

PHYSICS FOR PROFIT AND FUN

Developing products for industry can be intellectually challenging and financially rewarding, but it's not without its frustrations.

John F. Waymouth

This article is an edited version of the talk "Allis in Wonderland or Doing Physics for Profit as well as Fun" that John Waymouth gave when he received the American Physical Society's Will Allis Prize in June 2000.

I spent my entire working life using physics to grub for paydirt in an industrial setting. By this I do not mean the central research laboratory of a multibillion-dollar technological conglomerate able to support "pure" curiosity-driven study. I mean the product development laboratory of a nose-to-the-grindstone division engaged in a battle for market share in a rather prosaic industry that nevertheless depended on mastery of some complex and challenging technology. In such a setting, any project that yielded only meeting presentations or publications in refereed journals had to be considered essentially a failure.

Academic colleagues, as well as those in central-research-laboratory environments, have often expressed concern that such focused investigations stifle creativity and preclude following up unexpected discoveries. However, I never in my entire career had to write a proposal for a government research grant to get my work supported. Because (at least in recent years) four proposals might have to be written to get one grant, I conclude that I have been spared an enormous drain on my productivity that has at least partially compensated me for having to take on a lot of mundane tasks. And, the curious thing is that many of those mundane tasks turned out on closer examination to involve some interesting physics.

In any case, I had fun, and I didn't feel my creativity was particularly hobbled by the constraint of utility superposed on the requirement of novelty. I did have the advantage that my area of study was the technology of light sources, a field hitherto plowed primarily by experiment. It was the lamp industry, after all, that gave the term "Edisonian research" to the world of technology.

I take great pride in having been the key man for two major product-family developments that were firmly rooted in physics: very high output (VHO) fluorescent lamps, and metal-halide high-intensity high-pressure discharge lamps. The successful development and introduction of these two product families took my employer from the status of clever copier to a technology leader in the industry. The products' market success, by my (completely unauthorized and

unconfirmed) estimate, had generated one half billion (1988) dollars of cumulative marginal contribution to profit by the time of my retirement, and they continue to spin off a profusion of cash today. Of course, nowadays Microsoft stock values go up or down half-a-billion between morning coffee break and lunchtime, but it was then, and still is, a big number to me.

Back to 1954

Because I can no longer show you the frontier of research, I'd like to take you back into the development history of one product to show you that 1) physics and physicists can make a real difference even in what might be considered a pedestrian activity; and 2) once the physics is done, 99% of the job still remains. That you can make a difference is what makes working in industry so rewarding. Academic scientists can point to their publications as the validation of their life's work. I can see mine whenever I go to the mall and look up at the lights.

The product I'd like to talk about involved developing a family of VHO fluorescent lamps operating at 2.5 times the power level of the so-called standard fluorescent lamps of the time. This effort actually started with the physics, but its successful execution involved stumbling over, and having to solve, a number of other fascinating problems along the way.

Let me take you back to the year 1954, when I was a young physicist working on electroluminescent lamps for the lamp division of Sylvania Electric Products (then principally a vacuum-tube manufacturer). My boss hired MIT's Francis Bitter (who is shown in figure 1) as a consultant to teach the engineering staff how fluorescent lamps worked so they would be better able to solve problems and make better lamps. Because I was the only physicist in the place, I was about the only person Bitter could talk to as a colleague and he dragooned me into helping him in this teaching job. We soon realized, however, that neither of us had the slightest idea how the things worked. We hand-waved our way through a couple of lectures and then retired to study papers by Walter Schottky, Hans von Engel and Max Steenbeck, and Carl Kenty.

As you may know, the fluorescent lamp is a gaseous discharge device in which a modest current is passed through a mixture of a rare gas at a few torr and mercury vapor at a few millitorr to produce the ultraviolet resonance radiation of mercury. The plasma is diffusion controlled, nonequilibrium, and collision dominated. What makes the lamp unique among complex technical devices

