

The Productive Scientific Career of Charles Pedersen* (October 3, 1904–October 26, 1989)

HERMAN E. SCHROEDER

4031 Kennett Pike, # 74, Greenville, DE 19807, U.S.A.

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Abstract. Charles Pedersen's career is reviewed from the time of his early life in Korea and Japan and scientific training in the United States to the present. His 42-year research career was practically and scientifically productive, leading finally to a share of the Nobel prize in chemistry for 1987. Commercially significant accomplishments included a large improvement in the yield of tetraethyllead antiknock and discovery of the first oil soluble agents for inhibiting catalytic effects of copper in degradation of petroleum products and rubber. This led to a study of the interactions of metals with chelating agents and the resultant effects on oxidation reactions, thence to the behavior of peroxides and their reactions with substrates. He also discovered the antiknock activity of ferrocene. While studying the effects of ligands on the catalytic behavior of vanadium he discovered the crown compounds and their ability to include alkali metal ions. He devoted the last years of his career to elaborating their chemistry.

Key words. Charles Pedersen, 1987 Chemistry Nobel Prize, du Pont industrial chemist, oil soluble agents, ferrocene, crown compounds, alkali metal complexation.

1. Introduction

On October 14, 1987 it was revealed that a relatively unknown and unrecognized du Pont industrial chemist had been awarded a share of the 1987 Nobel prize in Chemistry for his "development and use of molecules with structure-specific interactions of high specificity". While this surprised many chemists even in the du Pont company, those aware of his pioneering work with 'crown ethers' had been awaiting such recognition. In 1967, he had startled the world of coordination chemists with a description of his studies at a conference in Japan and in a paper which Marshall Gates, Editor of the *Journal of the American Chemical Society*, said was "a monumental piece of work".

What sort of man was this who had made so 'lucky' a find at the age of 58, in an industrial laboratory of all places? I write this as one who has known Charlie Pedersen as friend, associate, and when I was Director of Research, as a treasured member of my staff. To understand him we need to know of his interesting personal background and its effect on his character. These events, together with a stimulating industrial environment, led to an unusually productive 42-year career in research with the du Pont company which gave a basis for his discovery of the crown ethers and his recognition of their significance. Fortune surely smiled on a prepared mind.

* Taken in part with permission from *Current Topics in Macrocyclic Chemistry in Japan*, E. Kimura (ed.), Hiroshima University School of Medicine, Hiroshima, 1987.

The breadth of Pedersen's interests and his creativity are revealed in 65 patents and about 28 papers, many of which are listed in the reference section. A partial review of his accomplishments shows how a capable and creative scientist can shape his career to fit his unique abilities, though in a practical environment devoted largely to the support and growth of existing businesses. It also shows the beneficial effects of proximity to the varied problems of a highly diversified chemical business in broadening Pedersen's interests and stimulating his natural ingenuity.

2. Early Life

Charles John Pedersen was born October 3, 1904 in Fusan, Korea and died at his home in Salem, New Jersey, October 26, 1989. His father was Brede Pedersen, an expatriate Norwegian engineer, and his mother Takino Yasui, a Japanese from Kyushu whose family had emigrated to Korea to trade in soybeans and silkworms. His sister, Astrid, who was five years older and became his youthful mentor, played a very important role in his young life. They lived at the Unsan gold mines in northwestern Korea where his father worked as a mechanical engineer. The 400 square mile American concession abutted the Yalu river in a primitive area where pony harnesses had bells to ward off the Siberian tigers which still roamed the countryside. In the bitter cold of winter nights, wolves devoured children and foxes slept against rooftop chimneys to keep warm.

Since the Unsan mines were in an American enclave, life there was as American as possible and much gentler than on the American frontier. Social life centered at the country club and the common language was English, even in the Pedersen household. Life at an isolated American outpost undoubtedly influenced the boy strongly and fostered his independence. The procedures and attitudes involved in operating the mine and gold refinery plus the availability of interesting minerals generated his interest in technology.

