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A Different Kind of Chemistry: A History of Tungsten Halogen Lamps

Harold Wallace, Guest Editor

Ed Owen, past editor of this History column, suggested that we run an article on the history of the tungsten halogen lamp. Ed, with an assist by Ed Hammer, a Past Chairman of the IAS Committee for Production and Application of Light, procured the service of Hal Wallace to be the author of this month's article about the history of the tungsten halogen lamp.

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The 1992 Energy Policy Act (EPACT) brought significant changes to the U.S. electric-lighting industry. One such change required replacing many ordinary incandescent lamps with more energy-efficient tungsten halogen lamps. Tungsten halogen, though, is by no means a new development. As we near the golden anniversary of the halogen lamp's invention, it seems appropriate to look back and explore the roots of the most important extension of incandescent lighting technology since 1913.

Background

Various designs for electric incandescent lamps originated during the late 1870s, but two are of special importance. In early 1879, British chemist Joseph Swan publicly displayed a lamp that used a thin arc-lamp carbon to emit light. Although Swan's lamp functioned well enough for research purposes, low electrical resistance made it commercially impractical. Later that year, Thomas Edison and his team in Menlo Park, New Jersey, produced a lighting system that featured a lamp with a high-resistance (about 100 Ω) carbonized filament. Edison's lamp not only attained commercial success, but also quickly became the very symbol of simplicity [1].

Despite users' perceptions of simplicity, producers found incandescent lighting a complex technology. Many refinements were needed to address various problems and to make mass production economical. A major problem that plagued Swan, Edison, and subsequent inventors became known as "lamp blackening." Material evaporated from the hot filament and deposited on the inner wall of the glass envelope. As deposits thickened, light transmission fell and the lamp became useless.

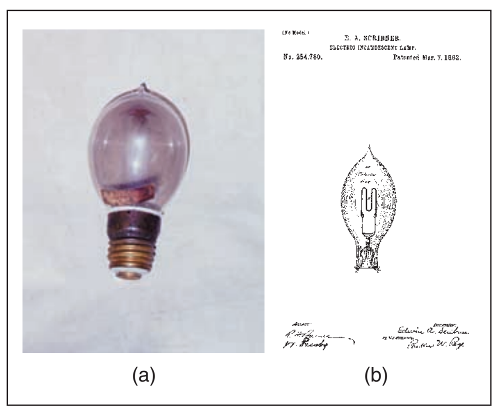


Fig. 1. (a) Waring Novak bromine lamp, 1892. (Mt. Vernon Museum of Incandescent Lighting, Baltimore, MD). (b) Drawing from Edwin A. Scribner's 1882 patent for a lamp containing chlorine.

An early attempt to remedy blackening involved the use of halide gasses. In March 1882, Edwin Scribner, of the United States Electric Lighting Company (USELC), received a U.S. patent for a carbon-filament lamp containing chlorine. He stated, "I have found that under certain conditions the presence within the globe of chlorine effectively prevents [lamp] clouding...." While it appears that neither Scribner nor USELC actually marketed a chlorine lamp, John Waring's 1892 Novak lamp was partly based on Scriber's patent (Fig. 1).

The Novak (short for "no vacuum") contained bromine, rather than chlorine, but its makers declared, "absolute maintenance of candle-power throughout life at INITIAL EFFICIENCY at last obtained." Yet, as the name implied, Waring had a strategic goal that was more important than lumen maintenance: evading the stranglehold of Edison's vacuum-lamp patents. Waring Electric Company quickly drew the ire of the Edison interests. Commenting on the resulting patent suit, *Electrical World* noted that "many buyers and users have been looking to the Novak lamp for relief from the present [monopoly] situation." The effectiveness of bromine in keeping the lamp clear was questionable, and the issue became moot in 1894 when the Novak was declared an infringement on Edison's patents and removed from the market [2].

Tungsten versus Carbon Filaments

Incandescent lamps' energy efficiency (or efficacy) depends on several factors. In general, the higher a filament's operating temperature, the more efficient a lamp becomes. Although carbon has a melting point of 3,490 °C, the maximum operating temperature of carbon filaments is considerably lower as carbon evaporates at a high rate above 1,700 °C. Tungsten can be operated much closer to its 3,380 °C melting point. Ordinary tungsten lamps typically operate around 2,700 °C [3].

