Pilot Doyle Krumrey brings the ER-2 in for landing after an arduous and hazardous flight over Antarctica.

NASA aircraft is packed with complex scientific instruments for sampling compounds in "ozone hole."

Mission is to determine if widening hole is natural or if it is caused by chemicals manufactured on Earth.

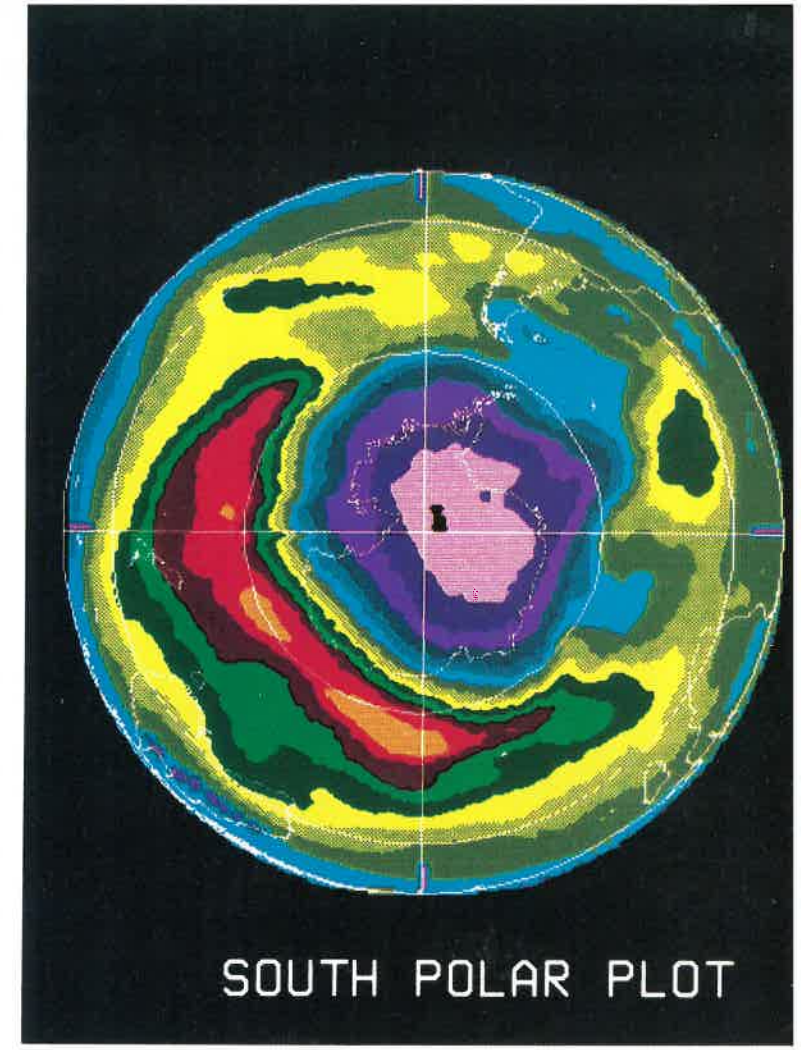

Image recorded by Nimbus-7 satellite over the area shows ozone hole (center) at peak last year, October 15.

By Ellen Ruppel Shell

Solo flights into the ozone hole reveal its causes

A NASA expedition sends experiment-packed plane ten miles up into the stratosphere to find what is destroying Earth's protective shield

The first thing I notice on our final approach into Punta Arenas airport is the rainbow. It forms a bridge between the mudflats and the Strait of Magellan. It makes me hopeful that the warnings I've been given about the dismal climate here, the southernmost city on Earth, have been exaggerated. But the rainbow is the last bit of natural color I will see for some time. Even the penguins have left in search of more hospitable shores. Few visitors come to Punta Arenas in late August, austral winter, when droning rains can turn the gloomy streets into aquatic parking lots, and winds sometimes flatten the forests.

All this makes the clumps of English-speaking scientists and technicians even more conspicuous. There are roughly 150 of them and they are everywhere—bundled in rain jackets, checked-flannel shirts and parkas. Tightly clustered, collegial, secretive, they gather before a meeting in the lobby of the city's one luxury hotel. They are edgy and excited, short-tempered and ecstatic. They are, they know, a sort of scientific SWAT team, handpicked from among the best in the world. Some of the younger and less experienced among them cannot help but swagger under the glow of this distinction. But most are sobered by the weight of their assignment. They have eight short weeks to get to the bottom of one of the most startling scientific mysteries of the decade, eight weeks to find out why the stratosphere above Antarctica loses nearly half of its ozone every year.

