In Memoriam: Ernest G. Cravalho: A Pathbreaker for Interdisciplinary Research in Thermal Science—Personal Recollections

I first met Ernie in the Fall of 1989, after I had joined the MIT mechanical engineering department as an assistant professor. We were assigned to coteach the undergraduate engineering thermodynamics course together with Prof. Joseph L. Smith, based on the book Ernie and Joe had written about 20 years before.

Ernie had to go out of town at short notice, and the next day I gave my first lecture in front of 200 impatient students expecting to be taught by a seasoned professor and not by an inexperienced guy just out of graduate school! But Ernie trusted me with this, and this was typical of him: He had full confidence in his students and colleagues, and he showed many of us this trust clearly, which I found most encouraging.

Ernie (1967) and I (1989) had both received our doctorates working with Prof. Chang-Lin Tien, with 22 years in between, and Ernie had been associated for some time with the Cryogenic Engineering Laboratory founded after the war by Prof. Samuel C. Collins and since 1964 lead by Joe Smith [1]. For Ernie, it was natural to take me under his wings, and I have greatly benefited from our association, which led to five papers we published together with the students we cosupervised [2–6]. At that time, we investigated the optical properties of superconductors and semiconductors and the design of devices made from these materials. In addition, Ernie introduced me to his freshly minted Ph.D. student, Prof. Mehmet Toner, who today himself is a pre-eminent figure in the biomedical technology field and whose lifelong friendship I treasure.

Ernie was extremely dedicated to his students, both as a teacher and a research supervisor. He and his first wife were also highly engaged housemasters in one of MIT's undergraduate dormitories. He gave students his full attention, and they were able to reach him almost any time. He deeply enjoyed his interactions with them and drew great personal satisfaction from them.

What really set Ernie apart, however, was his courage and ability to enter entirely new fields based on his strong footing in heat transfer and thermodynamics.

Looking at the paper Ernie had written with Prof. Tien and R.P. Caren in 1967 [7] based on his doctoral thesis, one can only marvel at the extent to which it was ahead of its time. At that moment, the mechanical engineering profession had just started to absorb a much deeper physical understanding in its curricula and engineering practice, in part driven by the tremendous progress in aerospace and other emerging high-tech industries, as well as demanding defense technology applications. But the majority of teaching, research, and engineering practice were based on continuum formulations of physical laws.

Most papers in heat transfer at that time dealt with rather traditional engineering problems related to heat conduction, convection, phase change, and, to a lesser extent, radiation, with a strong bias toward application and much less emphasis on physical fundamentals.

In contrast, Ernie's paper stands out because it addresses deep fundamental questions of radiative energy transfer in a situation where the continuum-based Stefan-Boltzmann radiation law was inadequate because the wavelength at liquid–helium temperatures is of the same order of magnitude as the spacing of the dielectric solids which were studied. This influenced the net energy transfer through wave interference and radiation tunneling at spacings below about three wavelengths.

Clearly, Ernie was influenced in this approach by Prof. Tien, and many of my colleagues, I am sure, have Prof. Tien's voice still in their ears: "Go to the extremes—that is where you find new research problems!" But it was Ernie who carried out the research, and he demonstrated later in his career many times over his willingness and capability to successfully enter new fields of research or rather creating them.

Around 1990, when many of us graduated from Prof. Tien's group, the new field of microscale and later nanoscale heat transfer emerged, yielding tremendous benefits, more than 20 years later after Ernie and Prof. Tien had been inspired for their research by the problem of vacuum insulation of cryogenic systems.

Only four years after he had joined MIT as an assistant professor, Ernie once again entered a completely new field, part of heat and mass transfer in biotechnology, on which this issue of JHT is focused. Together with Kenneth R. Diller, Ernie invented a cryomicroscope that made it possible to investigate freezing and thawing in biological cell suspensions between liquid nitrogen and room temperatures [8]. One year later, this experimental approach bore rich fruit: Ken Diller, Ernie, and C. E. Huggins were able to establish precise boundaries for the cooling rates leading to intracellular ice formation in frozen human erythrocytes [9].

