ENGINEERING
CORNELL QUARTERLY
VOLUME 5
NUMBER 2
SUMMER 1970
OUR POLLUTION QUAGMIRE
America's SST: ± Fallouts /2

A long-time proponent of American development of the SST, A. Richard Seebass, who is associate professor of aerospace engineering at Cornell, nevertheless presents an unbiased review of the proponents' and opponents' viewpoints concerning American development of the supersonic aircraft. The article concentrates on the pollutant aspects of the SST and the economic arguments for its development.

Electricity: Tomorrow's Car Fuel? /12

In an interview with Quarterly associate editor Vicki Groninger, Wally Rippel, a graduate student in the School of Electrical Engineering at Cornell, presents some of his views on the need for development of electrical power systems as an alternative to pollution-ridden combustion process for driving automobiles.

The Ultimate Pollution /16

Professor Franklin K. Moore, Chairman of the Department of Thermal Engineering at Cornell, presents an engineering strategy for controlling thermal pollution. He discusses approaches to achieving high thermal efficiencies at power plants and methods of getting heat into the atmosphere with as little disturbance to the environment as possible.

Vantage /26

A photo feature depicting summer in Ithaca.

Faculty Publications /30

Editorial /36

AMERICA'S SST: ± FALLOUTS

By A. Richard Seebass

In May the United States House of Representatives approved a $290 million appropriation to extend the development of two prototype supersonic transports (SSTs). While consideration of this appropriation by the Senate is not likely to occur until early fall, the debate on the merits of an SST program has been resumed and promises to be even more heated than usual. Renewed impetus has resulted in part from the National Environmental Policy Act (NEPA), which requires that all Federal agencies include in their recommendations for Federal action affecting the quality of the human environment a detailed study of the environmental impact of such action. The outcome of the SST debate is clearly in question. Many of us will wish to inform our senators of our own opinions regarding the development of such aircraft. In my view, much of the information from which conscientious citizens will try to evolve their opinions has been misleading, almost to the extent of deceit. From one side we have heard contradictory and evasive testimony, as well as statements that should surely cause alarm. In this article I will review some of the more important arguments for and against the SST.

THE AIRCRAFT

Commercial transports have always flown less than the speed of sound because subsonic flight is inherently more efficient than supersonic flight. Supersonic flight involves an added constraint on the aircraft called wave drag; this drag may be thought of as the force that results from the aircraft having to push through the air the conical system of waves that cause the sonic boom. But other more important quantities, such as the range of the aircraft and its productivity, increase with the aircraft's speed. To be commercially competitive with subsonic jets, SSTs must fly at least twice as fast.

Flights at speeds up to twice the speed of sound—that is, a little more than twice the speed of current transports—can be accomplished with existing technology. However, the faster an aircraft flies the greater the frictional heating of the air flowing past it will be. At speeds slightly greater than twice the speed of sound, aluminum, the conventional aircraft material, loses its strength. To take greater advantage of speed, new materials technology is needed. The United States SST was envisioned as an aircraft that would take maximum advantage of its increased speed: it is to carry 300 passengers more than 3,000 miles at three times the speed of current subsonic jets. And because it will use a materials technology based on titanium alloys, speeds up to four times those of subsonic aircraft should be possible.

By virtue of its great speed, the United States SST can be used by the airlines more than twice as often as its subsonic counterparts, and it will be the most productive aircraft ever built. A single SST will provide nearly double the number of seat miles per hour available from the giant of productivity, the Boeing 747, and four times that of the advanced versions of 707s and DC-8s. It is this enormous productivity that makes the SST economically com-
petitive with subsonic aircraft. Of course, the major benefactor of this increase in speed is the passenger, who will have his air travel time cut in half.

POLLUTANT ASPECTS OF THE SST

There are several ways in which the SST will impinge unfavorably upon our environment. Two aspects of this interaction of the SST with the environment are new and essentially unique to aircraft capable of high speed and high-altitude flight.

Because the SST flies at supersonic speeds, it creates a sonic boom; the pollutant aspect of this phenomenon is so severe that the aircraft’s operations must be restricted in a way that dramatically alters its economic vindication. To fly efficiently at supersonic speeds the SST must have a graceful swept-back wing. This wing is inefficient at subsonic speeds, and the aircraft requires a large amount of engine thrust for take-off. For the engines to be efficient at supersonic speeds, they must have a small, cross-sectional area. This in turn requires a high-speed jet to produce the necessary thrust for take-off; and, the higher the speed of the jet, the greater its noise.

Engine size and aircraft speed also dictate the altitude for most efficient flight. For supersonic transports this is inevitably above the tropopause; the tropopause divides the lower unstable and well-mixed portion of the atmosphere, the troposphere, from the stable and quiescent stratosphere. Thus, the SST will contaminate the stratosphere with its exhaust products. Now, the
major products of combustion, carbon dioxide and water, are not usually thought of as atmospheric pollutants; however, their introduction into the dry and relatively pristine stratosphere has caused a certain amount of alarm.

AIRPORT NOISE

Noise has long been a pollutant of our environment. Like any other pollutant, its acceptability must be judged in relation to the advantages that accrue from utilizing the devices that cause the pollution. Turbojet aircraft have increased the speed and reduced the cost of air travel at the expense of increased noise pollution near our airports. Airport and community noise levels have increased to such an extent that Congress empowered the Federal Aviation Authority (FAA) to control and abate aircraft noise. On November 3, 1969 the FAA promulgated standards insuring that future subsonic aircraft will be certified not only for air worthiness but also for noise acceptability. Presumably, SSTs were exempted from such regulations because it was anticipated that they would only operate routinely from selected coastal airports and because it seemed unlikely that they would meet the rigid standards that would be imposed on future subsonic jets.

Because of the enormous thrust of their engines, SST aircraft will climb even faster than current subsonic jets. By the time they are over the communities that surround the airport they will be high enough to meet the current standards prescribed by the FAA for community noise during take-off. Also, because of a unique feature of the engine design that allows it to operate efficiently at various supersonic speeds, it has been possible to suppress the compressor whine that is so annoying during the approach of subsonic jets. This in turn insures that the aircraft will meet current standards for community noise during approach.