The stratospheric ozone layer is often called a shield, but this metaphor is misleading. It is more a gossamer canopy, a sparse scattering of molecules accounting for no more than three parts per million of atmosphere, tiny specks floating in a boundless sea. And what little ozone there is, is extremely fragile. The bonds holding the three oxygen atoms that make up the ozone molecule are easily parted by any number of reactions. This is of no concern in the lower atmosphere, where ozone is a nuisance, a particularly noxious constituent of smog that we would do far better without. But cast into the stratosphere, that vaguely construed slab of air that is roughly 10 to 30 miles above the Earth's surface, ozone is precious stuff. It is the Earth's only defense against the effects of potentially harmful ultraviolet radiation from the sun.

Certain wavelengths of ultraviolet radiation (UV) that are called UV-B can wreak havoc with all things organic. UV-B is known, for example, to cause skin cancer and to disrupt the life cycle of plants. Unchecked, it would make life on Earth impossible. But stratospheric ozone intercepts most of the life-threatening UV in a reaction that results in its own breakdown into molecular and atomic oxygen. These bits of oxygen are quickly united to create new ozone molecules. Left alone, nature keeps the creation and destruction of ozone in careful balance. But it has been years since nature has held sole rein over this process.

Man-made chemicals emitted freely into the atmosphere have disrupted the equilibrium. Some fear that the ozone hole above the South Pole is a consequence of this hapless process, the first physical sign that we are systematically destroying the very substance that made life as we know it possible in the first place.

Until three years ago, there was no reported evidence that the ozone was thinning, let alone that a seasonal balding patch the size of the continental United

Photographs by Ian Yeomans

One of five pilots who can fly plane, Ron Williams doffs helmet after taking the ER-2 into ozone hole.

States had developed. The hole was stumbled upon by an obscure team of scientists from the British Antarctic Survey. The leader of that team, Joseph Farman, is an ironic, self-deprecating man who has quietly monitored ozone levels since 1957. His instruments are based at Halley Bay, a lonely outpost on the Antarctic coast. Farman had noticed a decline in ozone levels every September and October since 1977, but he hesitated to report his findings. After all, no computer model had predicted the decline, nor, apparently, had it been spotted by the Nimbus-7 satellite. Launched in 1978 by the National Aeronautics and Space Administration (NASA), Nimbus-7 carries, among other instruments, a Total Ozone Mapping Spectrometer specifically designed to monitor ozone levels. Farman is a careful man, not given to premature outbursts, and he was puzzled by NASA's failure to report the hole. By late 1984, however, he decided that he had no choice but to go public with his findings. His paper, published in May 1985 in the British journal *Nature*, set the world's insular and circumspect atmospheric-science community on its ear.

NASA scientists scrambled to find an explanation. A careful combing of past reports revealed that the satellite had indeed picked up the hole, but that computers receiving data back at NASA had set aside the finding as an aberration. No one had anticipated that ozone could reach such low levels in the Antarctic stratosphere. It was clear, as one scientist put it, that Farman's finding was the monitoring scoop of the century. But how to explain it? Although several promising theories emerged, none was considered definitive. The truth was that no one knew enough about the chemistry of the Antarctic stratosphere to come to any informed conclusion.

A chunk of atmosphere like no other

The stratosphere above the South Pole is like no other chunk of air in the atmosphere. For one thing, it is dominated by the coming and going of the polar vortex, a tightly twisted whirlpool of winds. When this vortex breaks up in November, the region is replenished with air from other parts of the stratosphere. This explains why the ozone hole disappears every spring—ozone-rich air rushes in and fills the gap. The Antarctic stratosphere is also extremely cold, so cold that it causes nitric acid to freeze into crystals that gather into wispy, pink clouds. These polar stratospheric clouds, which are rare beyond the Antarctic, were thought to play a crucial role in the breakdown of ozone. But again, this was only a theory; there were no data to back it. In August 1986, a hastily assembled team of scientists was sent to Antarctica to see if they could get some.

Right after ER-2 landing, two members of James Anderson's team wheel a pod carrying his experiment to hangar where raw data can be fed into computer to measure compound considered a prime suspect.

