE). Under scrutiny were identical bills before both houses of Congress that would provide means for a cooperative arrangement between the then AEC and the State of Utah to (1) conduct an assessment of the abandoned Vitro uranium mill in Salt Lake City and (2) recommend appropriate remedial action to minimize exposure of area individuals to radiation from this site. Because of the existence of other sites with similar problems, the study was divided into two phases. The first phase was to extend considerations of the need for action to all such sites initially on the basis of observations made during site visits. Accordingly, phase II would involve in-depth assessments, including an evaluation of the various problem areas as well as a study of alternative solutions. Phase II studies would also serve to identify costs and to specify the engineering details required for corrective action. ERDA's Assistant Administrator for Environment and Safety, James L. Liverman, then testifying for the AEC, proposed that the studies be undertaken by the concerned states and the appropriate Federal agencies, such as ERDA (later) and EPA. The JCAE agreed, and the program commenced in mid-1975. ERDA awarded the engineering firm of Ford, Bacon and Davis, Utah of Salt Lake City a contract to perform an engineering evaluation of each site and to propose alternative solutions to the attendant exposure problems. For the radiological surveys, remedial action criteria, and the estimation of potential health effects from continuous exposure to radiation from these piles of tailings, the ORNL health physicists were brought in.

ORNL Goes West

In August 1975, a caravan set out from Oak Ridge bound for Salt Lake City. In it were Haywood, Fox, Perdue, and Bill Shinpaugh. The vehicles consisted of the Health Physics Division's mobile laboratory van, a veteran of many years of field study; the vast, computer-equipped semitrailer laboratory that requires a diesel tractor for its transport; and Perdue's yellow Mustang, on the front seat of which was strapped to a foam rubber cushion the supersensitive "GeLi," a germanium-lithium gamma-ray detector that must be kept in a bath of liquid nitrogen to maintain it at the required −196°C. Even so, the agitation of the trip, described by one of the travelers as "ten miles up and down for every mile forward," caused enough nitrogen to evaporate that the bath had to be replenished weekly. In its home-base repose, the GeLi requires fresh nitrogen only about once a month. The little car served another purpose: its relative comfort offered a rotating relief to those who were compelled to ride in the ancient, jolting van.

In the van, however, was a wide assortment of necessary equipment: air monitoring instruments, gamma-ray detectors, equipment for measuring the profile of radium at different depths in the ground and in soil and water samplers, multichannel pulse-height analyzers, high-resolution gamma-ray spectroscopy detectors, and additional miscellaneous test and support hardware, including its own portable 12-kW electrical generator. The 8- by 35-ft semi is equipped as a workshop, laboratory, and office and is used on such trips as the base of operations. It contains a computer-based, pulse-height-analysis system for identification of radionuclides in soil, water, and other material. Additional computer flexibility is provided in the use of the ORNL PDP-10 on timeshare by FTS hookup in the evening. Places where this lab may be used are limited because of the need for telephone and electrical connections. It is usually parked at Government-owned facilities.

In Salt Lake City, the field office was parked at the General Services Administration Building. The pile of tailings lies at the corner of 9th West and 33rd South Streets in the city and covers about 110 acres. Ford, Bacon and Davis, Utah estimates that it contains 1.7 million tons of the residue. This firm, incidentally, was chosen for its well-known ability to estimate quantities of material in geologic formations and its expertise in estimating the requirements and costs for moving large quantities of earth.

At the Salt Lake City mill, the Vitro Chemical Company extracted uranium from ore from May 1951 to February 1964, and the mill was used to extract vanadium until 1968. After that the mill was dismantled, leaving the tailings where they had been dumped. Since then, commercial and residential development has been on the increase in the area, adding to the concern about potential health effects of this source of radioactivity.

In assessing the characteristics of the pile, 4-in. wells were bored through the tailings and into the subsoil, and the gamma-ray reading was logged at 1-ft intervals along the length of the bore. These logs were used to determine the position of the interface between the tailings and the subsoil. Next to these wells, core samples were retrieved. These were dried and pulverized at the Bureau of Mines' facilities in Salt Lake City and were brought back to Oak Ridge for analysis. More than 400 samples were taken in the area, primarily to determine the migration of radium and uranium into the native soil, but also to assess the lateral extent of contamination.