Unfortunately, even the most optimistic predictions of the noise in the vicinity of and at the airport indicate that SST aircraft will be substantially louder than current subsonic jets and certainly unable to meet the “sideline” noise standards prescribed for future subsonic jets. Were SST aircraft to operate routinely from all the country’s major airports, this intense noise might prove to be an insurmountable barrier to their development. However, constraints imposed by the other noise pollutant, the sonic boom, will restrict most operations to major coastal airports, where the acceptability of the sideline noise should be determined on an airport-by-airport basis. Future construction and land acquisition at such airports can be planned in a way that will minimize the adverse impact of this noise on the airport environs.

SONIC BOOM

A new dimension has been added to the problem of noise pollution with the possibility of commercial air transport at supersonic speeds. When an aircraft flies at supersonic speeds it lays down a carpet, or boom corridor, in which the pressure experienced at the ground rises very abruptly to a higher value through a shock wave. This increase in pressure is referred to as the “overpressure.” The pressure then decreases with time until it is as much below normal atmospheric pressure as it was above it.
A second shock wave then brings the pressure back to its original value. This type of pressure signature is what we call a sonic boom. It is characterized by two simple quantities: the "overpressure" and the "duration." For typical SST aircraft, overpressures of two to three pounds per square foot directly under the aircraft and durations of about one-half second are anticipated. At the edge of the boom corridor, some twenty miles to the side, the over-pressure will be reduced to a little less than one and one-half to two pounds per square foot; the duration there will be unchanged.

The sound of this pressure signature—the sonic boom—while often heard, is not well understood. The pressure levels involved are 5,000 times larger than those of ordinary conversation; in fact, they are comparable to those measured in the vicinity of pneumatic hammers. Because of the very rapid rise to the maximum pressure and the very slow, essentially inaudible decay to the minimum pressure, followed by a second rapid rise back to atmospheric pressure, this non-continuous "bang-bang," while very startling, is certainly less objectionable than the sound of a pneumatic hammer.

Our very cursory knowledge of the annoyance associated with this sound stems from two types of experiments. In one, subjects were asked to compare the relative acceptability of a sonic boom with another sound, usually that of a subsonic jet at low altitude. In the other, residents were subjected to the sonic boom generated by military aircraft, and their reactions were surveyed. These studies have led to the establishment of a relationship between overpressure and annoyance. A further aspect of annoyance is the amount of exposure: one boom a week is not likely to bother anybody while fifty booms a day will annoy almost anyone. From such studies "psycho-acousticians" have arrived at a composite noise rating (CNR) for sonic booms. They tell us that whenever the CNR exceeds 90 complaints will be made; when it exceeds 100 there will likely be an organized group reaction; when it exceeds 110, legal recourse will be sought. If
supersonic transport over populated areas were unrestricted, it is estimated that in 1975 in the United States alone about fifty million people would be exposed to a CNR above 90, fifteen to twenty million people would be exposed to a CNR above 100, and about two million people would be seeking legal recourse.

As well as being acoustically annoying, the sonic boom causes observable physical damage to structures. Based on past complaints and damage claims it has been estimated that paid claims, at an average of about $70 each, could amount to $50 million per year. Damage claims seem to be inextricably intertwined with annoyance. Knowledgeable engineers believe that if annoyance is reduced sufficiently, even at the expense of some increase in real damage, the damage claim problem will disappear. The real expense here is investigating claims to determine if they are legitimate. Relative to the physiological impact of the sonic boom on humans, the actual physical damage to structures they would cause seems to be a minor problem.

Recently, research that we have conducted at Cornell has allowed us to determine what can be done to reduce the most annoying features of the sonic boom of an SST. Our results indicate that by modifying current designs for overland operation the CNR would be reduced by about five percent. By resorting to more exotic schemes it is conceivable that the CNR could be reduced by ten percent. While this represents a substantial decrease in annoyance level, it would still leave between fifteen and twenty million people exposed to a CNR above the complaint level. And it would still be literally true that the privileged few would be riding across the eardrums of the nation.

From an annoyance standpoint alone it is clear that commercial transport at supersonic speeds over populated areas cannot and will not be tolerated. Belatedly recognizing this fact, the FAA has proposed a rule that would prohibit the operation of such aircraft in any way that would cause a sonic boom to reach the surface of the United States. This rule is likely to be modified to exclude that part of Alaska north of the Arctic Circle. The Friends of the Earth and the Sierra Club consider this rule "totally inadequate and completely unacceptable" and insist that sonic booms should be regulated by an Act of Congress. Their concern is understandable when one notes that the FAA Administrator John Shaffer once testified that "... it is quite possible that pressure from people who want to use... this airplane for profit... may drag it into that market which one might identify as east to west or west to east over populated areas." The former head of the SST program, General J. E. Maxwell, remarked that "... People in time will come to accept the sonic boom as they have the rather unpleasant side effects which have accompanied other advances in transportation." Such insensitivity on the part of Federal officials has done little to advance the case for the SST.

CHANGING THE WORLD'S CLIMATE?

Judged on the basis of conventional pollutants such as carbon monoxide,
oxides of nitrogen, and particulates, the SST will produce twice as many pounds of pollutant per seat mile as a subsonic turbojet. But this still amounts to one-twentieth of the number of pounds of pollutant per seat mile produced by contemporary automobiles. Air pollution levels are high near airports because turbojet engines idle very inefficiently. There is a simple cure for this problem: tow the aircraft into position for take-off and avoid the long idling time caused by current air traffic control problems. But, as I mentioned earlier, the problem here is not with conventional pollutants but with conventional exhaust products being released in an unconventional environment.

Supersonic transports will burn about 100,000 pounds of fuel per hour. Roughly speaking, the combustion of each pound of fuel will produce one pound of water and three pounds of carbon dioxide. But water vapor and CO₂ are rare in the stratosphere, where most of the SST fuel will be consumed. Furthermore, the stratosphere is so stable that a typical residence time for contaminants is one to two years. This will lead to a measurable accumulation of water vapor and CO₂ in the stratosphere, with unknown consequences on global climate. I think it is safe to say that the one percent anticipated increase in CO₂ will have no noticeable effect on our environment. Water vapor in the stratosphere is more worrisome in that our climate, in addition to the stratospheric ozone that protects us from the sun’s ultraviolet rays, is insensitive to the water vapor content of the stratosphere. While there is no concrete evidence of detrimental effects that might be produced by increased stratospheric water vapor, there is no unequivocal assurance that such effects won't occur. Stratospheric water vapor has increased fifty percent in the last six years, presumably due to natural causes. Current subsonic jets operate near the tropopause and may have contributed to this increase. Should the United States proceed with the construction of an SST prototype, then research scientists must determine the effects of increased stratospheric water vapor before production aircraft are built. To delay prototype construction until this research is completed, however, would place the United States SST at a serious competitive disadvantage to the Anglo-French SST.