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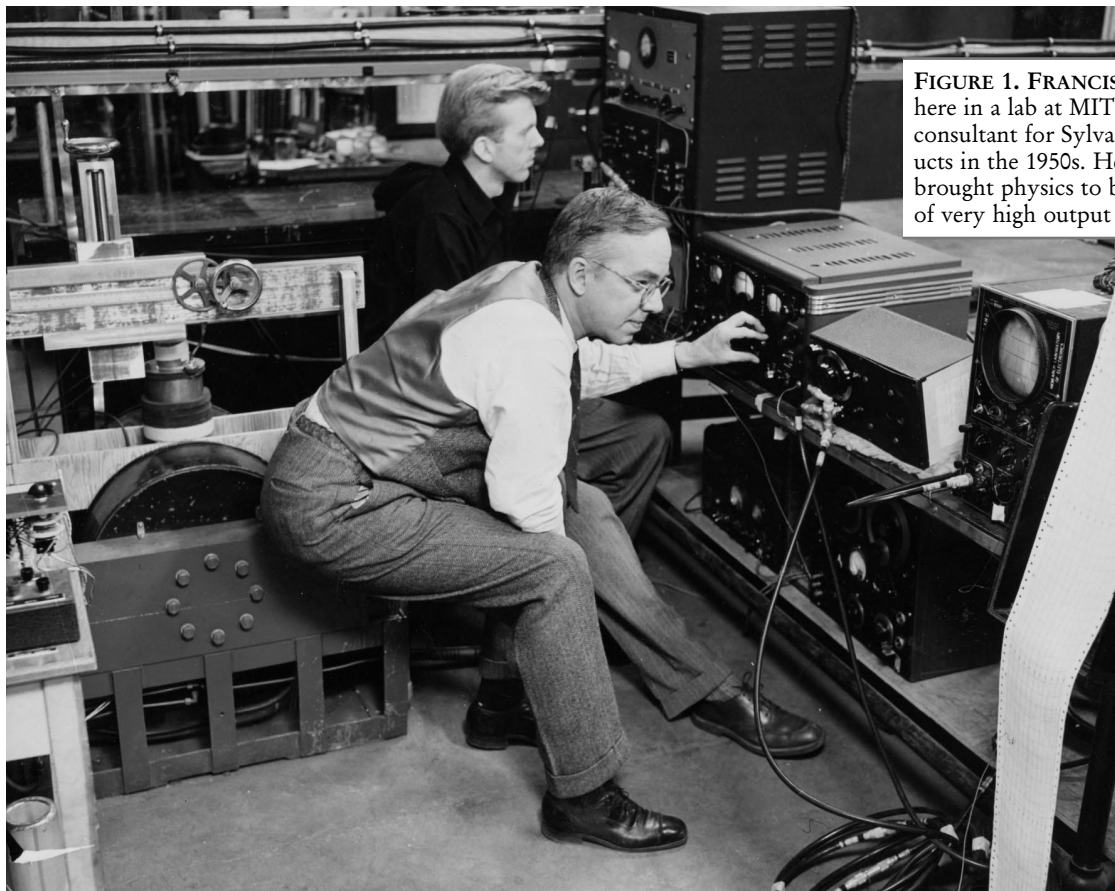


FIGURE 1. FRANCIS BITTER, shown here in a lab at MIT, was a scientific consultant for Sylvania Electric Products in the 1950s. He and the author brought physics to bear on the design of very high output fluorescent lamps.

is that 60–65% of the electrical power consumption is converted to, and dissipated as, ultraviolet resonance radiation. This was the conversion process that we were trying to understand. To find a system of so many degrees of freedom concentrating its output to such a degree in one channel was as surprising to us as if one molecule made off with half the energy content of a gaseous ensemble.

Kenty,¹ who worked in General Electric Co's lamp development lab, had published in 1950 calculations of excitation rates of the mercury energy levels at the values of electron density and temperature determined experimentally by the Langmuir Probe measurements of Mary Easley.^{2,3} From these calculations, Kenty derived some interesting insights, but of more value to Bitter and me was the paper's self-consistent set of cross sections for excitation of the various levels, as well as an estimate of the imprisonment time for mercury resonance radiation (that is, the time it takes a resonance photon to escape from the lamp after successive absorption and emission events). Bitter pointed out that these cross sections and imprisonment formulas could be used to extend the calculations over a range of electron densities. When combined with an estimate of ionization cross section of the $3P$ excited states, Kenty's cross sections could be used in calculating electron temperature, thereby making it possible to do a closed first-principles calculation of the lamp's output.

What Bitter was suggesting, of course, was a straightforward "modeling" calculation, although we didn't call it that in those days. He left me to do the job, which I hid within an electroluminescence project. I would probably have been jailed for fraud if I had done the same thing under a government contract.