The team ascertained that contamination had spread outside the boundaries of the site and was deposited both on the ground and in the sediment of streams running through the site. If there has been a migration of the material to soil beneath the tailings, the movement is at least confined to 2 or 3 ft.

The Salt Lake City site, because of its situation within a major urban center, is of the most immediate concern, but it is only one of 23 such tailings piles in the western United States, ranging from Idaho to the "four corners" area where New Mexico, Arizona, Utah, and Colorado meet. One of these is left from the extraction of vanadium used in steel manufacture; four are on the Navajo Indian Reservation. Nearly all of them are now posted or fenced (generally by three strands of barbed wire), although the immediate problem is the education of the residents concerning the possible hazards of the material. At one of the sites, a trade school instructs Navajo youths in the use of heavy earth-moving equipment. A current objective of the school is to cover the tailings with sand and rock, thus reducing the radon emanating from the material and preventing radioactive particles from becoming airborne in high winds.

Complex Operation

The activities of this program are not limited to those in the field; after the environmental samples are collected, they are transported to Grand Junction to be dried and crushed. Then they are shipped by air to Oak Ridge, where they are weighed, packed into sample-counting containers, and recorded in a logbook. The time-consuming analyses are then performed by using both radiochemical and gamma-ray spectroscopy techniques to determine the radionuclide inventory in each sample. Phil Perdue does most of the gamma-ray counting and associated data reduction. Many samples (water and some soil) require radiochemical techniques for the analysis of nuclides such as thorium-230 and lead-210. Most of this work is done by Paul Lantz and Lou Henley. After the analyses are completed, it is necessary to define the radiological impact of each individual tailings pile as a distributed source of radioactivity. The principal radiological hazard is associated with the radon that emanates from the tailings and is dispersed by wind to populated areas. Bill Goldsmith is responsible for developing a radon source term from the results of sample analyses, as well as from other physical data taken in the field. In addition, it is Goldsmith's responsibility to estimate the total potential health effects on the people residing in an area affected by the radioactivity from individual tailings piles and to evaluate the various criteria that have been proposed as guidelines for determining the need for remedial action.

What's The Answer?

Among the solutions to this problem that are under consideration, one option is to turn the tailings to commercial use for further extraction of their valuable materials. They still contain up to 10% of their original uranium and most of the thorium-230 and radium-226; unfortunately the thorium and radium cannot be readily used. When the ore was originally processed, uranium had an artificially imposed price on it of $7 to $8/lb; as the price steadily mounts, more sophisticated removal methods become economical. However, for this alternative to provide an adequate solution to potential health problems, virtually all the radium and thorium must be removed. The compounds containing these elements are among the more insoluble materials in the earth's crust, and it may not be possible to achieve this desired high level of removal.

Stabilization of those piles located in more remote areas can be achieved by covering them with up to 2 ft of soil, fertilizing the area, and planting grass. All that is needed is a certain vigilance with the irrigation until the grass gets established, and then a routine irrigation and inspection program should prevent any widespread dispersion of the tailings. A third option to be considered is physical removal of the material to sparsely populated areas for containment before covering it with large quantities of earth.

How Much Danger?

The highest gamma-ray background found so far in this study has been 155 millirems per year, as opposed to an average of about 110 millirems per year for the rest of the country. However, near points of public access to tailings piles, the gamma radiation level has been found to be as high as 1750 millirems per year. Background radiation varies widely throughout the world: A densely populated area in Kerala, India, gives a natural reading of 1500 millirems per year; a thorium-rich area in France yields 200 millirems per year; the beach area at Rio de Janeiro has a background of 600 millirems per year; and in Minas Gerais, Brazil, a population of 11,279,872, give or take a few thousand, lives with a background radiation of 2000 millirems per year.

When their findings are complete, Haywood and company will submit their report to ERDA and EPA.

The advent of the Nuclear Age has presented man with the challenge of removal and control of radioactive materials resulting from gross processes. This challenge is especially apparent in management of wastes from various recovery processes. In Florida, for example, there are "hot" roads resulting from the use of the spoils from phosphate mining operations. This marl, which contains an estimated 75 to 150 ppm of uranium, can be used as fill under roadbeds and has also been mixed in the asphalt used for the highways in Central Florida. Such a use has been seriously proposed for the uranium tailings in the West, that is, putting the hot material in the center of the huge fills of the superhighways, banking it with ordinary fill, then covering it with asphalt.