ECONOMICS

I have reviewed the unfavorable ways that SSTs will interact with the environment and have pointed out that one of the pollutant aspects of this interaction, the sonic boom, will certainly limit the utility of the aircraft. The main vindications for SST aircraft have been economic ones. With constraints that insure that they will not unduly defile our environment, the case for or against the SSTs must ultimately rest on economic grounds.

To a certain extent the American supersonic transport was a response to the challenge presented by the Anglo-French SST, the “Concorde.” England and France led the way into the current era of turbojet aircraft. But American engineering superiority prevented them from reaping most of the profits from this immense and still expanding market. The Concorde was based on exist-
ing materials technology in an attempt to move into the next generation of aircraft far enough in advance of the United States to forestall a recurrence of this phenomenon. The Soviet Union claims to have decided to compete in this market, perhaps more for prestige than for rubles. It seems likely that the Russian SST, the TU-144, will enter commercial service in advance of the Concorde and well in advance of the United States SST, the Boeing 2707.

The reason for this intense competition is clear: without any sonic boom restrictions, the total value of commercial supersonic transports has been estimated to be $40 to $50 billion, a substantial multiple of our gold reserves. On the same basis, the net return from Boeing 2707 sales has been estimated to be between $10 and $15 billion. With the operation of commercial supersonic transports restricted to over-water use because of the sonic boom, however, such sanguine prognostications do not apply. Just how loudly the SST might ring this nation's cash register depends to a large extent on how softly it impacts the ear.

Recently, the FAA has reexamined the market for the United States SST. Their study assumed that the airlines would establish a higher fare for a superior level of service, and the SST fare was set at a level indicated by current Concorde costs. If there is no more than a one year delay between prototype development and production, then 420 SSTs would be sold. Presumably about half that number of Concordes would also be sold, making a total world fleet of more than 600 aircraft.
Boeing, which won the competition to develop the SST, estimates that around 300 aircraft will have to be sold for the program to break even financially. With an apparent market of 400 or more aircraft, the venture is attractive enough for Boeing to continue to supply ten percent of the development costs, which are likely to run as high as $2 billion. The FAA has evolved a complicated formula that determines the royalty schedule for the airframe and engine manufacturers (Boeing and General Electric Companies, respectively).

There is much dispute about the overall effect of a United States SST on our balance of payments. Because the SST will encroach upon the market for other United States aircraft and encourage more travel abroad, various estimates even differ on whether or not the effect will be favorable on the balance of payments. It is difficult to separate the wheat from the chaff in this prognostication, but an overall favorable balance of payments of $5 to $10 billion seems reasonable if both the Concorde and the Boeing 2707 enter production. If 270 United States SSTs are purchased abroad and 60 Concordes are purchased here, the net favorable balance of payments would be $10 billion; the effect of SST sales on the export of other American aircraft would reduce this amount somewhat. Should the United States decide not to develop the Boeing 2707, then the Concorde looks economically attractive. Should the development of the Boeing 2707 proceed, then the Concorde, which would capture at most one-third of the SST market, appears economically marginal. Should the Concorde’s upcoming flight tests at cruise speeds prove disappointing and the project be cancelled, then the United States has its choice: to decide that an SST is no longer needed to protect our economic position and cancel its development, or to rejoice that our only competition is the Russian TU-144. Of course, if the American SST causes the Concorde to be a financial disaster, then the profits from the United States program may be needed to shore up the pound and the franc.

TWO OPPOSING VIEWS

I have discussed the impact of the SST on our environment and the effect of environmental constraints on the economics of the SST. But there are other considerations that should also be taken into account in trying to obtain a balanced view of the desirability of proceeding with the development of this aircraft. To conclude, let me present the views of rational proponents and opponents to the program. Two caveats are in order here. First, no summary can possibly impart the fervor of either the proponents or the opponents. Second, there are many arguments for and against the SST that I consider spurious and have not included; these range from somewhat reasonable questions about government financing of this project to totally unreasonable alarm over the effects of sonic boom on the aquatic life in the oceans.

Opponent: The SST is an unnecessary luxury that has resulted from our misplaced priorities. Prototype development, which will cost nearly $300 million this year alone, seems out of line

Opponent: The SST is an unnecessary luxury that has resulted from our misplaced priorities. Prototype development, which will cost nearly $300 million this year alone, seems out of line
with a budget in which only $106 million is requested for air pollution control and $214 million for mass transit. The production airplane will be unacceptably noisy at the airport and may require a substantial fare surcharge. The ad hoc committee appointed by President Nixon to give its judgment on the effect of SST development on our balance of payments concluded unanimously that it was not a good investment. And if it is built and is not an economic success because it is restricted to over-water operation at supersonic speed, what real assurance do we have that the resulting economic pressure wouldn't result in supersonic flights over populated areas?

Proponent: The SST is the next step in an orderly progression of aircraft designs; it will more than halve intercontinental travel times for the traveller and provide the airlines with more than ample return on their investment. The development of the United States SST will assure our continued leadership in air transport and protect our balance of payments for many years to come. The Boeing 2707 will provide nearly twice the number of seat miles per hour as the giant 747; it will be the most productive aircraft ever built. The new materials technology required for the SST will undoubtedly produce important technological benefits. In addition, the industry and area that would produce the American SST need economic stimulation. There's going to be an SST. It is not going to fly over land and annoy people with its sonic boom. Will the United States sit idly by while Brit-
ain and France take over leadership of the air transport industry?

Congress considers a number of technological programs every year. Three current examples are the Space Shuttle, the Anti-Ballistic Missile System (ABM), and the SST. In my view, the first is unnecessary and the second unwise. The third, the SST, will at least provide benefits commensurate with its cost. And its cost is a fraction of either of the others'.

