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The unexpected confluence of plasma physics and climate science: On the lives and legacies of Norman Rostoker and Sherry Rowland

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The Norman Rostoker Memorial Symposium brought together approximately 150 attendees to share their recent work and to reflect on the contributions of Norman Rostoker to the field of plasma physics and the advancement of fusion as a source of renewable clean energy. The field has changed considerably in a few short decades, with theoretical advances and technological innovations evolving in lock step. Over those same decades, our understanding of human induced climate change has also evolved; measurable changes in Earth's physical, chemical, and biological processes have already been observed, and these will likely intensify in the coming decades. Never before has the need for clean energy been more pronounced, or the need for transformative solutions more pressing. As scientists work with legislators, journalists, and the public to take actions to address the threat of climate change, there is much to be learned from the legacies of innovators like Norman Rostoker, who have tackled complex problems with scientific insight and determination even when the odds were stacked against them. I write this from the perspective on an Earth system scientist who studies photosynthesis and the biogeochemistry of the oceans, and my statements about plasma physics and Norman Rostoker are based on information I gathered from the colloquium and from many enjoyable conversations with his friends and colleagues.

ENDURING LEGACIES OF GROUNDBREAKING SCIENCE AND PERSEVERANCE

Revolutionizing a field is not easy. The journey toward success is often met at first with questions and even cynicism from one's peers, and then with technological hurdles and opposition from outside interests. A common thread among many great leaders is the combination of scientific insight and the ability to stick with a problem until it is solved; a grittiness by which they stay the course despite challenges and objections. Successful perseverance, however, requires not only living with setbacks and keeping focused on the journey, but also on maintaining a level of objectivity by constantly testing and reevaluating the path forward.

Norman Rostoker's vision that fusion technology could provide the world with abundant, clean energy challenged many long standing paradigms in the field. Initial theoretical discussions about fusion pointed toward the use of deuterium/tritium fuels, which require less energy input but utilize neutron producing reactions that require complex engineering controls to make safe and operable[1]. Rostoker saw an opportunity to reduce engineering complexity by developing technology that would utilize aneutronic proton/boron fusion reactions, essentially putting

The Physics of Plasma-Driven Accelerators and Accelerator-Driven Fusion
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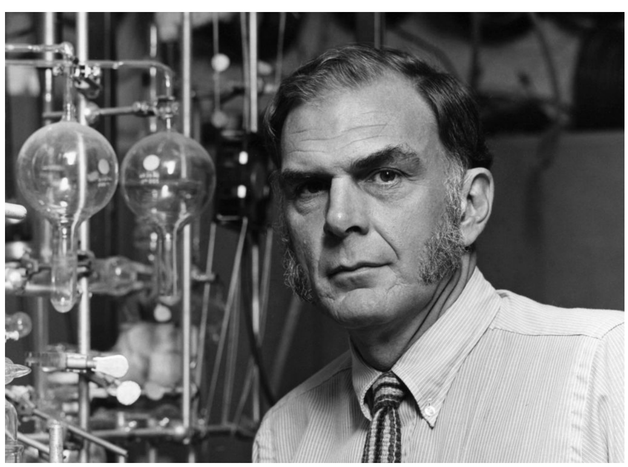
the challenge in the hands and minds of physicists. His vision was to see the physics community rise to the challenge of developing and realizing a new technology that many believed was not feasible.

Norman Rostoker. Courtesy of AIP Emilio Segre Visual Archives, Physics Today Collection

Like plasma physics, the field of Earth system science has also had its share of maverick researchers who challenge the status quo. Earth system science considers the Earth holistically as a coupled system in which human activity plays a significant role. Although now an accepted idea, many researchers and the public alike initially doubted that humans could affect the Earth on a global scale. One of the early discoveries of Earth system science was made by F. Sherwood (Sherry) Rowland and his post-doc Mario Molina, who in 1974 discovered that human-made chlorofluorocarbons (CFC's) would accumulate globally and contribute to the depletion of stratospheric ozone[2], an atmospheric trace gas that protects Earth from damaging ultraviolet radiation. At the time, ozone depletion had not been observed, and the work was initially met with skepticism from some of the science community and by outright hostility from CFC industry[3]. But like Rostoker, Rowland persevered, and more than a decade later his findings were verified when the science behind the Antarctic ozone hole, first reported in 1985, clearly identified CFCs as the culprit. His work ultimately led to the Montreal Protocol in 1987, an international agreement in which to date 196 countries have pledged to phase out CFC's. Rowland's story is one of the greatest success stories in the environmental movement, but it is worth noting that it took a decade or more for the tide of public opinion to change about his work.