Thus, while the most efficient carbon lamp, the GEM lamp of 1904, gave 4 lumens per watt (lm/W), first-generation tungsten vacuum-lamps, introduced that same year in Europe, gave 8 lm/W. Ten years later, Irving Langmuir's nitrogen-filled Mazda C lamps with coiled tungsten filaments produced 12-20 lm/W, depending on the wattage.

However, poor lumen maintenance (the ability of a lamp to sustain light output over its design life) due to blackening remained a problem. In the late 1920s, General Electric (GE) began placing a "tablespoonful of coarse tungsten powder" in some expensive, high-output tungsten lamps. When blackening became noticeable, a user could remove the lamp from its luminaire and swirl the powder around the inside of the envelope, physically scrubbing away the tungsten deposits. The Smithsonian's collection includes two lamps of this type: a 2,500-W searchlight and a 1,000-W underwater lamp [4] (Fig. 2).

Elmer Fridrich

Fridrich began his career at GE as a weld-works machinist in 1947, where he worked the night shift for about four years to support his young family. His job involved installing leads in radio tubes by "feeding parts into the machine." Bored with this repetitious task, he prepared to leave GE. But, as he did so, "I must have impressed someone," he recalled, "because I was recommended to Nela Park."

In 1952 he began working for Elmendorf. Fridrich worked on reducing the manufacturing costs of lamps made with Marvin Pipken's recently developed "Q-Coat" ("Soft White") coating. He also experimented on zinc-oxide coatings and generally extended his knowledge of incandescent-lamp design and production. Around this time, he was assigned to the heat lamp project and read about tungsten purification processes.

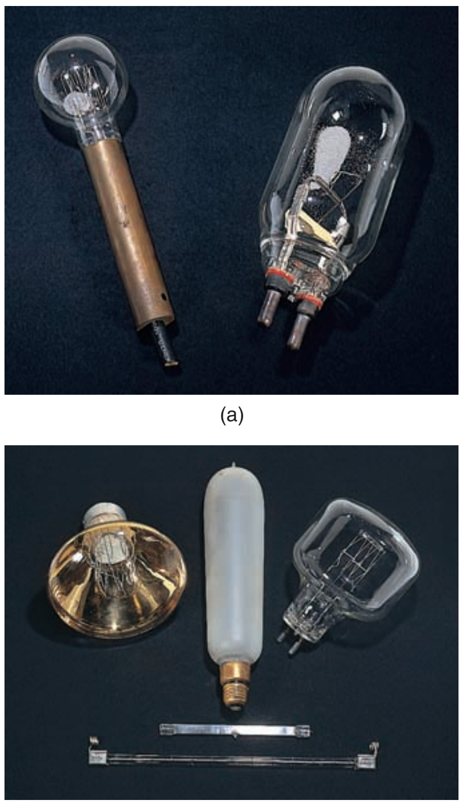
Elmer G. Fridrich, circa 1980. (SI neg. #99-4133, image courtesy of General Electric.)

Early Halogen Lamps

Other patents around this time show renewed attempts to use halogens. In 1918, George Meikle disclosed that a small amount of "iodin" added to his argon-filled cathode tube lowered "the loss of voltage in the arc." As he was attempting to improve a current rectifier, blackening was not a concern. Max Ettinger and Clemens Laise added a coating of halogen salts to an inside-frosted lamp in 1925. "These salts settle in the pores of the roughened inside surface...and have a beneficial effect on the quality of the lamps as to increase both the life and the efficiency thereof." A 1933 patent by Johannes van Liempt detailed the employment of "a halogen such as chlorine, bromine, or iodine or compounds or mixtures thereof." Since both of these latter attempts used ordinary gas-filled tungsten lamps, they achieved no better results than Scribner had [5].

Development at GE

In the late 1940s, development of a new heat lamp began at GE's Nela Park facility. Since the 1890s, several manufacturers had marketed special incandescent lamps designed to maximize heat production. Finding an envelope material that could withstand high temperatures became a challenge as carbon filaments gave way to tungsten. Even with the use of expensive materials like Pyrex and Vycor, heat lamps grew large and bulky. Building on war research, the GE development team turned to quartz for a radically smaller lamp envelope [6].