At least no one would build a house on it.

Solar Cells

Jim Richmond

John Cleland positions the light source to activate both the pocket-sized solar cell held by Dick Wood, l., and the bench model being adjusted by Rosa Young. On the right, Russ Westbrook proudly displays the pure silicon material that will later undergo neutron transmutation doping—the key technique in the ORNL process for making efficient photovoltaic solar cells.

R&D *Achievement* at ORNL

Researchers in ORNL's Solid State Division have produced solar cells from silicon doped with phosphorus by the technique of neutron transmutation doping. These photovoltaic cells, the first ever to be made of neutron transmutation doped (NTD) silicon, currently have an efficiency (output power divided by input power from the sun) of about 10%, which is about the same as the efficiencies of most commercially manufactured solar cells. However, cells made from NTD silicon have the potential for achieving substantially higher efficiencies once the parameters affecting their performance have been optimized.

Dick Wood, John Cleland, Russ Westbrook, and Rosa Young, with the assistance of numerous colleagues, fabricated and tested the NTD silicon solar cells in less than four months—a remarkably short time for such complex devices. Neutron transmutation doping of the silicon with phosphorus was achieved by placing silicon ingots in the Bulk Shielding Reactor for prescribed time periods. The ^{30}Si atoms, which comprise 3% of normally available silicon, were transmuted to ^{31}P atoms upon capture of thermal neutrons from the reactor. Since this transmutation occurs randomly throughout the ingot, the resulting concentration of phosphorus is uniform. By contrast, conventional methods of doping (such as adding phosphorus to the molten silicon from which single crystals are grown) introduce nonuniform or inhomogeneous concentrations of ^{31}P. These inhomogeneities in the dopant concentration take the form of striations that intersect the p–n junction and degrade the carrier lifetime, thus adversely affecting the performance of the cell.

The p–n junction is an electrical barrier which separates holes (p, or positive charges) from electrons (n, or negative charges); without this separation, electrons and holes would recombine and no electric current would be possible. Solar photons create electron-hole pairs in the solar cell, and the p–n junction drives the electrons to one surface of the cell and the holes to the other, thus building up a voltage difference that can produce a flow of electric current through an external circuit. It is the n-type semiconducting material in the NTD cells that is produced by doping silicon with phosphorus; phosphorus can supply negative carriers of electricity because it has one more electron than is necessary to satisfy the valence-bond requirements of the neighboring atoms of silicon. The p-type region in the solar cell is made by diffusion or ion implantation of boron into the silicon. Because boron has one too few electrons to satisfy the valence-bond needs of the surrounding silicon lattice atoms, positive holes, which can migrate through the crystal, develop. When p and n regions are created in the same crystal, a small fraction of the electrons from the n region combine with some of the holes from the p region to create the electrical barrier or p–n junction.

After doping silicon ingots with phosphorus by the neutron transmutation process, the ORNL team sliced the rods into discs, which were then cleaned, etched, polished, and diffused with boron on one side to form the p–n junction. The discs were then sent to Bill Early (in Ed Kobisk's Isotopes Research Materials Laboratory), who performed the metallization—laying down metal fingers, or current-collecting contacts—by sputter deposition of layers of titanium, palladium, silver, and gold through carefully machined metal masks. Once the cells were made, the ORNL team determined their efficiencies by measuring open-circuit voltage, short-circuit current, and the so-called "fill factor."

Dick Wood, theoretical physicist in charge of this ORNL team, says that the group is also "excited about the possibility of using polycrystalline silicon (polysil) for making solar cells." The researchers believe that NTD polysil, which is much less expensive than single-crystal silicon, shows promise for having an efficiency significantly improved over that of conventionally doped polysil solar cells. Says Wood: "The highest efficiency of single-crystal silicon solar cells attained to date is 15% (achieved by an undisclosed, proprietary technique used for the U.S. space program). Theoretically, this figure could be close to 20%. Many device theorists think that inhomogeneities in doping may be a significant factor in the inability to attain the theoretically estimated efficiencies in single-crystal silicon cells." Current efficiencies in conventionally doped polysil cells are of the order of 1 or 2%, and it is here that the ORNL researchers believe the elimination of inhomogeneities by neutron transmutation doping has the greatest promise.