The scientists of the National Ozone Expedition worked with as much precision as time and weather conditions would allow. They used carefully calibrated instruments called spectrometers to monitor the gases of the stratosphere from the ground, and launched other experiments directly into the hole in enormous helium balloons. After more than two months of 18-hour days spent studying the Antarctic stratosphere, they found the chemistry to be, as one of them put it, "highly perturbed." But their work, while excellent, was inconclusive. The cause of the ozone hole remained a mystery.

And so, on to the campaign in Punta Arenas, called the Airborne Antarctic Ozone Experiment. Everyone in this thriving port city of 90,000, it seems, is delighted to play host to the scientists, who bring a welcome diversion from the rainy months—as well as a large infusion of much-needed money.

"Everyone is waiting for news about the hole," says Fernando Calentta, a 37-year-old documentary film producer. He was born and has lived his entire life in Punta Arenas. "We are worried that, if the hole gets much worse, we will not be able to go out during the day. The irony is that we have very little sunlight here—to not be able to enjoy the few sunny days we have would be tragic."

Other Punta Arenans—secretaries, waiters and shopkeepers—echo Calentta's concerns. The weather here has been unusually warm of late and there is not as much snow as there used to be. Could that, the proprietress of a cosmetics shop asks me, be the result of the ozone hole? What about the fish? asks a cab driver. Could the ozone hole be the reason why the catch has been less abundant this year? No one in authority has suggested that it is, but the uncertainty is unsettling. It is said that local property values have declined since the ozone hole's discovery.

Residents of the city are hungry for information from the NASA team, but as of now they are told very little. The mission is conducted in secret to prevent data from leaking prematurely and being misinterpreted by journalists or other outsiders. Every day, the scientists rise early, breakfast in their hotel, then

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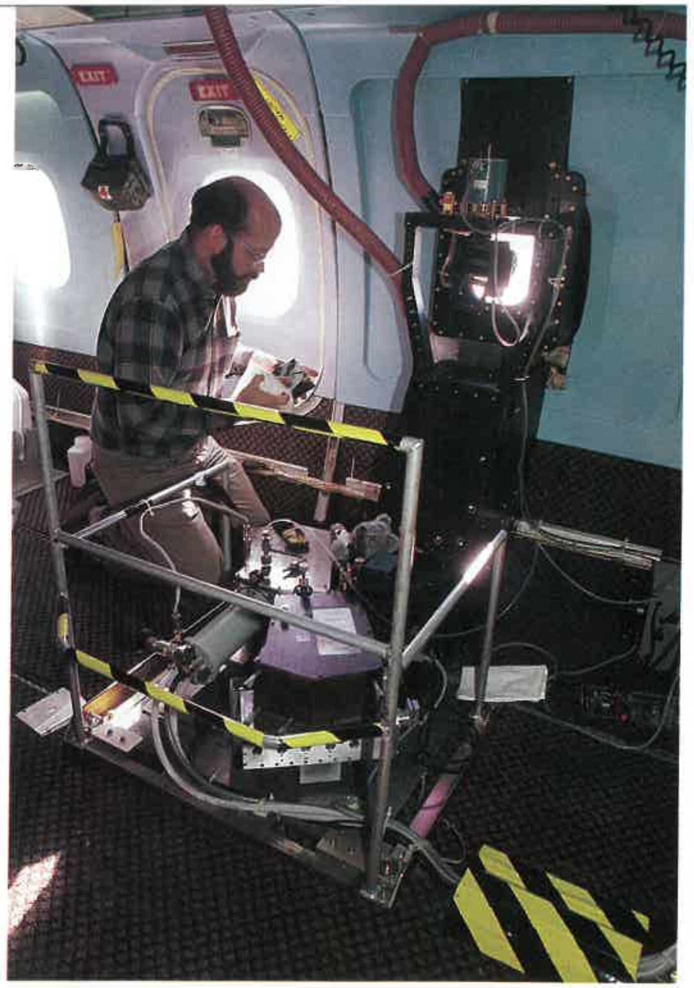

NOAA investigator Roger Jakoubek sets up device to detect ultraviolet through quartz window on DC-8.

Inside DC-8, scientists and their instruments turn the converted passenger cabin into a flying laboratory.

board a sorry-looking fleet of rental cars and vans for the 15-mile drive to the airport. The experiments are conducted in makeshift laboratories there, behind well-guarded doors. No one is permitted inside without a pass, and no one is issued a pass unless he or she is assigned to the mission. From the first it was decided that this mission would be definitive—nearly every chemical related to the breakdown of ozone in the stratosphere will be monitored. This time, the cause of the ozone hole will be revealed.