(a)

(b)

Fig. 2. (a) Two lamps containing tungsten powder to correct lamp blackening. The grey powder is clearly visible in both lamps. (SI neg. #2001-1916, by Richard Strauss. Left to right: 1,000-W GE diver's lamp, circa 1957; 2,500-W GE searchlight lamp, circa 1955.) (b) Changing the technology of heat lamps. The material savings in both lamps and luminaires obtained by converting to new, smaller heat lamps is apparent when the lamps are compared side by side. (SI neg. #2001-1918, by Richard Strauss. Clockwise from upper left: Westinghouse infrared drying lamp, circa 1955; carbon filament heater-tube, circa 1905; Sylvania R48 Vycor heat lamp, circa 1963; GE clear heat lamp, circa 1975; GE sand-quartz heat lamp, circa 1963.)

By 1952, they had made experimental heat lamps that featured a recoiled tungsten filament axially mounted in a tubular quartz envelope. But tests revealed that the filament's close proximity to the bulb wall exacerbated blackening. Team member Elmer Fridrich then read a journal article describing a "metal-purification process involving a hot wire of tungsten [and] iodine" [7].

The journal article percolated in Fridrich's mind "for about six months while I was still working on the heat lamps," and he began to consider the possibility of making a visible-light lamp. When he made inquiries with his GE colleagues, he was told that halogens had already been tried and had shown little promise. However, Fridrich came to believe that the higher temperatures and smaller diameters of tubular quartz envelopes might make a critical difference (along with a novel method of sealing molybdenum "foil" leads into the quartz).

He borrowed a vacuum system from a coworker and, with the help of physicist Emmett Wiley, placed some iodine in a heat lamp. Fridrich later recalled, "Eureka! We put it on and instant success. We started with either a 300- or 500-nominal-wattage heat lamp in clear quartz and we could run this up to 1,000 W and it was just beautiful." Yet, success was sporadic, and the ability to consistently produce working lamps eluded Fridrich and Wiley over the next month.

GE managers decided to forego halogens for the new heat lamp in late 1953. Since that lamp operated at a lower temperature than a visible-light lamp, the rate of tungsten evaporation was also lower. Filament supports made of tantalum or titanium controlled blackening and simplified the heat lamp's internal chemistry. Four ratings of the heat lamp were introduced in 1954 by GE [8].

Despite inconsistent tests and loss of the heat-lamp application, Duryea Elmendorf (in charge of Nela Park's Lamp Development Laboratory) saw the potential for a visible-light halogen lamp, if it could be produced reliably. Alton Foote (head of Nela's Large Lamp Department) assigned chemist Edward Zubler to find out what was happening inside Fridrich and Wiley's iodine lamps.

Research Breakthrough

Zubler had completed his Ph.D. after the war and arrived at Nela Park in January 1953. "Much to my dismay I got shoved onto electroluminescence....But I had decided to stay at least one year. Towards the end of the year, I made my unhappiness known to management." Zubler's unhappiness intersected with the need for a chemist to investigate the iodine lamp, though not everyone believed there was a future for incandescent lamps.

Zubler recalled, "When I was working hard on the tungsten halogen lamps, I remember one of the old-time engineers telling me, 'don't get involved with this because incandescent lamps are on their way out. Ten years from now, when you're still gonna be here, they're gonna be gone'" [9].