Frank Sherwood Rowland. Courtesy of UCI Libraries' Special Collections & Archives

Rostoker and Rowland exemplify how scientific insight combines with gritty perseverance to create real change both in science and society for the benefit of humanity. Yet their similarities don't end there. Rostoker and Rowland's careers overlapped extensively at UC Irvine. Both were early members of the faculty and played pivotal roles in shaping their departments. Rostoker joined the Physics faculty in 1972 and served as Chair from 1973-1976[4], laying the groundwork for the department to become a leading institution for research in plasma physics. UCI's current Dean of Physical Sciences Ken Janda noted, "At UC Irvine, [Rostoker] positioned the Department of Physics & Astronomy at the forefront of fusion research and was an inspiration and mentor to many dozens of students who are today's leaders in applied physics and technology.[4]" Rowland was the founding Chair of UCI's Chemistry Department in 1964, and in 1995 was a founding member of UCI's Earth System Science department, now recognized as one of the most influential academic departments in the nation devoted to studying Earth as a system.

Ultimately the vision and perseverance of Rostoker and Rowland were recognized broadly in their respective disciplines, with both researchers receiving high academic honors. In 1995 Sherry Rowland received the Nobel Prize in Chemistry for his work with CFCs, and in 1988 Rostoker received the American Physical Society's James Clerk Maxwell Prize for Plasma Physics. In 1998, Rostoker founded the fusion power company Tri Alpha Energy to bring his ideas about clean energy to fruition. In both cases, Rostoker and Rowland understood their journeys would be long and hard fought, but in both cases their dedication paid out. Chief Technology Officer of Tri Alpha Michl Binderbauer observed, "[Rostoker] excelled at the 'never surrender' notion. Without his steadfastness and strength of conviction, our vision would have remained on paper, and we would not have been able to conclusively demonstrate the merits of some of Norman's groundbreaking ideas in fusion research."[4]

The remarkable stories of Rostoker and Rowland reached confluence in 2005, when Rowland joined the scientific advisory board for Tri Alpha Energy, along with Nobel winning physicists Burton Richter and Arno Allan Penzias. Rowland brought his expertise in environmental science and his early training as a nuclear chemist to bear as a Tri Alpha adviser, while Rostoker got down to the nitty-gritty of making his brand of fusion energy a reality. Having persevered in their research and pioneered their respective groundbreaking fields, the two became friends and collaborators through Tri Alpha.

Through it all Rostoker and Rowland never lost their sense of humor about life and science. "Sherry was a story teller who laughed and smiled easily," recalls Don Blake, UCI Chemistry Professor and a former postdoc in the Rowland lab, and who lived across the street from Rostoker in University Hills. "Norman's sense of humor was more playful; a pinch of mischievousness with plenty of goodness. Norman would play with my children in the front yard - he had this toy bird that he would wind up and throw that would flap its wings - Norman and the kids both loved it." Rowland was also great with children, and at 6'5" was a gentle giant. "I remember when my son Tim was two years old Sherry took him on a walk to the chemistry mail room...he had to lean way down so the little guy could reach up and grab one of his enormous fingers." A final similarity is that Rostoker and Rowland were both devoted husbands of roughly six decades. Blake tells the story of how Rostoker's wife, Corinne, held the family's ownership of Tri Alpha. "When they sold their first set of shares Norman quipped, 'My father would be proud, he always wanted me to be married to a rich woman.'"

Rostoker and Rowland were two remarkable, revolutionary scientists who shared more in common than would be expected based on their seemingly disparate backgrounds. But perhaps the main thread in their stories is that they both possessed a sense of tenacity and critical scientific evaluation that enabled them to see their paradigm shifting ideas through to fruition. Now, as the world faces the challenge of climate change, both as scientists and as members of society, we have much to learn from the bold brand of science and innovation embodied by Rostoker and Rowland.