As of now, two major theories have emerged to explain the hole. The first is meteorological—it involves the simple movement of air from one place to another. It could be, for instance, that ozone is just pushed out of the stratosphere every September by an influx of ozone-poor air rising from the troposphere, the region of atmosphere closest to the Earth. This natural effect would have no dangerous implications.

The alternative theory is far more troubling. It is that chemicals produced on Earth are catalyzing the breakdown of ozone above the South Pole at a rate so great that it bodes ill for the ozone layer protecting the rest of the planet. The chemicals of most concern are chlorofluorocarbons, better known as CFCs.

CFCs, in one form known as Freon, are incredibly useful substances. They figure in foam insulation, in air conditioners, in fast-food containers and in solvents used for cleaning microchips. The United States, Canada and several Scandinavian countries banned the use of CFCs in aerosol sprays in 1978, but other nations such as England, West Germany and Japan continue to propel everything from deodorant to whipped cream with the chemicals. However, CFCs need not be squirted from a nozzle to be released into the atmosphere: air conditioners and refrigerators leak, foam insulation gets burned and solvents evaporate. Eventually most of the CFCs manufactured on Earth will find their way into the sky.

James E. Lovelock, a British biospheric chemist, was one of the first to measure significant quantities of CFCs in the atmosphere in the early 1970s. Lovelock is perhaps best known as father of the Gaia hypothesis, the concept that the planet Earth is a living organism with a life force of its own. He was not terribly concerned with his finding of CFCs in the atmosphere, for he believed that the Earth was perfectly capable of coping with one more pollutant. And, in a way, he was right. CFCs are the opposites of ozone in the sense

Lab's role is to determine chemical composition of lower air masses and to "look" up into the hole.

that they are remarkably stable compounds. Since they rarely react with other chemicals they are neither toxic nor flammable. Hence the presence of these seemingly benign chemicals in the atmosphere appeared to pose no threat—until scientists started thinking about where the CFCs were going.

Two such scientists were Sherwood Rowland, a chemist at the University of California, Irvine, and Mario Molina, who was then his postdoctoral fellow. Rowland was intrigued by the notion of a compound as stable as CFC being released into the atmosphere in such great quantities. Rowland and Molina quickly determined that 99 percent of the CFCs ever released would end up in the stratosphere. This troubled them. The upper stratosphere above most of the ozone layer is rife with ultraviolet radiation from the sun. Ultraviolet light is one of the few things that can break down CFCs into their constituents of carbon, fluorine and chlorine. Chlorine is a very reactive chemical and ozone is a very vulnerable molecule. It soon became clear that chlorine released from CFCs would attack the ozone layer in a chain reaction that begins with the formation of chlorine monoxide from CFCs and ends with thousands of ozone molecules being turned into oxygen. Oxygen, unlike ozone, does not screen out harmful ultraviolet radiation. Rowland immediately sounded the alarm: if CFC emission is not controlled, he warned, ozone will deplete dramatically by the middle of the 21st century, exposing Earth to untold levels of ultraviolet radiation.

The controversy over Rowland and Molina's theory was fierce. The CFC industry was particularly incensed. It argued that no erosion of ozone had been detected and that Rowland's hypothesis was just that—a theory with no proof. But other scientists corroborated Rowland's conclusions and today there is no disagreement that ozone is being destroyed by chlorine in the stratosphere. The only question is how much and how fast. Rowland and Molina, as well as many other scientists, predict that, given current production levels of CFCs, there will be a significant loss of stratospheric ozone around the globe within the next 50 to 60 years. But not even these alarming predictions anticipated the sharp annual drop in Antarctica. If, in fact, the hole is formed as a result of chlorine liberated from CFCs, it might be that the current calculations overlook some factor that would cause ozone to deplete faster than is currently thought. Such a finding would affect not only a multibillion-dollar chemical industry, but international environmental policy.

That's why the $10 million being spent on the mission in Punta Arenas is considered by many to be a bargain. Put simply, its goal is to sample the air in the Antarctic stratosphere, analyze it, and determine once and for all if either chemicals or wind patterns are to blame for the hole. Collecting and analyzing air samples in the hole, at altitudes of up to 67,000 feet, is not simple. It requires extraordinary skill, extraordinary precision, extraordinary planning—and two airplanes. One, a DC-8, is a passenger plane that was gutted and refurbished to accommodate more than 40 scientists and technicians and seven different experiments.