Since foreign-language schools did not then exist in Korea, the youth went to Japan at the age of eight, where he enrolled for two years in a convent school in Nagasaki. Two years later he moved to St. Joseph's College, a French preparatory school in Yokohama run by Marianist priests and brothers, where he completed his secondary education. He returned to his family in Korea only during the summer vacations, traveling by train and boat in the style of a European. With his father's encouragement he came to America for his college education in 1922 shortly before his 18th birthday and enrolled at the University of Dayton (Ohio). He became vice-president of his class and received a chemical engineering degree in 1926 and then an M.S. in organic chemistry in 1927 at Massachusetts Institute of Technology. His professor, James F. Norris, recognized the ability of this unassuming young man and tried to persuade him to seek a doctorate, but Pedersen no longer wished to burden his father financially and chose to go to work.

With Norris's help he obtained a position with the du Pont Company where he spent his entire career of 42 years, mostly at Jackson Laboratory, their most diversified applied research organization. It served businesses in dyestuffs, intermediates, refrigerants, and made products for the rubber and petroleum industries. Here he had a distinguished career in industrial research with many notable accomplishments of both a practical and a scientific nature, valuable contributions

to chemistry and to our material well-being, all well before his discovery of the crown ethers.

3. The du Pont Years

He started in analytic work and after a brief indoctrination came under the wing of two mentors, his leader W. S. Calcott and his associate A. S. Carter. Like many who had been responsible for the young man earlier, they did all they could to guide and encourage him while at the same time becoming close friends. Calcott sensed Pedersen's unusual quality and chose to keep him in research rather than send him to manufacturing as was usually done with those who lacked a doctoral degree.

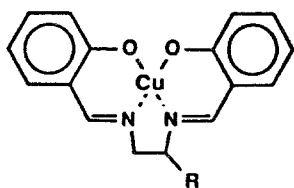
They also fostered some of his lifelong interests: love of the natural world, stamp collecting, and fishing which was originally inspired by his father's love for the sea. He learned the native flowers and where to find them, the birds, what they ate and where they lived, and their unusual traits. Though he became seasick at the slightest wiggle of a boat, he loved to fish and pursued it wherever he could, locally, in Wyoming and Alaska, and with me for several weeks in Iceland. In life, as in science, Pedersen has been a fine student. A voracious reader, he rapidly broadened his knowledge of science and of art, history and nature. He once read through much of the Encyclopedia Britannica to satisfy his consuming desire for knowledge. He even read it during his lunch hour to pass the time more pleasantly.

Pedersen soon learned the nature of research and of relevant du Pont technology. He also developed a personal investigative style which was intuitive and unfettered by scientific dogma, and remarkably gifted. Though scientific in his methodology he was very much an industrial chemist. He wanted his research to be useful, to have practical and beneficial applications. A hands-on chemist, and experimentalist rather than a theoretician, he was a keen observer of what was happening with an uncanny ability to ignore confusing details and focus directly on his goal. He had an eye for fruitful problems and a flair for appraising situations quickly. His approach to a problem was surprising in its simplicity and often led directly to the answer. Little activity was apparent on a visit to his laboratory; yet with simple set-ups and measurements he produced a prodigious amount of work. It is hard to appreciate that the monumental studies described in the first publications on the crown compounds were not the work of a professor with a corps of scientists. It came solely from a lone research scientist, Charles Pedersen, with an able but technically untrained technician, Ted Malinowski. Pedersen's research managers soon learned how much he could accomplish so they loosed their reins and urged him to follow his own intuition. He rewarded them with a flood of interesting and valuable discoveries.

After several successes with a variety of problems, he was asked in 1932 to find out how to increase the yield of antiknock TEL (tetraethyl lead) in the plant process where consumption of sodium-lead alloy indicated more TEL had been produced than was isolated from the steam distillation. Pedersen noted that the reaction mass was a sludge of very fine lead particles and guessed that the TEL was so strongly adsorbed that it could not be recovered. This he proved by taking 10 mL of TEL, adding 100 g of the most finely powdered lead he could obtain, and

steam distilling. He recovered only 10% of the TEL compared with 99% recovery in a similar experiment where TEL was distilled in the presence of *coarse* lead shot. He then added a non-foaming wetting agent to the experiment with the powder. A 15 minute distillation yielded the rest of the TEL! Thus he enabled a 15% increase in plant yield of a high volume process and made what was probably the most profitable discovery of his career [1]!