Polysil is produced by chemical vapor deposition—depositing silicon from silane vapor onto a substrate of silicon, aluminum, graphite, aluminum oxide, steel, or other materials. Microcrystals, or grains, that are formed are separated by grain boundaries, to which impurities freely diffuse at elevated temperatures during deposition. The ORNL measurements show that transmutation doping of polysil incorporates the phosphorus dopant uniformly into the bulk of the grains, thus preventing its aggregation in the grain boundaries. The Solid State researchers are also investigating the use of the Schottky barrier technique for producing solar cells. These cells are formed from doped silicon by putting down a thin (100 Å), translucent layer of gold between the NTD silicon and the metal fingers. The gold is sputter-deposited at low temperatures and does not diffuse to the grain boundaries, as is the case with the diffusion of boron to form p–n junctions.

The first work in transmutation doping of semiconductors was carried out in the early 1950s at ORNL when K. Lark-Horovitz of Purdue University and his graduate student, John Cleland, came here to use the Graphite Reactor for studying radiation damage in semiconductors, particularly germanium. Recently, both German and American workers have demonstrated that NTD silicon gives significantly improved performance when used in avalanche detectors, high-power rectifiers, thyristors, and other electronic devices. (On April 20, ORNL and ERDA held a Conference on Neutron Transmutation Doped Silicon, organized by Wood, Cleland, and Carol Oen of ORNL's Office of Technology Utilization/Commercialization.) Now transmutation doping may become an important key to improving efficiencies of photovoltaic cells, which are, as Wood calls them, "batteries run by the sun."

MORE . . .

R&D *Achievement* at ORNL

Using the neutral beam injection technique pioneered in Oak Ridge, ORNL researchers have heated magnetically confined plasmas of hydrogen ions and electrons in the ORMAK fusion research machine up to 15 million degrees Celsius, the highest ion temperature ever achieved in a U.S. tokamak experiment. This temperature record, achieved earlier this year through the injection of 350 kW of particle beam power (neutral hydrogen atoms), is about a factor of 3 greater than temperatures attained with resistive heating in ORMAK last year. After ORMAK is dismantled next year and replaced in late 1978 with ORMAK Upgrade, a $7.3 million machine designed to have an injection power of 2000 kW, ORNL researchers hope to attain ion temperatures approaching 60 million degrees—the minimum temperature believed necessary to cause hydrogen ions to fuse, provided that the plasma is sufficiently dense for a long enough time (about a second). If fusion reactions of hydrogen isotopes (deuterium and tritium) are achieved at specific critical temperatures, large amounts of energy can be released for such uses as the production of electrical power.

Concerning the ORNL temperature record, Robert L. Hirsch, Assistant Administrator for ERDA's Solar, Geothermal and Advanced Energy Systems, said: "The ORMAK achievement is significant for at least two reasons. First, it indicates that plasma temperatures in tokamak systems can be increased many times over by increasing the power injection heating systems. Second, the temperatures produced are in substantial agreement with theoretical predictions."