GLOBAL CHANGE AND THE NEED FOR CLEAN ENERGY SOLUTIONS

Much like the careers of Rostoker and Rowland, the fields of plasma physics and Earth system science have shared parallels during their histories. These fields are now reaching an unexpected nexus with the mandate for clean energy coming from the need to constrain global mean warming to 2°C above pre-industrial levels. Climate change has upped the ante in the quest for clean energy, making technologies like fusion, and others, all the more necessary to achieve sustainability on Earth. Below is an overview of modern climate science that highlights why the need for clean energy is so pressing.

Earth's climate system is strongly influenced by greenhouse gases in the atmosphere. These gases modulate how much the Earth must warm to radiate the amount of solar energy it absorbs. Greenhouse gases that are directly altered by human activities include carbon dioxide (CO_2), methane, nitrous oxide, as well as the CFCs and ozone studied by Sherry Rowland. The natural abundance of greenhouse gases has kept the Earth's average surface temperature at about 14^{o}C as opposed to approximately -16 ^{o}C that the planet would be if an atmosphere was not present[5]. Indeed, without an atmosphere containing water vapor and other gases like CO_2, Earth's surface would be frozen and uninhabitable by humans.

Earth's climate has experienced changes in the past, and scientists are able to measure these changes using an array of paleontological data. One example of direct paleo-atmosphere data is from the gas bubbles trapped in Antarctic ice. By analyzing the isotopic and chemical composition of gases trapped in the ice long ago, it is possible to reconstruct Earth's climate[6]. The longest ice-core record we have, and that seems possible, goes back about 1 million years. During this long time period the Earth's climate has cycled through glacial (usually long) and interglacial periods (usually short, about 20,000 years). Analyses of ice core bubbles have revealed a tight coupling between atmospheric CO_2 levels and temperature over these transitions, where the highest temperatures coincide with the highest CO_2 levels[6]. In terms of causation, warmer temperatures usually precede the rise in CO_2, but the CO_2 increases amplify the subsequent warming. Remarkably, throughout this long record the concentration of CO_2 in the atmosphere has remained below 300 ppm until very recently.

Modern atmospheric CO_2 levels are increasing rapidly due to human activities like the burning of fossil fuels and deforestation[5]. The trend has been recorded for nearly six decades at the Mauna Loa Observatory in Hawaii, beginning in the 1957 International Geophysical Year by C. David Keeling. The data set overlaps with and matches the ice core record, and has revealed an increase from about 315 ppm in 1958 to almost 400 ppm in 2014. The annual average for the year 2015 is on track to exceed 400 ppm for the first time in at least the last 800,000 years.

The Intergovernmental Panel on Climate Change (IPCC) was formed in 1988 in order to deliver unbiased, internationally accepted, scientific assessments of climate change for the anticipated 1990 United Nations Framework Convention on Climate Change (UNFCCC). The UNFCCC remains the international body addressing climate change to this day, and recently held its 21st meeting in December 2015 (COP-21, the Paris Climate Conference[7]). The IPCC generates assessment reports that synthesize scientific data and utilize climate models to present future climate change scenarios. The latest report indicates that under baseline scenarios where greenhouse gas emissions remain unchecked and no additional mitigation is introduced, global mean surface temperature will increase 3.7 - 4.8 ^{o}C by the year 2100[5]. The effects of past increases in CO_2 on temperature are already coming to bear: the ten hottest years on record have all occurred since 1998; and our most recent year 2015 is the hottest[8].

One particular reason for concern as we head into our unexplored 21st century climate is the uncertain positive feedbacks between global warming and the carbon cycle. Over the past ice ages we have seen a self- reinforcing cycle in that an initial warming caused by the Earth's orbital changes appears to cause increases in CO_2 that in turn amplify the warming. We have identified several mechanisms that might increase CO_2 in the coming century above and beyond that expected from our emissions alone. For example, as the Arctic warms, permafrost soils thaw, become biologically active, and their large stock of carbon may be released to the atmosphere. Additionally, the ocean absorbs much of the CO_2 we produce, but with warming the upper layers become more stable and less CO_2 can be stored.

Other examples of climate feedbacks could also occur. For example, as warming temperatures cause snow and ice to decline, these reflective substances melt to reveal land and liquid water, which are darker and absorb more heat. The greater heat absorption by land and water further warms the planet, intensifying the warming cycle. Evaporation also increases with climate warming, contributing more heat-trapping water vapor to the atmosphere, and in turn causing more water to evaporate and more warming to occur.