Flying lab and modified spy plane

The plane is essentially a flying laboratory: it will cruise for as long as 18 hours at up to 40,000 feet over the Antarctic continent taking measurements all the way. The DC-8 uses remote-sensing devices to "look" up into the hole, but it cannot fly into the hole itself. For that, a completely different aircraft is required, a whimsical-looking machine called an ER-2.

There is only one ER-2 in the world and it belongs to NASA. A modified version of the U-2 spy plane, it is often described as a rocket with glider wings. The ER-2 cockpit is compact, big enough to hold a single pilot but little else. Its wings are long and graceful and they flex, birdlike, to absorb the weight of the plane when it lifts from the ground. Just after takeoff,

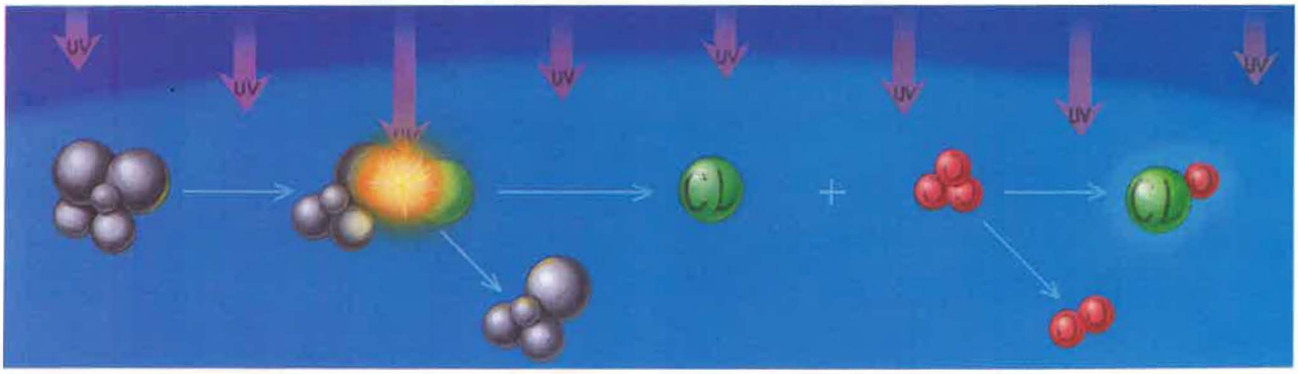

Diagram shows chemical reaction that contributes to ozone hole: CFC molecule (left) is split by UV rays, freeing chlorine, which then splits ozone into oxygen and chlorine monoxide, the "smoking gun."

the plane is a little hard to handle—it's not entirely at home at low altitudes. But above 60,000 feet, the pilots say, it's as smooth as a Cadillac on a Sunday drive. The ER-2 was, after all, designed to fly high specifically to carry experiments into the stratosphere. The plane flies too high to allow scientists to control their experiments from the ground, so the pilot triggers the experiments with simple on-off switches. Twelve miles up, the pilot is in complete charge.

There are only five men who are currently qualified to pilot the ER-2. Four of them are taking turns in Punta Arenas, flying the seven to eight hours from Chile to the heart of the hole and back without a break. All of these pilots are specialists; they fly high and long all the time. But these flights, the first series the ER-2 will make over the South Pole, are clearly not routine. Tomorrow it is Doyle Krumrey's turn to fly, and there is no question that he is nervous. I catch up with him in the lobby of his hotel and we talk about tomorrow's mission.

Krumrey is a Vietnam veteran and former reconnaissance pilot. He is taller and broader than one would expect, given the size of the ER-2 cockpit. He is also gruff and fiercely independent. "We've had the ER-2 for five years and all that time it's flown like a dream," he says, his eyes fixed on the wall, his hands busy with a cigarette. "It's extremely dependable in all environments. However, putting a single-engine airplane into an environment like this is not like riding a bike down a street. The chances of us recovering, if we have to eject from the plane, are very, very slim."

So when Krumrey prepares the next morning for his turn at the controls, the usual preflight air of anticipation has condensed into a low-level tension. His suit, five layers of Nomex and neoprene fastened with airtight zippers and topped, astronaut-style, with a ten-pound helmet, appears as comfortable as a straitjacket. As 10 A.M. approaches, he is driven to the plane, a life-support technician by his side. Slowly, he climbs on board, shakes hands with the technician, puts on his gloves. The technician hooks up an umbilical cord from Krumrey to the plane's oxygen supply. The ER-2 is ready for takeoff.