A. Richard Seebass has long been a proponent of the SST and feels that its development is essential to continued progress in air transportation. In this article he tries to review the case for and against the SST in an unbiased manner, allowing the reader to come to his own conclusions.

Currently he is a member of the National Academy of Sciences Committee on the SST-Sonic Boom, an advisor to the Sonic Boom Research Panel of the Interagency Aircraft Noise Abatement Program, and a member of the NASA Research and Technology Advisory Subcommittee on Fluid Mechanics. He has been a consultant to the General Applied Sciences Laboratories, the Department of Transportation Office of Noise Abatement, and the Institute for Defense Analyses.

In addition to his teaching and research responsibilities at Cornell, Professor Seebass has served as acting director of the Center for Applied Mathematics. He has published articles in the areas of fluid mechanics, aerodynamics, magnetohydrodynamics, and sonic boom and is a reviewer for several technical journals.

Professor Seebass is an associate fellow of the American Institute of Aeronautics and Astronautics, and a member of the following professional societies: the American Association for the Advancement of Science, the American Association of University Professors, the Society for Industrial and Applied Mathematics, and Sigma Xi. During the spring term he was on sabbatical leave at the Boeing Scientific Research Laboratories in Seattle.

Associate professor of aerospace engineering at Cornell, Professor Seebass was graduated from Princeton University magna cum laude in 1958, with a Bachelor of Science in Engineering degree. He received the Master of Science in Engineering degree from Princeton in 1961 and the Doctor of Philosophy degree from Cornell in 1962. While studying at Princeton, he was a Guggenheim fellow; at Cornell he was a Woodrow Wilson fellow.

In 1966–1967 Professor Seebass spent a year at the National Aeronautics and Space Administration (NASA) Headquarters. While there he was a staff member of the Research Division of the Office of Advanced Research and Technology and established the current NASA contract program on sonic boom research.
Two years ago Wally Rippel, who was a student at the California Institute of Technology, won the Great Electric Car Race between his school and the Massachusetts Institute of Technology by crossing the country in 210 hours and 30 minutes in his specially designed electric car. This year he has been improving the design of the electrical control system for a future electric vehicle as part of his work for the Master of Science degree in the School of Electrical Engineering at Cornell. Some of his observations about the promise of electric vehicles and the need for development of electric power technology, made to Quarterly associate editor Vicki Groninger, are presented below.

What first got you interested in electric propulsion technology?

I guess I would have to say I was first influenced by my father, who is an electronics engineer. In high school I was interested in the fundamentals of physics and electricity and in aesthetics. My ambition is to teach physics at the university level—particularly the physics of electrochemical reactions. (Next
year I hope to begin work for the Ph.D. degree in chemical engineering at Caltech.) Of course, the overriding reason for my involvement in this area is to help develop electric vehicle technology as a long-range alternative to combustion-powered systems. During the next fifty years combustion processes could entirely ruin our planet. Even smog-free combustion engines must emit carbon dioxide into the atmosphere. It is likely that in time this pollution will cause adverse changes in global weather, not to mention what may happen to all living things.

The dean of engineering at UCLA says it is unfair to fool the public about the lack of pollution from battery-driven cars since power stations will pollute our environment if the cars don’t. What do you think?

The Department of Health, Education, and Welfare says that automobiles are responsible for sixty percent of all air pollution. Edison Electric Institute, which represents all publicly owned utilities, claims if all ground vehicles were converted to electrical power the consumption of electricity would be increased by fifty-five percent. But if the power companies, which may be said to account for the remaining forty percent of all air pollution, grow by fifty percent, then the pollution from them will be up to sixty percent (the same as that produced by gas-powered automobiles today). Total air pollution, however, would be down by forty percent.

Why do you think the development of electric vehicles will be acceptable to the utility companies?

They will profit from this development. A ten percent increase in capital investment by the utilities would take care of converting most of our autos. Besides, the ideal situation for power companies is a constant load. Right now they are not making as much money as they could on their equipment between midnight and 5:00 a.m. since people are using substantially less electricity during those hours. Electric car batteries could be recharged during this period.

The problem is not a matter of cost and maintenance, since electric energy is cheaper than gasoline energy, and electrical systems last longer and require less maintenance than combustion engines. It is simply that the battery-driven car cannot compete with the gas engine. One pound of today’s batteries stores only one percent the energy stored in one pound of gasoline. A ten-fold improvement in battery power is necessary before the battery-driven car can compete with the gasoline-driven one.

Why haven’t batteries been improved?

First, because of engineering problems. The problem has been to utilize chemical reactions that store a large amount of energy per unit weight of the chemical, to develop a system where reactions can proceed quickly when necessary to enable high electrical power output, and to avoid undesirable side effects such as corrosion. Second, because of the lack of theoretical models. Researchers haven’t been trying to develop theoretical models for several reasons; one is that they aren’t patentable. I believe the responsibility for breakthroughs in battery technology
Testing the circuitry for the operation of their electrical control system are Wally Rippel, the chief designer, and his assistants, Foster Hinshaw and Mark Hoffman (left and center, respectively, in the photo at top of page).

The power control system we have been building is a three-in-one system. The first mode involves charging the batteries at high rates; the second mode requires controlling the amount of power flowing from battery to motor; and the third mode involves regenerative braking. The electronic gear lets the flow of power reverse, helping the motor to act as a generator. Power passes back to the batteries to be used again as electrical energy (instead of wasted as heat, as happens in conventional disc and drum braking systems) and the vehicle slows down with little use of the brakes.

The test facility consists of a 40-horsepower electric motor, a 1,000-pound steel beam fly wheel that tests inertia and acceleration, and a magnetic particle brake, which adds a force is at the university level. Today's battery companies are using medieval technology. The task is to get the universities to do research on energy storage systems for the future.

Would you describe your work at the electric vehicle laboratory on campus?

The power control system we have been building is a three-in-one system. The first mode involves charging the batteries at high rates; the second mode requires controlling the amount of power flowing from battery to motor; and the third mode involves regenerative braking. The electronic gear lets the flow of power reverse, helping the motor to act as a generator. Power passes back to the batteries to be used again as electrical energy (instead of wasted as heat, as happens in conventional disc and drum braking systems) and the vehicle slows down with little use of the brakes.

