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Anneke Levelt Sengers: An international authority in the thermodynamics of fluids and a passionate advocate for women in science

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Johanna Maria Henrica (Anneke) Levelt Sengers, a Dutch-American physicist, an international authority in the thermodynamics of fluids and fluid mixtures, especially near critical points, and a passionate advocate for women in science, passed away at Asbury Methodist Village in Gaithersburg, Maryland on February 28, 2024, a few days shy of her 95th birthday.

Anneke was born in Amsterdam on March 4, 1929. Her father had a PhD in chemistry and her mother had a master's degree in physics and astronomy. During World War II, her father was arrested by the Nazis and survived imprisonment in the Buchenwald concentration camp. As the oldest daughter, Anneke helped care for her nine siblings in her youth and kept in loving contact with them over the years.

As a highly distinguished scientist and mother of four children, a very rare combination in the 1960s and 1970s, Anneke was well ahead of her times. Despite being born at a time when women were not welcomed into science and engineering, Anneke chose a career in physics. She was among those women whose determination, persistence, and excellence as scientists changed the landscape for the women who came after them. Anneke grew up during a time when the Imperial German slogan, according to which women were fit only for "Kinder, Küche, und Kirche" (children, kitchen, and church), was still generally accepted. She did enjoy those more traditional roles: she gloried in her children and grandchildren, and she was an excellent cook. However, she did not let those roles define her life.

Anneke obtained her PhD in physics at the University of Amsterdam in 1958. Her dissertation, *Measurements of the Compressibility of Argon in the Gaseous and Liquid Phase* (1), was supervised by the distinguished physicists Antonius M. J. F. Michels, and Jan de Boer, the latter in informal capacity. Anneke's measurements of the equation of state of argon were among the most accurate ever made. Upon comparing her argon data with xenon data, she found departures from the theory of corresponding states. At Amsterdam, Anneke also contributed to measuring the equations of state of hydrogen and deuterium, and she developed and tested a quantum-mechanical cell model with data for their liquid phases.

After a year as a postdoctoral researcher at the University of Wisconsin, she returned to the van der Waals Laboratory in the Netherlands. Anneke and fellow van der Waals Laboratory physicist Jan V. Sengers were married in 1963. Their loving partnership of 61 years was an essential pillar throughout their careers. Soon after getting married, Jan and Anneke emigrated to the United States, so that she could have a career. Anneke joined the National Bureau of Standards (NBS), now the National Institute of Standards and Technology (NIST). While her career was centered at NBS/NIST, Jan's was based at the nearby campus of the University of Maryland. Thus, Anneke and Jan circumvented many of

Anneke Levelt Sengers (1929 to 2024) in 2014. Image Credit: the National Institute of Standards and Technology Digital Collections.

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the obstacles faced by married couples conducting related research. In the course of her 31-year career at NBS/NIST, Anneke served as a Scientist, Leader, and Fellow. She retired in 1994 and remained active as Emerita for more than two decades, in both research and public service.

At NIST, Anneke Levelt Sengers established herself as an international authority in the area of critical behavior of fluids and fluid mixtures. Through her deep involvement in IAPWS, the International Association for the Properties of Water and Steam, she was instrumental in creating a database and coordinating the research activities on thermodynamic properties of aqueous systems for the power-generating industry and for fundamental science. For decades, Anneke served as an indispensable liaison between the best European schools of thermodynamics, especially in the Netherlands and Russia. Her book *How Fluids Unmix: Discoveries by the School of Van der Waals and Kamerlingh Onnes* (2), written in a friendly and passionate style, introduced the spectacular discoveries of the Dutch thermodynamicists to the broader international scientific community. Much of Anneke's research emphasized testing the best available theories of thermophysical properties with the most accurate measurements and advocating for the use of the test results in engineering applications.

At NBS/NIST, she measured the equations of state of carbon dioxide and ethylene, with emphasis on their behavior near their respective critical points. Because ethylene is the precursor of polyethylene, these data had significant engineering value. In the early 1960s, the physics and statistical mechanics communities were deeply interested in the universal character of the divergences of physical properties, such as the compressibility and thermal conductivity, near critical points of fluids, fluid mixtures, and lattice models of fluids. Anneke used the new theoretical concepts of scaling and critical exponents to correlate numerous measurements from literature data for diverse fluids and fluid mixtures, including steam, isobutane, isobutane-isopentane, and ionic fluid mixtures, that have significant engineering applications. She attracted a series of postdocs and young experimentalists to NBS/NIST (including two of us: S.C.G. and M.R.M). Her evolving team developed novel techniques to accurately measure diverging thermophysical properties as close as possible to diverse critical points. The techniques used included magnetic suspension densimetry, light scattering, and precision measurements of the dielectric constant, refractive index, and viscosity. Kenneth Wilson's 1982 Nobel Prize in Physics Lecture mentions the importance of this work: "Throughout the sixties a major experimental effort pinned down critical exponents and more generally provided a solid experimental basis for theoretical studies going beyond mean field theory..."