A group of scientists, bundled against the chilling winds, stand outside the ER-2 hangar to wish the airman a safe trip. The engine starts, the plane taxis down the apron and onto the runway, picks up speed, then seems to pause momentarily, as if to take a deep breath. Then, with a roar of thrust, the ER-2 disappears into the deep-blue Chilean morning. It will be out of sight for the next six and a half hours. During that time, Krumrey will sit, fixed, in the pilot's seat.

One by one, the scientists filter back into the airplane hangar where the Chilean government has built them a row of simple offices. Because it is on the military side of the airport, the hangar is tightly guarded. A silent soldier with a submachine gun is posted outside. Inside, there is a scattering of human touches: an exercise bike, a pile of cots. The overall impression, however, is dreary. Instant coffee is made by pouring bottled water into a Styrofoam cup, sprinkling in some crystals and heating the mess in a microwave oven. Most of the work goes on in the offices at the rear of the hangar—cramped, whitewashed spaces jammed with computers and hung with computer printouts of vast quantities of data. But the scientists don't complain; ambience is the last thing on their minds.

There are more than a score of research teams from the United States and Great Britain in Punta Arenas, and each will make an important contribution to whatever conclusions are drawn from the expedition. But months earlier Robert Watson, the brilliant and outspoken NASA scientist and administrator who masterminded the Punta Arenas project, told me about one of the keys to the success of the mission. It is an experiment that has great potential for determin-

After ER-2 lands, Anderson connects pod experiment to his computer to copy out data collected in flight.

Melanie Steinkamp, researcher at NOAA Aeronomy Laboratory, gets air sampler from just-landed ER-2.

ing whether chlorine liberated from CFCs is causing the ozone hole, and it is directed by chemist James Anderson, holder of the Philip S. Weld Chair in Atmospheric Chemistry at Harvard.

Soft-spoken, intense and keenly charismatic, Anderson is one of the most highly respected experimentalists in his field. His specialty, making precise measurements of chemicals in the stratosphere, is difficult because the stratosphere is so distant and because the chemicals it contains are so scarce—as scarce, Anderson says, as a drop of vermouth stirred into an Olympic-size pool of gin. He is interested in the most elusive of these elusive substances, a group of oddball molecules and atoms known as free radicals. Like a green branch torn from a tree, free radicals are ripped from a mother molecule, a process that strips them of an electron and leaves them hungry for any substance that will fill the void. Some free radicals, including chlorine, find gentle ozone, with its weakly bonded oxygen atom, to be a particularly tempting target. He measures the rate of this reaction by monitoring the levels of chlorine monoxide, the unstable byproduct of the collision of ozone with the chlorine atom. Where there is chlorine monoxide, there is ozone destruction.

Anderson has detected chlorine monoxide in the stratosphere and this alone is proof that ozone is being destroyed by chlorine. But it is not evidence that chlorine from CFCs is to blame for the formation of the ozone hole. For that, Anderson will have to determine how much chlorine there is in the Antarctic stratosphere and whether the amount is adequate to account for such a rapid breakdown of ozone. He will also have to consider the work of fellow scientists who have come to Punta Arenas to measure levels of other chemicals that could, conceivably, combine with chlorine, rendering it harmless. If levels of these other chemicals are high, then the chlorine radical is probably not to blame for the ozone hole.

Redesigning a critical experiment

Anderson generally launches his chlorine monoxide experiments in gigantic helium balloons, diaphanous hulks five times the size of the Goodyear blimp, that require a launch crew of ten and ideal weather conditions. Antarctica is known to have some of the cruelest weather in the world. It was clear that if Anderson were to participate in the Punta Arenas expedition, his experiments would have to be borne by the ER-2. He had never designed an experiment to work on any airplane, let alone a plane with such strict constraints. NASA administrator Bob Watson gave him five months.

Anderson gathered together his team of scientists, engineers and computer programmers, and set to

Peter Salter of United Kingdom Meteorological Office is Punta Arenas weatherman for DC-8, ER-2 flights.

work. His experiment detects molecules by using a very delicate and easily perturbed device, and air must flow through it slowly and without touching any surface. This is no problem in a balloon, but a bit difficult in the wing of an airplane flying many hundreds of miles per hour. Anderson called for help from an old college friend, Paul Soderman, an aerodynamicist at NASA's Ames Research Center in Mountain View, California.