The test facility consists of a 40-horsepower electric motor, a 1,000-pound steel beam fly wheel that tests inertia and acceleration, and a magnetic particle brake, which adds a force
against which the engine must work. The accelerator is made up of specially designed air core inductors, six diodes used in the recharge mode, and capacitors. These elements constitute the chopper which converts one d.c. voltage to another.

I understand that you have been trying to get a car built that will be able to test your power system. Is anyone else from Cornell working on this project?

Yes, Mark Hoffman (from Pottstown, Pennsylvania) is working on the auxiliary power systems (for headlights, etc.) for such a car; Foster Hinshaw (from New York City) is developing the circuitry for the optical tachometer and handling the calculations for the systems; and Peter Lord (from Huntington, Long Island) is doing the fabrication and some of the design for our system. And my adviser, Professor Joseph Rosson, has been a wonderful sounding board for all of our ideas.

What keeps you going in spite of so much skepticism about electric vehicle technology?

I've logged over 150,000 air miles on projects related to electric vehicle technology and I've been in close contact with both the academic world and industry. There have been many rewards. The impact of one idea on social behavior can be tremendous (consider the incandescent lamp, for instance), and I think the excitement of this idea keeps me going. Transportation is one of the primary factors in our economics, and changes in transportation will have significant social and cultural ramifications.
Thermal pollution is the consequence of dispersing waste heat from industrial processes, especially electric power generation, to the environment. Compared with the impact on our environment of air pollution, chemical water pollution, and noise, it is of minor importance. A single Boeing 747 can deliver heat to the atmosphere at a rate comparable to that rejected by a typical power plant such as Milliken Station on Cayuga Lake (a few hundred megawatts), but who would claim that heat is the most important insult to the environment posed by the jumbo jets? It is therefore curious that, of all forms of pollution, the thermal variety is the only one to have acquired general notoriety and to have become the subject of federally mandated state regulation before becoming a national disaster!

Nevertheless, we do well to be concerned because thermal pollution is the ultimate pollution—the only inevitable kind—ordained by the second law of thermodynamics (that any real heat engine must waste heat to some degree). For example, measures to clean up our air will require increased energy expenditures for exhaust afterburners and the operation of air-conditioning equipment. The same is true for solid waste disposal; an extreme illustration is the recent proposal for a plasma torch which would use enormous amounts of power to thermally dissociate waste material back to elemental form. Thus, if we are wise and lucky, all other forms of pollution will in time be exchanged for thermal pollution.

Accordingly, we should think of thermal pollution in global terms and try to estimate future levels of power use. For the past century world-wide power generation has doubled every ten years. If this trend continues throughout the next century, power generation will be increased 1000-fold, to a level of about 5 megawatts per square mile of earth’s surface. This amount would be one percent of the solar input; the earth receives heat from the sun at an average rate of about 540 megawatts per square mile and radiates nearly the same amount back to space. If this situation develops, the earth’s average surface temperature would have to increase by 1°F to maintain thermal balance. Such a measurable temperature change due to thermal pollution could be taken as the threshold of serious global trouble. (Instead of simply extrapolating with the present-day power doubling rate to reach this figure of 1000, we may observe that it would result if the world population increased by a factor of five and the world per capita power consumption increased by a factor of two hundred, which is about forty times the present level in the United States.)

Now, the foregoing is not offered as
an apocalyptic vision, but rather as a basis for judging the appropriateness of our engineering research and regulatory policies. Long before we generate one percent of the solar input in heat, we will have extreme, world-wide problems with the concentration of heat near generation sites. We should anticipate these problems now. In this article, I will try to suggest an engineering strategy for thermal pollution and point out certain relevant, applied research activities at Cornell.

THERMAL EFFICIENCY

A modern 1000-megawatt power station has a thermal efficiency of about thirty-three percent. Thus, 2000 megawatts of waste heat must be disposed of near the station site. (Of course, the 1000 megawatts delivered to the electric power distribution system are finally “wasted” too, but on a widely dispersed basis.) Clearly, radical improvements in thermal efficiency are needed for the future, for two reasons: (1) to reduce the proportion of total heat lost, in anticipation of a day when total heat may be limited by law (then thermal efficiency will have an economic value greatly transcending considerations of fuel cost); (2) to reduce the concentrated impact of heat on the environment in the vicinity of the plant.

Even engineers sometimes have difficulty accepting the fact that waste heat must be wasted. American ingenuity, it is often felt, should somehow find a use for all that surplus heat. As much heat as possible is, in fact, used in the low-pressure turbine, from which steam is discharged at a pressure of a few inches of mercury and condensed at only about 100°F. Further use for 2000 megawatts of heat, offered at body temperature and delivered at the back door of the power station, would seem unlikely.

Obviously, dramatic improvement of thermal efficiency is a matter of increasing maximum power cycle temperatures far above the 1000°F level of today’s nuclear plants. The entire energy-conversion process would have to be rather independent of material limitations. With nuclear power, two approaches seem promising and both are under study at Cornell.

First, the gas-core power reactor is a conceptual possibility. A gaseous uranium cloud would undergo fission, become extremely hot, and transfer heat by thermal radiation to a working fluid introduced between the cloud and the reactor vessel walls (see fig. 1). Provided that the cloud could be “contained” without touching the walls, its temperature might be permitted to rise to tens of thousands of degrees. The resulting very high, working-fluid temperatures would lead to high thermal efficiencies only if mechanical or electrical energy could be extracted at very high stagnation temperatures. A magnetohydrodynamic (MHD) generator would presumably be used to derive electrical energy directly from the working-fluid plasma.

At Cornell we are working on the crucial containment problem under sponsorship of the National Aeronautics and Space Administration. We feel that the rather recently studied phenomenon of “vortex breakdown” may be promising in this regard. Rather large, encapsulated flow regions may be main-
tained in swirling flow, where the necessary lateral restraint is provided by rotational inertia of the outer fluid (which we visualize as the working fluid flowing around the enclosed region). We are studying various possible flow arrangements and are concerned especially with questions of stability that arise if the contained gas is much denser than the surrounding flowing gas. We feel that once containment of the power source is established, existing knowledge about MHD systems can be applied to the conceptual design of a power-generation system.