Following Wilson's Nobel Prize, the interest of the thermophysics community shifted to the properties of complex fluids near phase transitions and critical points. By then, Anneke had expanded her interest in formulating highly accurate correlations of the thermophysical properties of water, steam, aqueous solutions, and ionic fluids. She chaired an international working group studying the thermophysical properties of water and then served as IAPWS President in 1991 and 1992. She coauthored the truly heroic paper *Sixteen Thousand Evaluated Experimental Thermodynamic Property Data for Water and Steam* (3). She wrote definitive papers on the wavelength-dependent refractive index of water and on water's dielectric constant.

One of Anneke's important collaborators was her husband Jan Sengers. Together, Anneke and Jan coauthored more than a dozen publications, including highly cited reviews (4). Throughout her career, Anneke collaborated productively with the group measuring and modeling thermophysical properties of fluids at NBS/NIST's Boulder Campus. She was particularly effective in attracting and mentoring outstanding postdoctoral researchers from outside the United States to NBS/NIST.

When Anneke joined NBS in 1963, the only opportunities for women scientists were with the federal government, as universities and industry would not begin to hire women researchers until the late 1970s. At "The Bureau", Anneke was one of three women scientists in the Heat Division. For women in science in the 1960s and 1970s (and even today), the question was how much time and energy to devote to directly advocating for women in science, versus setting an example by doing really good science. Anneke did both. For example, in the early 1970s, there was a budget crisis at NBS and one proposed plan for its solution would have placed women scientists on leave without pay. Anneke opposed this plan, which was ultimately rejected. She also supported women by being an active scientist, visible at NBS and in the broader scientific community, in the US and abroad. Her presence on the scientific scene and her continuing contributions to the literature and at conferences set an example for other women, who could see that such a life was possible.

After she formally retired from NIST, Anneke undertook international activities on behalf of women scientists. She cochaired the Advisory Panel for the 2006 report "Women for Science", published by the Inter-Academy Council, a multinational organization of science academies that was formed to study major global issues. At the age of 84, she cochaired the Women for Science Working Group of the Inter-American Network of Academies of Sciences (IANAS), leading to the publication, in 2013, of the bilingual book *Women Scientists in the Americas – Their Inspiring Stories*. Both reports are still informative and inspiring. In 2015, the IANAS Women for Science Working Group announced the establishment of the Anneke Levelt-Sengers Prize for young women scientists.

Anneke received numerous awards and recognitions. She was a member of both the National Academy of Sciences and the National Academy of Engineering. She was a Correspondent of the Royal Netherlands Academy of Sciences and of the Royal Holland Society for Sciences, and a Fellow of the American Society of Mechanical Engineers, the American Physical Society, IAPWS, and the American Association for the Advancement of Science. In 1992, Anneke received an honorary doctorate from the Technical University of Delft: She was the first such female honoree in the 150-year history of this university. In 2003, Anneke was the L'Oréal-UNESCO Award for Women in Science Laureate for North America. Among her other honors are the Department of Commerce Silver (1972) and Gold (1978) Medals, the NBS

Eugene Condon Award (1978), being named NBS/NIST Fellow (1984), induction to the NIST Portrait Gallery (2000), and the Yeram Touloukian Award of the American Society of Mechanical Engineers (2006).

With the passing of Anneke Levelt Sengers, the world has lost not only an eminent scientist, but also a visionary, passionate, and stunningly effective advocate for women in science and engineering.

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2. J. M. H. Levelt Sengers, *How Fluids Unmix: Discoveries by the School of Van Der Waals and Kamerlingh Onnes* (Royal Netherlands Academy of Arts and Sciences, Amsterdam, 2002).
3. H. Sato *et al.*, Sixteen thousand evaluated experimental thermodynamic property data for water and steam. *J. Phys. Chem. Ref. Data* **20**, 1023–1044 (1991).
4. J. V. Sengers, J. M. H. Levelt Sengers, Thermodynamic behavior of fluids near the critical point. *Annu. Rev. Phys. Chem.* **37**, 189–222 (1986).