Although straightforward, the modeling calculation

was fairly ambitious for its time. As shown schematically in figure 2, it involved simultaneously solving the ionization balance equation, the electron energy balance equation, and the conductivity equation. Because most of the ionization is two stage, the model had to include a subsidiary set of simultaneous equations for the populations of the triplet P states, the upper states for the resonance-radiation emission, the intermediate states for ionization, and the excitation of the upper-lying nonresonant states. The model's important simplifications were the assumption of a Maxwellian electron energy distribution (which was consistent with the experimental data of the time) and the lumping of the 3P_0 and 3P_2 metastable states into a composite metastable state. Even so, some fifteen excitation rate constants had to be determined by numerical integration at each temperature.

Doing the calculation today would take an afternoon's work with my obsolete Macintosh LC, but the only computational tools available to me at the time were a table of exponentials and a mechanical calculator. So it took six months of part-time button-punching and result-transcribing effort. Because Bitter and his MIT colleague Will Allis were close friends, we had the benefit of "informal" consultation from Allis. ("Informal" means Allis gave us opinions and advice, but wasn't paid for it.)

The model contained one adjustable constant, the ionization cross section for the 3P states, which was determined by matching the electron temperature determined by Easley at one mercury vapor pressure and one fill gas pressure. We were gratified that the calculated electron temperatures agreed with Easley's data over the entire range of mercury pressures she reported. There were two errors in the model, but they fortuitously canceled each

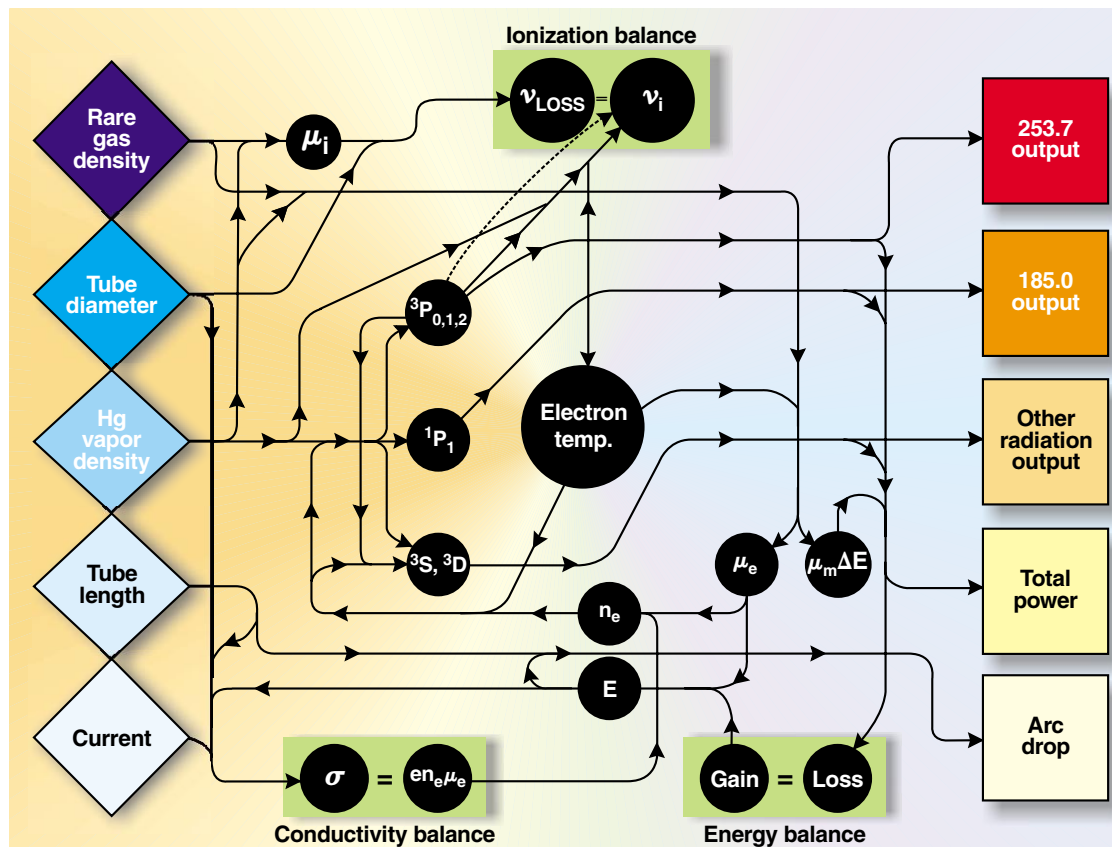


FIGURE 2. MODELING THE OUTPUT of a fluorescent lamp from first principles requires knowing many individual rates and performing many individual calculations. This diagram, which is adapted from the author's original, shows schematically how the calculations fitted together.

other out. The imprisonment time for mercury resonance radiation was too large and the associative ionization process was omitted entirely.