Rereading both papers today, I cannot help but be impressed by the diligence of the design of the cryomicroscopic apparatus complete with an analog electronic temperature control built from scratch. Ernie was both an accomplished theoretician and a gifted experimentalist. In the latter, he was undoubtedly supported by the strong craftsmanship tradition in the Cryogenic Engineering Laboratory. The second paper shows that Ernie and Ken Diller had to absorb a vast body of literature on physicochemistry and the properties of biological tissues, which was completely new at least for Ernie.

One has to view the situation Ernie was in: As an assistant professor trying to get tenure, the natural approach would have been to play it safe and continue to work in the field with which he was familiar: cryogenic heat transfer in industrial applications.

When I asked Ernie what had driven him down this riskier path, he told me that he always yearned to make positive and lasting contributions to humankind and that he had felt at the time that entering the biomedical field would be the most direct approach for him, irrespective of the associated risks.

In this sense, Ernie was a true pathbreaker for many of us who followed in his footsteps, branching out from heat transfer into–and the list is far from complete–combustion science, thermal atomic force microscopy, integrated electronic circuit design, infrared spectroscopy, heat pipe design, laser analysis and design, nuclear reactor safety, micro-electromechanical systems, etc. Had the heat transfer field not taken to this path of interdisciplinary research, it would have become an auxiliary science to other disciplines like electrical engineering, aerospace, biotechnology, etc. Furthermore, I am convinced that the *Journal of Heat Transfer* as our primary archival publication would not have the importance it has today.

Now, from an industrial vantage point, I do believe that we in the mechanical engineering profession are at a similar juncture today. The last decade has brought significant advances in data science, artificial intelligence, and machine learning. Through the application of cloud native computing to dynamic control systems, many industrial fields will be disrupted in the coming years. As mechanical engineers, once again we must pay attention so that we do not become an auxiliary field carrying out mechanical tasks handed to us by the intelligence which is implemented in the algorithms developed by computer scientists. We as a profession must embrace these new technologies and fuze them with our traditional mechanical engineering disciplines, just as we did with mechatronic systems, to create new know-how and applications. Systems design is the hallmark of mechanical engineering. Better than anybody, we mechanical engineers are able to affect real-world benefits based on new algorithms or neural networks, e.g., in energy efficiency, climate protection, human health, and safety. But in order to achieve this, we must venture into data science just as Ernie ventured into electrodynamic theory and cryobiology 50 years ago.

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I do want to close these reflections on a personal note. When I had to make the hardest decision of my professional life, i.e., whether to leave academia, MIT, and the collaborations with my esteemed colleagues for a new career in industry, Ernie supported me. He stepped in and took over the supervision of my students Jeffrey P. Hebb, Christopher G. Malone, and MacMurray D. Whale, who would complete their master (J. P. Hebb, who obtained his Ph.D. with Klavs Jensen) and doctorate degrees (C. G. Malone and M. D. Whale) under his supervision. They worked on microscale radiative transfer as well as on spectroscopy and other optical measuring techniques. Ernie took a great load off my shoulders and relieved me from the concern that my students, who had come to my group expecting me to be there for them, would suffer from a decision that I felt I had to take. Also, in this case, Ernie demonstrated his devotion to the MIT students. I was happy to see that their collaboration resulted in another five papers they published together [10–14], and that these students had successful careers thereafter, just as the students whose research I supervised completely myself.

Let me quote Mac Whale [15]: "His lasting legacy was in his encouragement as a mentor and advisor … His insights still carry weight for me: Whether it's why and how to do science, how to live your life with meaning and intention, how to be an effective parent and mentor students when I was an assistant professor myself, or even now as a partner in an investment bank: it is people and relationships that matter most. I may have been taught that from my parents, but it was Ernie who crystallized that to me as a young adult."

As a teacher, a researcher, a research supervisor, and a human being, Ernie Cravalho remains one of the most outstanding individuals I have come across.

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