A second approach to achieving very high thermal efficiency would be through the controlled-fusion power source, expected by many to be practical within twenty years. In some versions quite high working temperatures would be produced by absorption of energetic neutrons. Certain fusion reactions would give most of their energy to extremely hot, positive ions in the contained plasma. In these cases, direct MHD conversion could be used to exploit the high plasma temperature, resulting in extremely high thermal efficiencies. The Laboratory for Plasma Studies at Cornell is deeply involved in the study of the containment and loss mechanisms in the basic plasma source.

It certainly seems safe to predict that within twenty years we will understand quite clearly what the possibilities and costs are of achieving thermal efficiencies of the order of seventy percent or higher. At that time the overall thermal impact on the world environment will be under control, at least potentially, and waste heat considerations of power
"New technical developments in cooling tower design could have more immediate and favorable effects in regard to thermal pollution than any other I can imagine."

METHODS AND CONSEQUENCES OF HEAT REJECTION

Although a revolution in thermal efficiency is a future necessity, the amounts of heat to be rejected into the environment will continue to increase (as a smaller fraction of a much larger total). The sources of this heat will continue to be concentrated in the localities of power-generating sites, although sources related to power use may become important as well. A portentous example is the air-conditioning system of the new Trade Mart in New York City. It is expected to reject heat at the rate of 180 megawatts.

It is important to realize that no matter how or where the actual release of heat occurs there is a definite sequence of heat reservoirs that come into play. Working backwards, the ultimate receiving reservoir is outer space, at perhaps 3°K. Because of the opacity of the atmosphere to infrared radiation and the size of the radiators needed it would seem impractical to reject heat directly to outer space. Nevertheless, it should be noted that if power could be generated with a very high temperature cycle, the rejection temperature could also conceivably be high. If it were 1500°K an area of only about 100 meters square would suffice for black-body radiation of 2000 megawatts to space. The problem of penetration of the atmosphere would remain, of course, even at the elevated temperature. Apart from such questions of feasibility, direct radiative rejection to space may be kept in mind as the ultimate or ideal answer to thermal pollution—the only way to reject heat without involving the environment.

Next in the hierarchy of reservoirs is the atmosphere. The opacity of the atmosphere requires that heat rejected at the earth's surface must be absorbed in the atmosphere before it can radiatively dispose of the heat to space. Fortunately, the atmosphere is quite well mixed by its inherent thermal instability and by global wind patterns.

Thus, in rejecting heat, the practical objective must be to get the heat into the atmosphere with as little fuss as possible. The engineer has two basic ways to make this connection with the atmosphere: through cooling towers and (more indirectly) through surfaces of bodies of water.

COOLING TOWERS

The most direct possible connection to the atmosphere is the cooling tower, in which a coolant or the working fluid itself gives up heat directly to the atmosphere. There is an enormous body of engineering experience concerning the design and operation of cooling towers; however, their application in the power range of 1000-megawatt power stations has generally been limited to the natural-draft, wet type of tower, usually hyperbolic in shape and very large (see fig. 2). The basic principle may be illustrated in this way: If $1.9 \times 10^6 \text{ ft.}^3/\text{sec.}$ of ambient air at 90°F and 60% relative humidity (wet-bulb temperature of 78°F) is made to flow through a tower into which water to be cooled is sprayed, it can evaporate a small fraction (2.3%) of the water and emerge saturated at 90°F, having
acquired from the water $1.9 \times 10^6$ Btu./sec. or 2000 megawatts of latent heat.

Actually, one would provide more air flow in the tower to avoid condensation in the plume. When the ambient air is nearly saturated, as in winter in the northeast, condensation will occur nevertheless. Fog and freezing rain produced by wet cooling towers are serious drawbacks to their use. One must also consider the adverse aesthetic effect of a set of several objects four hundred feet high and four hundred feet in diameter. It is hard to believe that wet cooling towers represent the future.

If a dry cooling tower is used, perhaps with a closed coolant loop, and the air is to be warmed by $20^\circ$F, then quite a bit more air, about $5.4 \times 10^6$ ft.$^3$/sec., would be needed.

It is easy to make rough estimates of the necessary sizes of cooling towers using the foregoing numbers. Suppose the tower system has an effective diameter $D$, with an exit velocity $V$ (see fig. 3). Then

$$VD^2 = 2.4 \times 10^6 \text{(wet)}$$

or $6.9 \times 10^6 \text{(dry)}$ ft.$^3$/sec. (1)

If the flow is established by natural draft, then conservation of mechanical energy would suggest that

$$\frac{1}{2} \rho V^2 = (\Delta \rho) gH$$

where $H$ is the height of the tower system. The density decrement $\Delta \rho / \rho$ (bouyancy) is about 2.1% (wet) and 3.5% (dry). Thus,

$$V^2 = 1.3 H \text{(wet)} \text{ or } 2.2 H \text{(dry)} \text{ (2)}$$

Eliminating $V$ between equations (1) and (2), we find

$$D^2 H^{1/2} = 2.1 \times 10^6 \text{(wet)}$$

or $4.6 \times 10^6 \text{(dry)}$ (3)

Thus, if we choose $H = 300$ ft. and assume that we have two towers (as is typical), they would have diameters of 250 ft. (wet) or 370 ft. (dry). Despite the crudity of the foregoing calculation, the results are in the right range, and two noteworthy points emerge: (a) If heat can with equal effectiveness be transferred to the air by wet and dry towers, the wet tower requires a ground
area only two or three times smaller than does the dry tower. The transfer of heat is much more difficult to arrange in the dry tower, however, than in the wet one with its internal water spray. (b) Height is not as important as surface area. If in the example we limit height to 150 ft. for appearance's sake, we may keep the same diameter, adding another unit.

We should include in our comparison the forced-draft dry tower. (see fig. 4). Power is required to drive the fans in proportion to $V^3$; if we limit the power to 1% of a 1000-megawatt plant's output, or 13,000 hp., then

$$D^2V^3 = 8 \cdot 10^9.$$  \hspace{1cm} (4)

Again eliminating $V$ by use of equation (1), we find that $D = 430$ ft. for a single unit—about half the total ground area required for natural draft, with no height requirements. Interestingly, the area increases only as the square root of the ratio of generated power to fan power.