Soderman dug through the engineering literature and found a paper written in the 1940s that addressed a similar aerodynamic problem in World War II fighter planes. After many calculations and weeks of experimentation, he designed a duct system that slowed down the air, then captured a small core for analysis.

Anderson's group worked nights and weekends to integrate the new airflow system into their experimental apparatus. They also had to build an entirely new detection system, one that could operate with no human intervention. The pressure was crushing. But Bob Watson still pushed for the deadline. More data from Antarctica, he said, was essential for setting international controls on CFC production, negotiations for which began in earnest soon after the hole was discovered. An international agreement on any environmental issue would be precedent setting, and Watson was loath to break the momentum of this one. There was no doubt in Watson's mind that CFCs will, eventually, erode the global ozone layer and should be limited. But if CFCs were found to be involved in the ozone depletion over Antarctica, then surely their immediate reduction would be more critical. "The question is, is this a natural or a human-induced phenomenon," Watson says. "The smoking gun will be chlorine monoxide. We have to find out how much there is relative to other chlorine species."

Anderson's operation was tight-knit and streamlined. Every piece of equipment, every computer program, even most of the circuit boards in the computers were designed and built by members of his team. Nothing was left to chance and no outsiders were employed for the project. "In this business, subcontracting is death," he says. "Each person who works on the project must be totally dedicated to it; there is absolutely no room for screwups."

And there weren't any. In July, Anderson went to California to test-fly his new machine. It worked perfectly. The mission was go.

But flying off the coast of California in midsummer is nothing compared with flying into the Antarctic vortex. Anderson is not absolutely sure that his rig will work in Punta Arenas. Usually even-tempered and soft-spoken, here he is abrupt, even dismissive. On flight day he gets up at 4 A.M., too early for coffee, and drives himself and his team to the airport. It is dark, no one else is on the road, which skims close enough to the strait to be slightly hazardous. He pulls into a mud lot and everyone heads through the darkness into the hangar. Inside, the stereo comes on almost simultaneously with the lights. Bach, it seems, is to be an honorary member of the Anderson team.

The ER-2 takes off precisely at 10 A.M., and when I finally catch up with Anderson around lunchtime, he is too busy to eat or even talk. He's told me that an earlier flight was not entirely successful; some data were lost due to a freeze-up of part of the detection system. This one, he hopes, will be better. But there is no way to know how things are going until the plane lands at 4 P.M. Meanwhile, all anyone can do is calculate and recalculate probabilities, refine computer programs, fiddle with electronics. Time drags. A technician spends an hour pumping the exercise bike, working up a sweat in the 30-degree gloom. People scuttle back and forth among the cubicles, barely nodding hello.

Scientists applaud as the ER-2 lands

Finally, word comes that the ER-2 is preparing for touchdown. The hangar empties as scientists, engineers and technicians rush to watch the landing. The ER-2 circles, then swoops down, gliding effortlessly onto the runway like a skier skimming over hard-packed snow. It lands on two tiny wheels, then slowly taxis until its wings are cradled by the hands of two technicians. The scientists applaud and respectfully resist the temptation to storm the plane right on the apron. Krumrey, the pilot, takes off his helmet. He smiles, waves, gets out of the plane and lights a cigarette. In an hour he will meet with the scientists and give them his view of what went on inside the ozone hole. But for now, it's time for a shower and a beer. He has flown farther south in the stratosphere than any man. He is very happy.

The plane is towed into the hangar and instantly swamped by the data-hungry hordes. Some jump for the cockpit, others check instruments at the wingtips. Anderson and his chief engineers, Nate Hazen and Joe Demusz, get screwdrivers and quickly bore into a pod, the metal pouch on the left wing that holds their experiment. The team's two programmers, Maria Mueller and Norton Allen, roll out a small computer, then string a cable from it to the computer inside the experiment. The computer in the wingtip clicks on, then dumps the data it has collected every second for the past six hours into the waiting machine. Everyone's eyes are fixed on the computer screen. In seconds it's finished. Anderson leans over, grabs Demusz and plants a kiss on his cheek. The data record is complete.

The ER-2 makes 12 passes through the Antarctic stratosphere in August and September, and each trip brings new information. The chlorine monoxide level, as measured by Anderson's experiment, rises steadily until, at certain altitudes, it is 500 times normal concentrations. Equally startling, ozone levels drop precipitously. By the middle of September, about half of the ozone normally expected in the region has disappeared. The ozone hole is deeper than ever this year and chlorine is higher than even Anderson anticipated.