Associative ionization is most important at mercury pressures above the optimum, where it acts to reduce the electron temperature required to match diffusion losses. Omitting it resulted in the calculated electron temperature being too high, which, in turn, made calculated excitation rates too high. However, the too-high value for imprisonment time was most serious at high mercury pressures and effectively prevented the excess calculated excitation from escaping the tube as radiation. Thus, the model, despite its flaws, predicted the correct mercury vapor pressure for maximum efficiency.

All this effort resulted in a presentation at a Gaseous Electronics Conference and a paper⁴ in the *Journal of Applied Physics*, but it was more important than that. In common with other plasma modeling calculations, the model gave us access to the plasma's internal variables, which we could adjust, thereby determining in a numerical experiment which controlled what. It also gave us insight into how to manipulate the external parameters to select the desired values of internal variables.

At the time, one of the practical problems of fluorescent lamps had not been overcome: As the discharge current was increased, the output efficiency strongly decreased. For large-area, low-lumen devices, this limitation did not come into play because you could make low-cost fixtures in which you didn't have to shield the lamp from direct view—a commercial advantage. But those

lamps were excluded from many high-ceiling industrial and commercial applications because too many of them were needed to achieve a given light level on the floor. So it was of commercial interest to understand this limitation and to determine what, if anything, could be done about it.

The first step was, of course, to identify the real independent variable of the system: the electron density, which is nominally approximately proportional to current for any given set of lamp design parameters. The second was to plot every conceivable parameter and variable against electron density to see what resulted.

My "eureka" came when I plotted contours of constant ultraviolet power output on the plane of electron temperature and electron density (the red lines in figure 3). As electron density increases at constant electron temperature, the contours get very far apart; in fact, they become almost parallel to the electron density axis. This behavior is the result of the 3P states coming into approximate local thermodynamic equilibrium (LTE) with the electron temperature, with the rate of quenching nearly equaling the rate of excitation. Superpose on this the dependence of electron temperature on electron density for various fill gas species (blue lines in figure 3, decreasing with increasing electron density because the increasing population of 3P states increases ionization rate at fixed electron temperature). At high electron density, the two families of curves become essentially parallel.

Here, then, is the physics behind the limited light-output characteristic of the fluorescent lamp. The

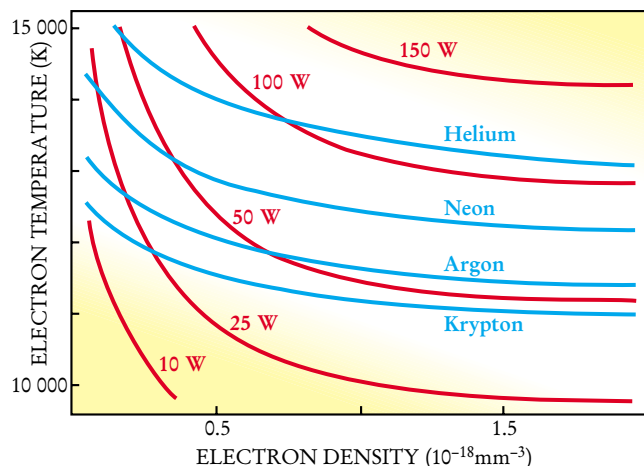


FIGURE 3. ELECTRON TEMPERATURE versus electron density for various constant power outputs (red lines) and various fill gases (blue). By creating and examining such a figure, the author realized how to dramatically increase the light output of fluorescent lamps without a drastic decrease of efficiency.

combination of approach to LTE plus declining electron temperature makes the UV output essentially constant, independent of electron density (and current!) at sufficiently high values. However, because all other energy losses increase with increasing electron density, efficiency suffers dramatically. But if you increase temperature at fixed electron density, the UV output increases exponentially, whereas elastic collision loss increases only as about the 3/2 power! Changing the rare gas fill to a lighter gas and lowering the pressure increases electron temperature and UV output at constant electron density.

This epiphany led to a hasty fabrication of several lamps and the collection of experimental data that confirmed my idea. Within a day or two, I could demonstrate to Sylvania's powers-that-be a lamp filled with neon instead of argon that could deliver four times the light output of the standard lamp at five times the power input. Because the standard lamp was incapable of delivering more than 2.5 times the output at any power, I felt that physics had led the way to a significant accomplishment.