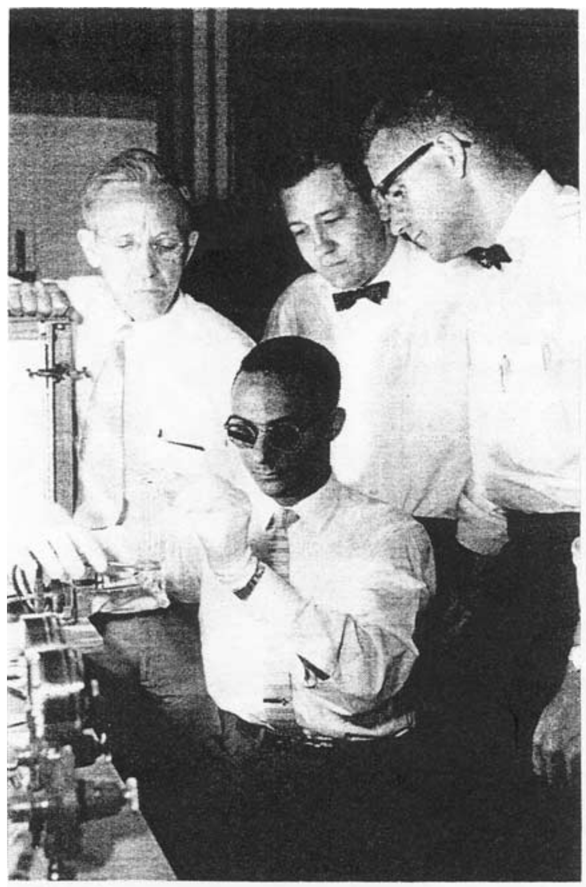
Zubler spent three years researching chemical reactions inside iodine lamps, trying to determine why some lamps blackened and others stayed clear. Believing the trouble lay in contaminants within the lamp, he concentrated on making lamps as clean as possible. "It finally dawned on me that the cleaner I made the lamps, the more likely they were to blacken. So just out of pure frustration I suddenly decided, 'I'm going to make a really bad lamp.'...I put some oxygen into it and, Eureka!,...the lamp stayed clean."

The chemical-transport cycle required a trace amount of oxygen to function. "We were not dealing with tungsten iodides, we were dealing with tungsten oxyiodides." Accidental impurities in earlier lamps had allowed them to function. Adding carbon in the form of methane to the lamp allowed the amount of oxygen (and a water-cycle) to be controlled by forming carbon monoxide and hydrogen and then flushing it out. The use of oxygen and carbon provided the answer to iodine lamp production. That answer, however, was unpalatable to "a number of older engineers...who had spent their lifetimes getting these two things out of lamps....When I started adding these two things back in they were appalled, they couldn't believe it,...they just wouldn't recognize that there was a whole new different kind of chemistry going on in these lamps."

The timing of this discovery was fortuitous as, according to Zubler, Elmendorf "was beginning to lose faith a little. At one point he suggested that maybe I should go find something else. I was just too bull-headed. The fact that it worked once said that the basics were there, we have to find out what they are....I did have to get involved with some other projects to placate him,...But I wasn't going to give it up."

By this time, Zubler was not alone on the project. In 1955, engineer Frederick Mosby transferred to the Lamp Division from GE's Aeronautics and Ordnance Division. His first assignment was to work with Zubler to develop a marketable iodine lamp. Substantially different from earlier filament lamps, iodine lamps required new handling procedures, production equipment, and luminaires. Mosby recalled that obtaining "clean wire" (tungsten wire with "very low levels of impurities" to prevent extraneous chemical reactions) involved "extensive work with our people at our wire plant." After determining the need for oxygen, carbon, and high-purity tungsten wire, "the development just took a rather normal course" [10].

The high bulb-wall temperature required for the cycle to function proved a major challenge. Mosby remembered that "in the beginning, there were some real problems with fixture manufacturers because they weren't used to working with lamps that hot." End-seals were also complicated. Molybdenum foils had a coefficient of expansion similar to quartz but, "because the lamp ran so hot, there was oxidation of the outer moly that came through [the seal]." Early fixtures that elevated a lamp's temperature compounded this problem. Two solutions were devised: a chromium coating on the molybdenum to prevent oxidation or "if you don't use



BRAIN TRUST — These four men were responsible for a large share of the research and engineering for the new "Quartzline" lamps announced recently by Large Lamp Department. Seated, shown "tipping" one of the new lamps, is Fred Moseby. Watching him, left to right, are Al Foote, Stan Ackerman and Ed Zubler.

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'Quartzline' Lamps Result Of Old Idea, Modern Know-How

Fig. 3. Alton Foote, Stanley Ackerman, and Edward Zubler (standing, left to right) watch Frederick Mosby (seated) tip off a tungsten halogen lamp in 1959. (SI neg. #99-4127, image courtesy of GE.)

chromium, then you must put in a glass that will soften or actually melt while the lamp is operating, so that it really seals the ends of the lamp."

Early lamps were made by hand "because we had no equipment at all to make these lamps yet." Pilot production began around 1957, though Foote expressed uncertainty about the lamp's readiness for this next step. The team persuaded him that putting the lamps into pilot production would allow them to make more lamps and expedite research.