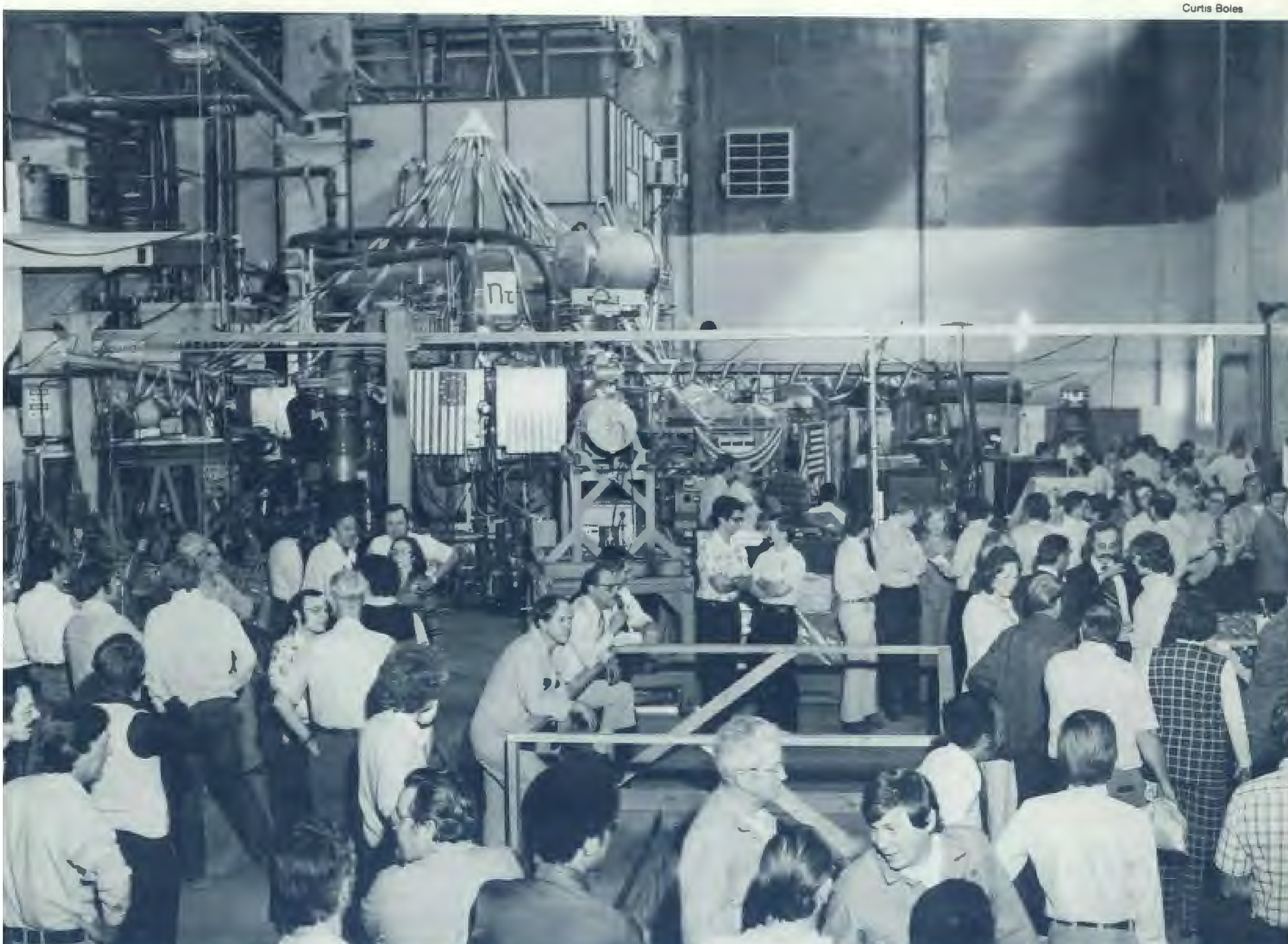
Another record established recently at ORMAK concerns the effectiveness of using magnetic field pressure to confine plasma in a standard-type tokamak. Plasmas must be confined so that there is minimum contact between the ions and the tokamak walls; if the ions are not kept away from the walls, resultant energy losses will destroy the plasma. At ORMAK, the ratio of plasma pressure to magnetic field pressure achieved was 1.5, a factor of 3 higher than previously recorded on the research machine.

This work was carried out by a number of groups in the Thermonuclear Division, of which John Clarke is director. Lee Berry heads the ORMAK experiment group, Jim Callen directs the theory group, and Bill Morgan and Larry Stewart lead the neutral beam technology effort.

Fusion Milestone

Thermonuclear Program members gather around ORMAK on March 1 to celebrate the achievement of an ion temperature of 15 million degrees, confirming theories on the application of advanced techniques in plasma heating.

Curtis Boles



Lab anecdote

Early group of computer users, with only the first three from left identified: Dave Holmes, Phyllis Johnson, and Jerry Fishel.

ACCOUNTANCY AND CRITICALITY

In the first several years of operation of the Graphite Reactor, a single accountant kept track of the plutonium produced in each of the 842 channels. He did this with Hollerith cards and an IBM card-reading mechanical calculator. Scientists elsewhere in the Lab used the more common Monroe calculators.

In a lecture last year, R. P. Feynman of Cal Tech related the story of wartime calculations at Los Alamos performed in a roomful of IBM accounting machines. While they awaited delivery of the machines, the calculating team debugged the computational programs with the Monroe calculators. The productivity of the assembly-line computations was greater than with each member doing the full string of operations independently. Parallel computation, an advertised feature of modern machines, was easily achieved then merely by using a differently colored deck of cards for each problem.