Not physics per se . . .

At this point, the physics was complete, but the job was just beginning. For starters, what had previously been an effort by one physicist plus a consultant became a PROJECT. As the father of this baby, I was promptly sucked up into it, becoming a most uncertain leader of a team. I had gone into physics instead of sales or law because objects behaved predictably, whereas people did not. I apologize to those who suffered through my on-the-job training.

Second, a number of engineering problems had to be solved: the design of electrodes for a discharge current of 2.5 A instead of 0.4 A; the invention of a novel method to prevent mercury pressure from rising too high despite a high tube-wall temperature; the provision of a "cold spot" at the end of the lamp by providing a radiatively shielded space behind the electrode (see figure 4). Not physics per se, but physical insight helps.

Electrode design required a number of iterations, each of which had to be fabricated and tested. And the larger electrodes required processing changes that had to be worked out in the lab. Fortunately, management was reasonably patient with us. I suspect they were somewhat at a loss as to how to use such a product, which would not operate on existing ballasts (as current-stabilizing impedances in fluorescent lamps are known). And they possibly doubted the company's ability to unilaterally introduce a totally new illuminating system.

While all this was going on, our rivals at GE announced a family of high-output lamps using a geometric solution to the limited-light-output problem. By indenting a large-diameter tube, GE obtained a larger area of cross section that could carry 1.5 A at modest electron density but with a smaller transverse dimension. This neat, but expensive, solution decreased the diffusion length while increasing the ambipolar diffusion loss rate and electron temperature. GE announced it as a product operating at 1.5 A instead of the usual 0.4 A, yielding 2.2 times the light output at 2.5 times the power of the standard lamp designs.

We could easily retarget our design to meet the same lumen and power specifications. But because Sylvania had traditionally followed GE in fluorescent lamp design, we in the labs were worried that Sylvania might slip again into clever-copier mode and our work would go for naught. Fortunately, Corning Glass came unwittingly to our rescue.

Sylvania at that time made no glassware, but purchased all its bulbs from Corning. To make GE-style indented bulbs, Corning demanded what we thought were outrageous tooling costs and required a commitment for a high annual piece rate at robber-baron prices. Faced with paying a dollar-plus for fancy bulbs while subsidizing Corning's investment to copy GE, Sylvania's management chose instead to adopt our standard-tubing version with electron-temperature control at a few pennies per glass bulb. I would like to say that beautiful physics carried the day, but I think I know better.

The decision was made to take our modified design into production as quickly as possible. This of course meant that the design that went into the factory was not the design we had been testing in the lab. New electrode designs were required again, and the end-chamber cold spot had to be redesigned because of the lower heat load. Moreover, every aspect of the design had to meet the additional requirement of lowest possible cost.

Fortunately, the factory was only four miles away from the lab, and every member of our lab team was well known there. In the past, we all had been called on to help factory engineers solve problems in the manufacture of the company's standard products, and so had acquired the all-important cachet of credibility. Consequently, the engineers looked on us not as troublemakers from the ivory tower, but as part of the solution of the inevitable fabrication, processing, and testing problems—of which there were many. The cardinal sin in a factory is to shut the production line down, even when nothing but junk is spewing out the far end. Learning to solve problems on the fly, without shutting down the machines, requires quite a bit of acclimatization. But nothing perhaps commands your attention and enthusiasm in problem-solving like being knee-deep in a rapidly growing pile of broken glass.

Despite the hubris inherent in introducing an untested product into an automated factory, the operation was successful, and we succeeded in getting our straight-tube lamps to market as quickly as GE and at a lower dollar price. As a result, we got our customary share of the market, plus a little bit more.

To complete the circle, GE eventually had to offer straight-tube versions like ours, as well as their own. But Sylvania never made indented-tube lamps. After receiving my PhD from MIT in 1950, I had been politely brushed off when I applied to GE for a position in their R&D labs. As you can imagine, I derived additional satisfaction from having made a significant contribution to Sylvania's coming of age in the industry at GE's expense.

High-power fluorescent lamps were largely supplanted in the mid-1970s by full-color white metal-halide lamps, but this family of lamps still sells in significant numbers today. Forty years of healthy profits amount to a tidy sum.