After further refinements, manufacturing engineers responsible for designing production equipment entered the process and initiated low-rate production. Mosby noted that, again, prior art (the removal of all oxygen from incandescent lamps) had to be reversed by engineers long accustomed to older ways. "They put getters in lamps to get oxygen out and here we are saying, 'forget your getters, we now put oxygen *in* the lamps....You have to get people comfortable with what you are doing." Initial production took place at Nela Park's Cuyahoga Lamp facility. "All of the lamps were manufactured there for some number of years because it required such close attention to the processing....It was very, very difficult to control. We were trying to control parts per million (probably no more than 10 ppm) of oxygen in the lamp."

As testing proceeded, the lamps demonstrated an unsettling tendency to explode in the test racks, showering nearby lamps with damaging fragments. Zubler recalled, "the explosion was the result of [the filament] arcing. The lamp would arc-out and the [internal] pressure would build up very suddenly to a high level, so I began pressurizing my lamps." Explosions were prevented because arcing would not appreciably increase the pressure in the already pressurized lamp. Pressurization also extended the filament's life expectancy by slowing tungsten evaporation, while leaving efficacy unaffected.

Interestingly, the use of iodine did not, in itself, bring higher energy efficiency. Higher efficacy came from the ability to operate filaments at higher temperatures. Higher operating temperatures were possible because the halogen cycle prevented lamp blackening. Efficacy ratings varied according to wattage, but the new lamps showed consistently higher efficacies than their conventional counterparts. Zubler and Mosby reported that at the 500-W rating efficacy went from 19.8 lm/W in a conventional lamp to 21 lm/W in the halogen unit. In high-voltage 1,500-W lamps, the rating jumped from 17.5 to 22 lm/W. Rated life doubled in both cases [11].

Marketing Challenges

GE announced the "quartz iodine" lamp in 1959 (Fig. 3), and marketing personnel quickly defined potential applications for the new product, though they could not convince senior management to accelerate production. "The first group of lamps we sent out was for the Unisphere for the 1964 New York World's Fair," recalled Mosby. Automatic lamp holders specially designed for the Unisphere each held four lamps. If one lamp failed, another would immediately rotate into place [12] (Fig. 4).

However, decorative lighting was not the first market to attract customers for the iodine lamp. "The first big application was really airport-runway lighting" which could use the small point-source in the center of runways to improve safety. This had been the original intention for the "little 45-W lamps" sent to the World's Fair. Aircraft manufacturers saw halogen lamps as a way to reduce the size and weight of wing-tip marker lamps. The automotive industry also saw the potential of a smaller headlamp, but GE had made a large investment in sealed-beam headlamp equipment in the early 1940s and was reluctant to make this profitable product obsolete.

Additionally, the U.S. Department of Transportation (DOT) did not know quite how to handle the new lamp. Zubler noted, "the halogen lamps were not allowed by the DOT. They had very specific requirements for light patterns, beams down the road and that sort of thing. The Europeans didn't have these [requirements] so ...they got a tremendous jump on us because they had the market and they were the first to develop high-speed, automated equipment for making these lamps. We didn't get started on that for several years, until we got approval in this coun-

(a) (b)

Fig. 4. (a) Experimental tungsten halogen lamps. Note the long exhaust tube extending from the side of the lamp at right. Varying the tube length on experimental lamps allowed the researcher to regulate vapor pressure within the lamp. (SI neg. #2001-1917, by Richard Strauss. Left to right: "LEAP" lamp made by Edward Zubler, circa 1972; mogul-based lamp with internal halogen tube made by Elmer Fridrich, circa 1955; an early linear lamp made by Fridrich, circa 1955.) (b) May 1964 cover of Life Magazine *showing the Unisphere at the New York World's Fair. Tungsten halogen lamps mark the national capitals, an early demonstration of the new technology. (SI neg. #99-4081, image courtesy of Time-Life.)*

try to use the halogen lamps for head-lighting systems. It was really unfortunate. Even I, buried in my laboratory, could appreciate that it was going to take a high-volume market to make this thing really go" [13].

Mosby, and others working on the project, entertained visions of very high volumes indeed. "When we were developing the lamp, we could see millions and millions of lamps, because that's [how many] we sell in A-lines. Some of our managers didn't agree with that, they felt it was a specialty lamp and would never get into the high-volume markets....As it turned out, they were right. It's not going to replace the standard A-line lamp, but other markets opened up for it" [14].