Although these estimates are crude and optimistic and ignore costs, except by inference, they do show the future promise of dry, closed-circuit cooling. Some tower builders claim that this type of cooling is economically feasible today for 1000-megawatt plants. Actual installations of dry, forced-air cooling systems have so far been limited to a type of air-cooled condenser for plants of not more than 150 megawatt capacity.

Research on the efficient transfer of sensible heat in very large, forced-draft devices, attempting to limit size, power costs, and atmospheric disturbance, is needed. In view of the relative unimportance of tower height in the natural-draft case, that type should be con-
SIDERED too. Studies of this nature have been begun in the Department of Thermal Engineering at Cornell. They are partly sponsored by the Rochester Gas and Electric Corporation. New technical developments in cooling tower design could have more immediate and favorable effects in regard to thermal pollution than any other I can imagine.

SURFACES OF BODIES OF WATER

The use of natural water bodies—lakes, rivers, and oceans—is obviously just another way of discharging heat to the atmosphere. The water is first used to cool the working fluid in the power plant and is then returned to the natural water environment, where the second exchange takes place at the water surface over a broad area. This principle also governs artificial cooling ponds, which I won't include in this short discussion. A water body gains or loses heat at its surface according to the approximate formula

\[ q = K \left( T_s - T_{eq} \right) \]  

where \( q \) is heat flux, \( T_{eq} \) is an “equilibrium temperature” which accounts for that part of the heat (that arriving from the sun, for instance) which is independent of the surface temperature \( T_s \). The coefficient \( K \) is typically about 100 Btu./ft.²-day.

For a lake, the natural yearly averages of \( T_s \) and \( T_{eq} \) must be equal because the average heat flux for a yearly cycle should be zero. If the lake water were used for cooling one typical nuclear plant, then the yearly average heat flux would be about 2000 megawatts. In

Figure 4. AN ELEMENT OF FORCED-DRAFT AIR-COOLED CONDENSER

(used in England for 150 mw stations)
“Inland United States waters are so trivial a resource for power plant cooling that it would be absurd and wasteful to commit them to that use now.”

In this case, the yearly average of $T_s$ would be higher than that of $T_{eq}$. Equation (5) reveals that the temperature excess would be 1°F for a lake of area 76 square miles. (Cayuga Lake’s area is 66 square miles, so the proposed Bell Station of the New York State Electric and Gas Company would increase its surface temperature by about 1°F.) The great bulk of the rejected heat is absorbed by the atmosphere.

At this point in a discussion of thermal pollution, it is customary to become hung up on biological questions. Is a 1°F increase of water surface temperature biologically negligible? risky? harmful? or disastrous? Check one. If you check “risky,” would a 3°F increase be merely “harmful”? Following Federal guidelines, New York State permits an increase of 3°F—the equivalent of three 1000-megawatt stations on Cayuga or Seneca Lakes! Even the expert biologist has great difficulty with these questions; in fact, as we shall see, the engineer has difficulty providing the biologist with the information he needs about the total three-dimensional physical impact of power plant use of river, lake, or estuarial water.

A lake like Cayuga which undergoes thermal stratification each summer presents a complicated thermal and fluid-mechanical picture, difficult to model in the natural state and hence in the state perturbed by heat from a power plant. One would like to know how a power plant affects the duration of summer stratification, when normally for about six months a layer of warm surface water (epilimnion) floats on a cold lower layer (hypolimnion). One would like to know if the temperature in the hypolimnion increases (perhaps not, because the heated water, first drawn from the cold hypolimnion, would presumably be discharged near the surface; but perhaps so, because the lake would be warmer in the winter and some of the temperature excess would carry over into summer). One would like to know the mechanical mixing effect of plant intake and discharge, equivalent by one estimate to the natural exchange between epilimnion and hypolimnion on six square miles of lake. Enhanced mixing would affect not only nutrient exchange but also the summer temperature levels in both layers by increasing the rate of diffusion of heat.

Figure 5 shows one model calculation carried out by a graduate student in the School of Mechanical Engineering at Cornell. His results suggest that the period of stratification in Cayuga Lake would be lengthened by about one week by one plant and by nearly a month by three plants. In each case, the artificial enhancement of mixing was very important, especially in producing a temperature increase in the hypolimnion. His model assumed a constant depth of stratification. More elaborate models presently under study in the Department of Thermal Engineering should shed further light on these problems.

Despite the inherent importance of efforts to understand these physical processes in natural water bodies, I have come to feel that studies of these processes and the consequent biological considerations are really of secondary importance in relation to thermal pollution. There is no need for a biological hang-up; we can draw valid conclusions about the use of natural water bodies for thermal discharge on engineering
grounds alone, without being distracted by problems that have no clear answers. In the following paragraphs I shall attempt to do so.

FUTURE CONTROL OF THERMAL POLLUTION

We recall that the object is to get waste heat into the atmosphere with minimum local disturbance, keeping in mind that a 1000-fold increase in world power generation is a possibility on an historically short time-scale. We have found that cooling towers may produce serious local environmental disturbances of the atmosphere, but that closed-cycle cooling towers may be improved to the extent that they would have an innocuous effect on the well-mixed, biologically inert atmosphere.

In contrast, while the use of natural water bodies for discharging heat to the atmosphere produces no disturbances in the atmosphere, where disturbances would be easily tolerated, it causes acute disturbances in the water body, which is biologically very active, much less well mixed, and more subject to stable stratification than the atmosphere. Clearly, this strategy makes sense only if the level of use is low, now and in the future.

Today, however, we have an explosively increasing need for cooling, and it is only rational to choose the methods with the proper growth potential. Regarding the use of natural water bodies for cooling, Professor K. Bingham Cady of Cornell’s Department of Applied Physics has pointed out that in the United States perhaps about...
7000 square miles of inland waters (lakes and rivers exclusive of the Great Lakes) are suitable for plant cooling. As we have seen, these would be heated by 3°F if 300 of our 1000-megawatt plants were cooled by them. But this number of new plants is only that needed in the next twenty or thirty years. A mere ten-fold power increase in the United States would require about 1200 new plants. I conclude that inland United States waters are so trivial a resource for power plant cooling that it would be absurd and wasteful to commit them to that use now. Accordingly, I think it is scandalous that the Federal and New York State water-use criteria tend to permit the building of three 1000-megawatt stations on lakes such as Cayuga.