Climate change has already begun to manifest in observable ways. The pattern and type of rainfall has changed in many places with fewer days having light rain and the days with greatest rain becoming not more frequent but more intense. The frequency and intensity of certain types of storms is shifting. There is some evidence that the floods and droughts are becoming more common or extensive. These regional changes and shifting temperature patterns cause plants and animals to move poleward and toward higher elevations to track the changing conditions on land and sea. The timing with which organisms become active over seasonal cycles can also be adversely affected, as when interdependent species that rely on each other for food or pollination have their cycles pushed out of sync.

Sea levels rise is climate change's elephant in the room. It threatens coastal and low-lying settlements, fresh water supplies, and the current coastal ecosystems that supply us with goods and services. The effects are particularly pressing in certain low elevation island nations, where entire nations of people could be displaced as climate refugees within this century. Over the last century the global mean sea level rose by approximately 0.2 meters [5], but projections indicate that the rate of sea level rise is accelerating. Even if we control greenhouse gases and limit warming to 2°C, the seal level will continue to rise by as much as several meters over the next few centuries. Further, sea level rise is not uniform and depends regionally on ocean warming, currents, and atmospheric winds. Sea level rise occurs via two mechanisms. First, the ocean has absorbed most of the additional heat from global warming, and this causes the water to thermally expand[5]. Second, melting glaciers and ice sheets on land add additional water to the ocean, further exacerbating sea level rise.

Aside from the thermal effects of global change, the ocean is affected by chemical changes that result from increased atmospheric CO_2 levels. The ocean absorbs the excess CO_2 from fossil fuel burning, which reacts with water to form carbonic acid, contributing to a phenomenon called ocean acidification. The pH of the ocean has already declined 0.1 pH units, and will continue to decline by an additional 0.2-0.3 pH units by the end of the century[5]. Like sea level rise, the increased acidity will depend on regional conditions. Ocean acidification affects the fitness of certain organisms like corals and shellfish that form shells of calcium carbonate, because this material is more soluble as pH declines. The growth of marine phytoplankton may also be affected as rates of photosynthesis and respiration adjust to the new CO_2 levels[9]. Together these effects on sea life have the potential to threaten industries that rely on marine organisms, as well as how the ocean contributes to Earth's biogeochemical cycles.

TOWARD A CLEAN ENERGY REVOLUTION

Climate change is a problem that is different from other threats humanity has faced before. The global scale and accelerating pace of climate change sets it apart from other problems that can be solved at a slower pace over the course of generations as new technologies develop and public understanding evolves. Additionally, there is no single technological or social solution for climate change, because many factors contribute to it. Climate change is a pressing, existential threat that requires rapid responses and bold solutions to be implemented now if the worst of the potential outcomes are to be averted. The extent to which we curb our emissions now will determine how much adaptation we will be required to do in the future.

Limiting climate change risks requires policies that bring about reductions in emissions and incentivize the development and use of low carbon technologies. Reducing emissions could be achieved by policies that would allow emissions to be priced according to their true cost to the environment. While there are concerns about how such costs would affect the economy, it is important to note that left unchecked, climate change will certainly affect the economy in adverse ways via the natural disasters described above. Making changes now toward a clean energy economy could open the path forward to create new jobs and open new markets in the energy sector. In addition to providing incentives to lessen emissions, carbon emission abatement relies on ingenuity and technological innovation, hence supporting research and development of clean energy technologies is critical[10]. Indeed, great strides have already been made in solar, wind, and geothermal energy technologies in a few short decades. The recent Paris Agreement negotiated during the 2015 United Nations Framework Convention on Climate Change in Paris[7] also signifies a breakthrough, with an international agreement across all countries to reduce effective carbon emissions.

Developing these new technologies will require scientific vision and perseverance, traits that were exemplified by Norman Rostoker and Sherry Rowland decades ago when their ideas were first put forward. Though the technology is still undergoing refinement, the example of Rostoker's willingness to challenge accepted paradigms captures the type of bold innovation that will challenge existing assumptions about how energy is produced and help humanity take steps toward clean energy and a sustainable future. The climate crisis needs disruptive, transformational solutions to be developed through the type of technological innovation and perseverance exemplified in Rowland's and Rostoker's research.

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