The introduction of quartz iodine lamps initially caught competitors by surprise, as none had found a way past the prior art that said that halides would not work and that oxygen and carbon were anathema. Mosby recalled attending a conference soon after the lamp was introduced, "it was pretty clear [competitors] had looked at this and had run up against the same problems that we had, ...they asked very, very good questions..." [15].

GE maintained a technical exchange agreement with Philips at that time, however, and the Dutch firm soon improved the lamp by using bromine instead of iodine. Zubler remembered, "we took a quick look, right in the beginning, at bromine and chlorine and we found out that they were much too reactive; they attacked the cooler supports in the lamp, ...And we didn't look beyond that; we were too busy trying to get control of the chemistry of the iodine cycle." Experiments in Eindhoven under the direction of Willem Elenbaas focused on problems with impure tungsten wire. "They set out to find a different cycle, and that led them into the bromine. What they did that we didn't do was use hydrogen bromine (HBr). Because of the high stability of HBr, it really reduced the activity of the bromine." Philips introduced their HBr lamp around 1966, and several manufacturers replaced quartz with less-expensive borosilicate glass at about the same time [16].

While its popular name shifted from "quartz iodine" to "tungsten halogen" after these changes, the special-use-only perception of the lamp remained firm during the 1960s for several reasons. Costs remained high as producers amortized new production lines. The need to invest in new luminaires deterred some potential users. The nature of the halogen cycle created problems for dimming circuits because lamps blackened

Observations on the Origin of Halogen Lamps

This account skims over many details of halogen lamp history, particularly the work of scientists and engineers who expanded both the technology and its applications. But several interesting observations emerge from the story of the lamp's origin [19].

The halogen lamp invention demonstrates the importance of unplanned inspiration in the rigid structure of a modern research lab. GE's initial motivation to combine halogens and incandescent lamps derived from a well-defined, focused project to reinvent the heat lamp, but the combination succeeded (that is, became used and useful) only when applied to the nebulous standing goal of improving visible-light lamps. Fridrich's realization that the new heat-lamp configuration made previous experience with halogens unreliable, and his conjecture that a visible-light lamp might therefore be attainable was unexpected. His freedom to put this realization to the test and prove it true provided a foundation upon which the subsequent "normal" research and development project was built.

The halogen invention is also an interesting case of an engineering discovery that absolutely required the input of intense scientific research in order to succeed. Though Fridrich's realization kindled the project, it took Zubler's meticulous three-year study of halogen-cycle chemistry to build the fire. Understanding why the lamp functioned (or not) was crucial. While Zubler's work was certainly not undirected "basic research" (i.e., knowledge for the sake of knowledge), he had to uncover the answers to basic questions of science before a commercial product could be planned. (In the 1970s, once GE management felt secure, Zubler was allowed to publish kinetic studies stemming from his work in a scientific journal [20].) The scientist's discovery of the essential role of oxygen and carbon gave engineers the knowledge they needed to design a reliable device and to assure managers of reasonable production yields.

Even though that research proved vital, halogen lamps were not an invention of any one person, but were the product of a team of highly trained specialists—and beyond the reach of a proverbial backyard inventor. Mosby's role especially demonstrates this. As Zubler unraveled the lamp's chemistry, Mosby engineered practical end-seal and terminal structures and interacted with both the scientist and tungsten wire specialists to define and achieve required wire purity. The invention then passed through the hands of production engineers, applications engineers, and marketing specialists, all of whom contributed to turning an experimental lamp into a mass-produced commodity. All of these professionals made use of the highly refined and expensive tools that a large corporation can provide.

Finally, the entire invention process, from Fridrich's realization to the World's Fair demonstration, took about ten years—far longer than inventors today have to demonstrate an idea's viability. According to many within the lighting industry, it seems that a significant shrinkage of "research horizons" (the time from inception to marketable product) has occurred. One or two years is today's expectation, attributed mainly to competitive business pressures. This suggests that several (ultimately, quite profitable) lamps invented during the 1950s and 1960s, including tungsten halogen, might not have left the laboratory, if invented today. Only a large corporation could marshal the resources needed to create tungsten halogen, but corporations competing in today's global market may lack the will or the flexibility to expend those resources on projects with long, difficult periods of development.

when dimmed below the minimum temperature needed for the cycle to function. Although a short period of full-power operation returned lamps to normal, this was hardly the simplicity users had grown accustomed to. Merely touching the tube with bare hands during installation could cause premature lamp failure, hence, some distributors refused to accept the return of opened lamp packages.