The scientists work furiously, meeting constantly to share data and ideas. It is rare that so many minds are put to a single scientific problem, rare that scientists can meet and discuss their work with so many without submitting it to outside scrutiny. The needs of the community are put before the needs of any individual, and sometimes data are released even before they can be analyzed by the scientist who gathered them. There is no time for egos to erupt, no time for competitiveness. This is not the way science generally proceeds and it makes some people nervous. Most, however, are exhilarated.

"We don't want to catch the criminal after the corpus delicti has cooled," Anderson explains. "We have to start with a living, breathing body. That means that every chemical that can be measured must be measured and measured precisely. There isn't a single instrument on either plane that, in the long run, won't be crucial. If there is any ambiguity in our findings, our impact will be weakened. The burden of proof is enormous."

And so is the pressure. The failure of one instrument has immense implications for the operation of others. There are several failures. But none of these turns out to be permanently disabling. As October nears, a chemical snapshot of the Antarctic stratosphere comes into fuzzy focus. Bob Watson, looking tired and out of sorts, travels to Washington, D.C. to announce the mission's findings. James Anderson makes a similar announcement on the same day in Chile's capital, Santiago. The news they have is not entirely good. The edge of the stratospheric ozone hole has crept as far north as the tip of South America, an area that includes Punta Arenas. Fortunately, the sun does not shine brightly in that part of the world in winter and the ozone depletion there is not severe. However, no one can say what will happen if the hole grows deeper or spreads farther, although the latter is unlikely. The ozone hole seems to wax and wane with the Antarctic vortex; any chunk of stratosphere beyond the grasp of this whirlpool of winds is not likely to be affected.

The evidence: CFCs are involved

Thanks to Anderson's measurements, there is no longer a question of whether chlorine monoxide is involved in the formation of the hole; unless current theories are entirely off base, it is. But it is also clear that more than chemistry is involved. At the very least, it is probable that the peculiar meteorology of the Antarctic stratosphere, with its extremely dry air, its polar stratospheric clouds and whirling vortex, contributes to the breakdown of ozone. In fact, there were several large-scale changes in total ozone—such as a 10-percent drop on September 5—where meteorology would be favored as the driving factor. But even without these or similar conditions the hole would probably develop.

What does this mean for other parts of the planet? The scientists say it will be months before they will be ready to generalize from what they've learned in Antarctica to the rest of the stratosphere. What they do know, however, is that CFCs have a lifetime of 50 to 200 years, and that there is plenty more of the chemical heading heavenward. Antarctica, with its unique meteorology, is perhaps a weak link in the stratospheric chain, but there is also no telling whether other stretches of stratosphere don't have soft spots that have yet to show themselves. We are pushing chlorine levels in the stratosphere higher every year—eventually even the sturdiest slab of stratosphere will be altered by the chemical invasion.

"The CFC industry has consistently taken the stand that even a chemical is innocent until proven guilty, and that we should wait to act until we see an actual depletion," Anderson says. "Well, we now know that this depletion is real, and that it is related to chlorine."

On September 17, an international protocol calling for a freeze and eventual reduction in CFC production in developed countries was signed by more than 30 nations at a meeting in Montreal. Anderson is convinced that the finding of chlorine at 500 times its normal levels in the Antarctic stratosphere, coupled with the record ozone depletion, will motivate a majority of countries to ratify the agreement, the first international protocol on any major environmental issue. The agreement will not mean that we will have to give up our air conditioners or refrigerators, but it will force CFC manufacturers to escalate the already substantial effort to find safe alternatives to the chemicals, alternatives that, at least at first, will increase consumer costs. However, Anderson points out, these costs are nothing when compared with the price we will pay if we allow an ever-thickening stream of CFCs to waft through the atmosphere.

"What we saw in Antarctica was a clear connection between high chlorine levels and ozone depletion," says Anderson. "Essentially, what we found was a low-temperature flame burning over an area the size of a continent. This is intolerable. There is no question that we should reduce the fuel for this flame. It is time we stopped using the atmosphere as a test tube for global chemical experiments."

Between flights ER-2 waits in hangar, with its nose opened for removal of experiments; NOAA scientists check instruments tucked into a bay on underside. Data it gathered proved CFCs are a cause of ozone hole.

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