Although I have encapsulated here an example of the satisfactions to be derived from applying physics in an industrial atmosphere, I must confess to some doubt that mine was a representative case. In fact, it could be argued that my personality and interests converged with commercial opportunities by happy accident and in circumstances that existed infrequently then and perhaps not at all now.

A dim view of management

Since becoming a man of leisure and an investor, I have devoted some attention to proxy statements and annual reports, and have acquired therefrom a dim view of the scientific and technical competence of the managements of most industrial companies in the US, at least those of the "old economy." I have in my own mind classified management in three categories: first generation, second generation, and third generation.

▷ **First-generation managers** are totally at home with the science base of the technology on which the company's fortunes rely. They have to be, because they basically invented the technology.

▷ **Second-generation managers** may not have been present at the founding, but they have been immersed in the company from an early stage. They have generally served in a number of technical and manufacturing positions, and have in-depth personal knowledge of the technology base, although their general scientific expertise may be limited.

▷ **Third-generation managers** generally have legal, financial, personnel, or sales background. Many of them were recruited from outside and joined an ongoing enterprise, bypassing homegrown candidates. They have the scientific and technical knowledge of the typical product of the US educational system, which is to say they haven't a clue how *anything* works, let alone the products that fund their salaries. Worse, they have no idea how to evaluate, measure, and manage the technologists and scientists they depend on.

It is a mantra of modern management lore that a good manager can manage anything. But third-generation managers have no independent means of assessing the quality of information being uploaded to them by the scientific and technical subordinates they depend on.

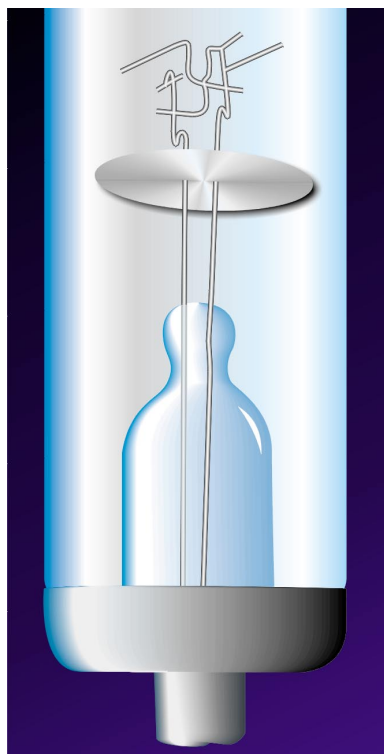


FIGURE 4. THE VERY HIGH output fluorescent lamp relies, in part, on a cold spot at the end of the lamp that stops the mercury vapor from overheating. To create such a spot, a nickel radiation shield (the silver-colored disk in the figure) was inserted below the electrodes.

They have no independent means of assessing the quality of the scientific and technical subordinates who are uploading information to them. Consequently, they are in grave danger of being led astray by the glibest talkers and the technical con men. Worse yet, their power and detachment impede the flow of bad news to them. And last, they are particularly prone to ignoring the farthest-out great ideas.

The hallmarks of third-generation managers are the frequent misuse of scientific and technical talent, the missing of scientific and technical opportunity, and being blindsided by new technology from sources previously presumed not to be worthy competitors. If you work under third-generation management, Dilbert® isn't funny. Third-generation managements are far too likely to be pointy-haired technical incompetents whose failure to understand, and therefore failure to protect and extend the technological foundations of the company's business, can destroy the company's prosperity.

Oh, by the way: Sylvania management during the development I described was second-generation in the industry, but first-generation in the fluorescent lamp business. All of the managers had been involved in Sylvania's independent entry into the fluorescent lamp market that GE developed in the late 1930s. "They could taste the fruits of our efforts," as one VP later told me.

It should be no surprise, then, that the Fortune 500, consisting of huge companies with third-generation managers, is not a fount of innovation and new technology in the US today. The source is smaller companies run by first- or second-generation managements. When they succeed, the Fortune 500 companies buy up the small companies and proudly trumpet the new technology as their own.

So, if I were a young physicist today considering employment in industry and looking for the kind of satisfactions I have described, I wouldn't waste my time on the multibillion-dollar technology conglomerates with third-generation managers that have at best a rudimentary knowledge of the science and technology their businesses depend on, no matter how shiny and well-equipped their laboratories might be. I'd figure my chances of success were slender.

I would look instead to work for smaller companies, managed by first- or second-generation managers who know opportunities when they see them, and who are willing to take risks to capitalize on them. But to share in the wealth of an eventual buyout, I would certainly ask for stock options.

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