In spite of these limitations, halogen lamps become ensconced in the market, valued for their high lumen maintenance, extended life, and increased efficacy. That latter consideration became increasingly attractive as the trend of ever-cheaper electricity reversed during the 1970s. As energy costs rose, designers chose halogens for a wider range of applications. For example, in 1981, the Illuminating Engineering Society noted that, "tungsten halogen lamps have nearly replaced normal incandescent types for use in the projection area" [17].

During the 1980s, halogens became popular for track-mounted area lighting in the form of small, low-voltage lamps referred to as MR-16s. Linear lamps with advanced, infrared-reflective coatings pushed efficacies above 30 lm/W. Manufacturers completely replaced ordinary parabolic aluminized reflector (PAR) spot and floodlamps by either placing halogen capsules inside PAR envelopes to retrofit old fixtures or designing completely new fixtures specifically for linear halogen lamps. However, the idea of replacing common A-line lamps with halogens did not fare as well.

First arose the (remote) possibility that a halogen lamp could explode in someone's living room.

Fig. 5. Three experimental lamps show safety features intended to mitigate the risk of explosion. For example, in the Gemini lamp (center), note the small twin tubes paralleling the central glass stem–these low-pressure, 60-V halogen capsules would not explode. (SI neg. #2001-1914, by Richard Strauss. Left to right: GE AT-lamp with heavy glass envelope, circa 1990; "Gemini" lamp mock-up made by Elmer Fridrich, circa 1972; A-lamp with quartz-wool filling, also designed by Fridrich, circa 1972.)

Engineers produced several special designs that compensated for this (Fig. 5). GE's Elmer Fridrich, after concentrating on short-arc discharge lamps for nearly 20 years, designed two halogen A-lamps in the 1970s. His Gemini lamp featured two small 60-V capsules in series and could not explode. In the other design, he surrounded an ordinary halogen capsule with a loose filling of glass-wool to diffuse light and contain shrapnel. Fridrich could not guarantee that the second method would work, though, "because I never could make one explode and find out." In the end, placing a halogen capsule inside a very heavy glass envelope emerged as the design of choice.

Fires attributed to halogen torchiers became a more serious–and more public–problem. Torchiers are floor-standing luminaires open at the top to provide indirect lighting. Flammable objects that fell on or into a torchier's open top could be ignited by the lamp's (250 °C and higher) temperature. Many torchier manufacturers began offering retrofit kits that allowed users to replace the halogen lamp with a cooler fluorescent lamp [18].

Perhaps most significantly, compact fluorescent lamps (CFLs) emerged as unexpected competition in the early 1980s. Though more expensive than halogen lamps, CFLs operated up to three times more efficiently and gave four times the rated life. Early CFLs suffered from poor color and starting problems, but have since been improved. Some recent models work easily with dimmers. As prices fall, CFLs rather than halogens seem a more popular choice when replacing common incandescent lamps.

Regardless, nearly 50 years after Fridrich and Wiley's "Eureka!" moment, tungsten halogen lamps are a ubiquitous product with an annual value exceeding $250 million [21]. Though the device remains technically complex (indeed, the fine details of internal lamp chemistry still stimulate debate), halogen lamps are beginning to attain that air of simplicity long associated with the common light bulb. Edison, the self-taught chemist, would have found halogen lamps fascinating.

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[7] E. Fridrich and G. Reiling, oral history interview by H.D. Wallace, Jr., tape 1, side B, 1 Mar. 1996. Author's note: Fridrich recalled the article as having been in the journal *Chemical & Metallurgical Engineering* (now *Chemical Engineering*), but I have been unable to confirm this. Fridrich's quotes throughout this paper are from this interview.