The Great Lakes (of which 60,000 square miles are the United States portion) and the oceans are another matter. They comprise a surface area that could accommodate the projected power increases. Even siting on oceans, however, leads to problems of ecological impact, and off-shore sites would be needed. If power plants were situated in the oceans, practical, long-distance, bulk-power transmission would be essential. Professor Simpson Linke of the School of Electrical Engineering has studied this problem and has found that “long distance” is apparently well within our reach by use of high-voltage, direct-current overhead transmission lines. Underwater d.c. cables up to seventy miles in length are now in operation, but long-distance underwater transmission poses difficult problems of supercooling and cryogenics and is probably decades away from being feasible.

In summary, I believe that control of thermal pollution requires serious long-range engineering research on the following topics: (a) high-temperature power generation cycles to maximize useful power when total power is curtailed and to minimize local environmental impact; (b) methods of closed-cycle air cooling for direct transfer of heat to the atmosphere to minimize environmental impact and related siting restrictions (high-temperature cycles will make this job easy, since temperature differences can be large and airflow rates correspondingly small); (c) thermal and fluid-mechanical impact of power plant discharges on natural water bodies. While I feel this research will become rather forensic in purpose, I think it is quite important, even so.

Much could be said about comparative costs of cooling methods. I have ignored this subject because future costs will depend so much on future public policy decisions and technical advances. Use of present-day, dry, forced-draft cooling towers would be many times more expensive than use of river water, for example, but it is not out of the question even now.

Finally, as an engineer, I think it is important to emphasize the need for technical advances. While it is surely appropriate that environmental concerns are most articulately expressed on the academic scene by social scientists and generalists, there is sometimes too ready a tendency to assume that the solutions to these problems will lie in non-technical, political or regulatory action.

Engineers, I think, will solve the problem of thermal pollution!

Franklin K. Moore is the Joseph C. Ford Professor of Mechanical Engineering at Cornell. He has been head of the Department of Thermal Engineering since he joined the Cornell faculty in 1965.

He was awarded the Bachelor of Science degree in mechanical engineering with distinction from Cornell in 1944 and received the Doctor of Philosophy degree in aerospace engineering from Cornell in 1949.

From 1950 to 1955 he did research on supersonic propulsion at the Lewis Laboratory of the National Advisory Committee for Aeronautics, predecessor of the National Aeronautics and Space Administration. He then joined the staff of the Cornell Aeronautical Laboratory in Buffalo, New York, where he served as head of the aerodynamics research department (1955–59) and director of the aeronautics division (1960–65).

Presently, Professor Moore is a member of the visiting committee for nuclear engineering at the Brookhaven National Laboratory and a consultant to the Cornell Aeronautical Laboratory. He has published many papers and monographs on fluid dynamics and is editor of Theory of Laminar Flows, High Speed Aerodynamics and Jet Propulsion, vol. 4 (Princeton: Princeton Univ. Press, 1964).

He is a member of the American Institute of Aeronautics and Astronautics and the American Physical Society as well as of the following honorary societies: Sigma Xi, Tau Beta Pi, and Pi Tau Sigma.
Swimming in Fall Creek Gorge on the north campus.
The newly built observation point at the foot of Taughannock Falls (215 feet high) in Taughannock Falls State Park, Trumansburg.

Ithaca is a watery place in summer. One can visit the many impressive waterfalls or enjoy the smaller ones in the parks and gorges that surround the Cornell campus and the city. Kayaking on Beebe Lake is a popular sport as are sailing on Cayuga Lake and golfing at one of the several fine courses in the area.
The main falls in Robert H. Treman State Park, Enfield.

A quiet view of Cayuga Lake from Taughannock Point.
Teeing off at the fifth hole of the Cornell University Golf Course.

Sunbathing at Flat Rock in Fall Creek.
The following publications and conference papers by faculty members and graduate students of the Cornell College of Engineering were published or presented during November and December 1969 and January 1970. If an earlier publication was inadvertently omitted from a previous listing, it is listed here with the date of its publication in parentheses. The names of Cornell personnel are in italics.

**AEROSPACE ENGINEERING**


**AGRICULTURAL ENGINEERING**


■ APPLIED PHYSICS


■ CHEMICAL ENGINEERING


■ CIVIL ENGINEERING


■ COMPUTER SCIENCE


■ ELECTRICAL ENGINEERING


**MATERIALS SCIENCE AND ENGINEERING**


**MECHANICAL ENGINEERING**


1969, at the University of Oklahoma, Norman, Oklahoma.


**THEORETICAL AND APPLIED MECHANICS**


**GENERAL**

Our Pollution Quagmire

Every fall for fifteen years the Editor has spent a long weekend with old college friends hiking in New Hampshire or Vermont. Last year our summit target was Mt. Adams in New Hampshire’s Presidential Range. The rewards of nine steady hours of climbing, walking, or stumbling that day were those of autumns past—good fellowship, a magnificent show of foliage colors, and the exhilaration that comes from observing the riches of nature.

Two other impressions of that day have remained with me. The first is of the growing numbers of people who are enjoying the outdoors. My friends and I were greeted by a group of six other hikers at Adams’s summit and earlier had difficulty finding a space to park our car along the Jefferson Notch dirt road. The second is of the growing difficulty Americans find in trying to get away from the ugliness caused by man’s pollution of the environment. Although Mt. Adams is 3500 feet above the valley floor, we could smell the effluents of a large paper mill some distance away. We could elude neither man nor his environmental impact.

Surely the contrasts between beauty and ugliness, tranquility and turmoil, and cleanliness and filth in our environment will sooner or later affect all of us.

While it is easy to speak eloquently about the causes of pollution and to witch-hunt the primary scapegoats, many of us do not realize that we are at the very least secondary partners in contributing to the undesired byproducts of our civilization. For some, the solution to the pollution quagmire lies in stopping all changes in technology. For others, technological changes represent new ways in which ingenuity can be applied for more direct humane ends.

Before we can decide how to get out of our pollution quagmire we must determine who should pay for environmental resuscitation and find environmental priorities that can be agreed upon by a majority of our citizens. Sooner or later rhetoric must give way to the realities of the hard, unglamorous work that lies ahead if we are to dig ourselves out of this mess.

The Editor