The Y-12 Plant had several accounting machines because its uranium accounting was a larger problem than plutonium accounting at X-10. Following the war, ORNL scientists applied the Los Alamos experience to reactor physics computations. Of that early group, Bob Coveyou, Ruth Arnette, and Phyllis Johnson are still in the Computer Sciences Division and Dave Holmes is in the Solid State Division. Alston Householder, now retired, was director of what was called the Mathematics Panel, which did its work with the accounting machines and desk calculators.

With the accounting, printing, and card-sorting machines used together, the speed was really no greater than manual work; but since the machines could be used around the clock and seldom got tired, they were more productive. With the first machines to use vacuum tubes came the patch board that could control them as one unit, and the card-programmed computer did increase the speed of computation notably. Then came the fast memories such as were used in the ORACLE at ORNL and later in the IBM-709 at K-25, the first really good computers. In the accounting machine days, the fast memory, the slow memory, and the long-term memory were Hollerith cards stored in boxes. One had to have plenty of stamina to carry the boxes from machine to machine and never stumble.—Herbert Pomerance

Awards and Appointments

David Trubey has been elected a Fellow of the American Nuclear Society.

Winner of an Award of Merit in the Technical Journal Articles category at the 1976 Recognition Programs of the Society for Technical Communication in Washington in May was "The ECCS Rule-Making Hearing," appearing in the January–February 1974 issue of *Nuclear Safety*, **William B. Cottrell,** editor.

Kenneth E. Shank was named winner of the Glenn L. Jenkins Recognition Award at Purdue University for his achievements in building the internationally known research and training program of the pharmacy school there. Shank joined the ORNL staff in August after being awarded the Ph.D. degree in bionucleonics at Purdue.

The Knoxville–Oak Ridge section of the American Institute of Chemical Engineering has named **Charles D. Scott** "Engineer of the Year."

Mike Guerin has been appointed to the National Cancer Institute's Tobacco Working Group.

Herman Postma has been elected to the Board of Directors of the American Nuclear Society. He has also been appointed to the Advisory Council of the College of Business Administration of the University of Tennessee.

W. D. Shults has been named director of the Analytical Chemistry Division, succeeding James C. White.

Pete Patriarca was selected by the board of directors of the American Welding Society to present the Comfort A. Adams Lecture at its annual meeting in St. Louis on May 10. This distinction is awarded in memory of the society's founder to an outstanding scientist or engineer for the presentation of some new and noteworthy technical development.

The "Significant Achievement in Management" award was presented to **Jim Weir** by the Tennessee Society of Professional Engineers during the WATTec conference in February. Also at the conference, **R. E. MacPherson** received the award for "Significant Engineering Achievements in R&D."

James M. Leitnaker was elected 1976–77 chairman of the Nuclear Division of the American Ceramics Society.

Bennie McNabb received the "Metallurgical Engineering Assistant's Award" presented by the Oak Ridge chapter of the American Society for Metals.

One of three members of the American Nuclear Society recently elected to a 3-year term on the Executive Committee of the society's Environmental Sciences Division is **Thomas H. Row.**

Herbert W. Hoffman is chairman-elect of the Heat Transfer and Energy Conversion Division of the American Institute of Chemical Engineering.

John Clarke was named a Fellow of the American Association for the Advancement of Science.

Dick Raridon was named president-elect of the Association of Academies of Science (AAS). He also received the "Distinguished Service Award" for having served four years as secretary-treasurer for the AAS.

Robert D. Birkhoff, Robert A. Nicklow, and G. D. O'Kelley have been named Fellows of the American Physical Society.

The **Oak Ridge National Laboratory** was selected by the National Safety Council to receive the 1975 Award of Honor, its highest order of recognition for outstanding occupational safety records. In the letter to Director Postma announcing the award, the statement was made that it is estimated that less than 5 out of 1000 of the nation's total number of work units would meet the Award of Honor requirements.

OAK RIDGE NATIONAL LABORATORY *REVIEW*

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Howard Hubbard, Bill Shinpaugh, and Troyce Jones (l. to r.) set up a high-volume air sampler to measure airborne radioactive particles near Tuba City, Arizona. (See article on p. 18.)

F F Haywood