[8] "Lighting," *General Electric Rev.*, vol. 58, no. 1, pp. 48-49, Jan. 1955. See also E.G. Fridrich, "Apparatus for and method of forming and mounting supports on coiled filaments," U.S. Patent 2 813 327, Nov. 19, 1957; E.G. Fridrich, "Electric lamp and similar device," U.S. Patent 2 813 993, Nov. 19, 1957; A.G. Foote and W.F. Hodge, "Infrared ray generating device," U.S. Patent 2 864 025, Dec. 9, 1958; E.G. Fridrich and E.H. Wiley, "Electric incandescent lamp," U.S. Patent 2 883 571, Apr. 21, 1959.

[9] E. Zubler, oral history interview by H.D. Wallace, Jr., tape 1, side A, 6 Mar. 1996; C.B. Collins and E.G. Zubler, "Iodine cycle incandescent lamps," U.S. Patent 3 132 278, May 5, 1964. Zubler's quotes throughout this paper are from this interview.

[10] F. Mosby, oral history interview by H.D. Wallace, Jr., tape 1, side A, 8 Mar. 1996; E.G. Zubler and F.A. Mosby, "Method of manufacture of iodine cycle incandescent lamps," U.S. Patent 3 160 454, Dec. 8, 1964. Mosby's quotes throughout this paper are from this interview.

[11] E.G. Zubler and F.A. Mosby, "An iodine incandescent lamp with virtually 100% lumen maintenance," *Illuminating Engineering*, vol. 54, no. 12, pp. 734-740, Dec. 1959.

[12] C.J. Allen and R.L. Paugh, "Applications of the quartz lighting lamp," *Illuminating Engineering*, vol. 54, no. 12, pp. 741-748, Dec. 1959.

[13] E. Zubler, oral history interview, tape 1, side A. Approval for the use of tungsten halogen lamps in U.S. headlights was granted in the mid 1980s.

[14] F.A. Mosby, "Electric lamp and support web," U.S. Patent 3 243 634, Mar. 29, 1966; F. Mosby, oral history interview, tape 1, side B. "A-line" and "A-lamp" are industry terms for the common incandescent light bulb.

[15] For a good description of early work at GE in Britain, see J.A. Moore and C.M. Jolly, "The quartz iodine tungsten lamp: Mechanism, design and performance," *G.E.C. Journal*, vol. 29, no. 2, pp. 99-106, 1962. I am grateful to L. Weymouth, company archivist at Marconi PLC, for supplying a copy of Moore and Jolly's article.

[16] J. W. van Tijen, "Iodine incandescent lamps: I. Principle," *Philips Tech. Rev.*, vol. 23, no. 8/9, pp. 237-244, Feb./Mar. 1962, and J.J. Balder, "Iodine incandescent lamps: II. Possible applications," *Philips Tech. Rev.*, vol. 23, no. 8/9, pp. 237-44, Feb./Mar. 1962. Also, G.R. T'jampens and M.H.A. van de Weijer, "Gas-filled incandescent lamps containing bromine and chlorine," *Philips Tech. Rev.*, vol. 27, no. 7, pp. 173-179, July 1966.

[17] Illuminating Engineering Society of North America, *IES Lighting Handbook*, 6th ed. New York: Illuminating Engineering Society of North America, 1981, vol. 1, p. 8-18.

[18] B.A. Masters, "Fires turn up heat on halogen lamps," *The Washington Post*, B5, Monday, 20 Apr. 1998; J. Bacon, "Jazz Legend Sues," *USA Today*, 9 Jan. 1998.

[19] For a detailed overview of tungsten halogen technology, see: S. Sirek and R. Kane, "The tungsten halogen lamp," in *Revolution in Lamps: A Chronicle of 50 Years of Progress*, R. Kane and H. Sell, Eds. New York: Upword Publishing Co., 1997, pp. 81-99.

[20] Zubler published in *The Journal of Physical Chemistry*. Publication was common in some organizations (Bell Labs, for example), but Zubler recalled becoming "turned off" about publishing due to difficulties in obtaining internal company permission due to proprietary concerns.

[21] U.S. Department of Commerce, Bureau of the Census, "Shipments, exports, and imports of electric lamps: 1994," Current Industrial Reports, form MP/94, table 10; "Manufacturing profiles: 1994, 7.3 Electric lamps," pp. 7-34. This figure was determined by adding the total value of exports and imports. 1994 seems to be the last year for which even such marginally useful figures are provided by lamp type—the *1997 Economic Census* lumps all lamp types into a single number.