Next came a succession of important patents: corrosion inhibitors and evaporation retarders for ethanol anti-freeze [2–4] and a very effective stabilizer, rosin acid, for sodium hydrosulfite which was then very important as a reducing agent for vat dyes [5]. By then the plant people had such faith in him that they asked him to treat each batch as it was produced in the plant. In 1935, he made another important discovery. He found the first good agents for deactivating metals in petroleum products and rubber. Heavy metals, especially copper, were normal contaminants in gasoline, oils, and rubber and were known to catalyze their oxidation. Clues he uncovered in a search for hydrocarbon soluble agents to precipitate copper led him to disalicylal ethylene diimine **1** but it was high melting and almost insoluble (<0.01%) in gasoline. So he made the 1,2-propylene diamine analog **2**. The melting point fell to 45°C and the solubility increased 100 fold, more than enough to make it practical. Disalicylal propylene diamine proved so effective in countering the degradative effects of metals it was soon used in almost all gasoline and much rubber. It is still important today [6–9].



1., R = H; **2.**, R = CH₃

The metal deactivator discovery reshaped his career. It turned his attention toward peroxide and radical behavior, the catalytic effects of metal ions, and especially the behavior of metals in complexes [10]. With loving care he varied structures of ligands to find the features which led to the strongest complexes and the most effective deactivation of transition metals. Over the next ten years he and his group studied oxidation of hydrocarbons with and without inhibitors and deactivators. He also examined the corrosive action of the oils on metals while seeking means of blocking those processes. He himself became inventor or coinventor of about thirty patents covering anti-oxidants, stabilizers and inhibitors, and chelating compounds. He also sought stable synthetic lubricants which could better resist heat and oxidation.

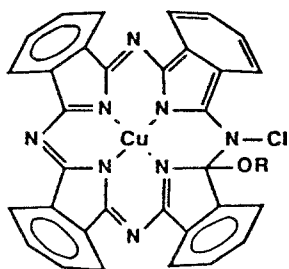
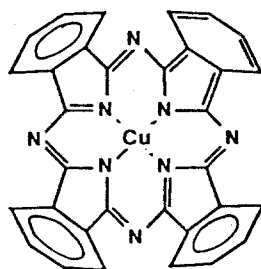
During World War II he experienced none of the difficulties endured by the Nisei on the west coast. Although carrying a Norwegian passport, he had never been to Norway to confirm it, so he was officially classified a stateless alien which kept him from research on certain problems. He continued to work in du Pont throughout World War II on urgent war-related problems especially on the oxidation of

lubricating oils. As an acknowledged expert in the stabilization of petroleum products he was of value to the government and the armed forces as a war-time consultant and was well liked and highly regarded.

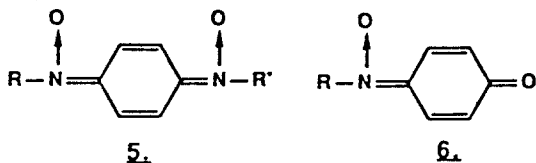
Shortly after the war he married Susan J. Ault. Sue and Charlie became devoted companions until her death in 1983. Concurrently, in recognition of his research talent, he was appointed Research Associate, the top scientific position then available in du Pont. This freed him from the supervisory responsibilities he never liked and allowed him to practice research as he wished, with full responsibility for his own programs. With this new freedom he returned to his studies of the mechanisms of oxidation and the various reaction products of peroxides.

During this period, I got to know Charlie Pedersen very well as we were among the co-founders of an evening seminar group wherein we discussed science and exchanged ideas. This gave me a fine chance to appreciate his abilities; so when I was promoted to Laboratory management I asked for responsibility for him. Thus began a close technical and personal association. I did two things for him. I was the first in his management to discuss chemistry with him, not only his work but also unusual science that either of us encountered. That stimulated us both and broadened his perspective. Second, I urged him to publish more. This led to twenty papers while we were together compared with four in the previous 24 years. Despite the change of focus toward science and publication, the flow of patents continued unabated, twenty-nine for the 19 years we were together compared with thirty-six for the earlier 24 years. This is testimony to what a good scientist can achieve if given encouragement and freedom to pursue his own ideas.

For a while Pedersen continued his studies of the pro-oxidant activity of metal chelates and of oxidation and peroxides [11–13]. Then came new developments. The first resulted from curiosity about the redox behavior of iron and cobalt phthalocyanines which did not appear to be shared by the copper, nickel or metal-free types. On closer scrutiny, he found that the purportedly stable types readily formed solvent-soluble adducts **3** with peroxides. Subsequent reduction, chemical or photochemical, restored the original pigments **4** [14]. He also showed that these reactions could be employed to produce brilliant fast blue and green colors on textiles or to generate photographic images. Similar conversions could be effected by careful treatment with chlorine in methanol to form an adduct from which the pigment was easily reconstituted.

**3.****4.**

Another interesting development arose because he wondered what happened to the *N,N'*-disubstituted *p*-phenylene diamine antioxidants when consumed during their protection of a substrate. This led to a new class of *N,N'*-disubstituted *p*-quinonediimine-*N,N'*-dioxides **5** [15]. He prepared many of these substances and found they had unusual properties. In their capacities of polymerization inhibitors and antioxidants they appear to react with hydrocarbon radicals and not the peroxy intermediates which generate them. Also when exposed to light (300–450 nm) they decompose rapidly and quantitatively into *N*-substituted *p*-quinoneimine-*N*-oxides **6** and azo compounds [16]. Further irradiation with light of 20 nm shorter wavelength converts these *N*-oxides to the *p*-quinone and azo compounds. Mixtures of azo compounds are obtained from unsymmetric *N,N'*-dioxides.



One afternoon in December 1951, Charlie came bustling into my office all excited. He had just read an interesting note in *Nature* about Kealy and Pauson's discovery of an unusual soluble dicyclopentadienyl iron complex later called ferrocene. He felt that they had not fully grasped the nature of the substance nor the significance of their discovery. He described his own conception of what they had, which later proved to be correct. On the strength of Pedersen's enthusiasm, I invited Pauson to visit our Laboratory to discuss his work and there we made arrangements to help Pauson file an appropriate patent case. We also secured a license so that we could use the invention in some of the areas Charlie visualized as of practical interest.

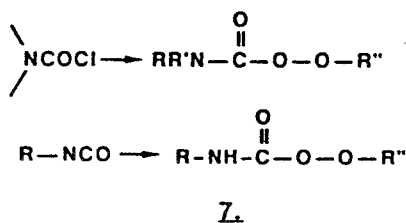
He went right to work on ferrocene and quickly made two important discoveries. He found that dicyclopentadienyl iron compounds were excellent combustion control agents, specially valuable because they were both hydrocarbon soluble and volatile [17]. Of most importance, ferrocene functioned as an anti-knock agent when added in very small amounts to gasoline. This was very exciting as these compounds were the first really different highly effective anti-knock agents since the discovery of tetraethyl lead and promised great advantages because they would avoid the toxicity problems encountered with lead derivatives. Charlie quickly filed a patent application on the discovery (March 19, 1952) [18]. In view of its importance, the application was immediately placed under a U.S. government secrecy order. This was rescinded in 1960 but by then larger scale practical tests had showed that the ferric oxide formed on combustion of ferrocene–gasoline compositions caused excessive engine wear. Nevertheless, the patent proved to be valuable as we were able to trade rights for a patent covering a new method for handling sodium–lead alloy which was worth over a million dollars to us.

His other discovery also related to the extraordinary catalytic effect of ferrocene in promoting combustion. Small amounts (0.1%) stop the formation of soot or smoke in a hydrocarbon flame by catalysis of combustion. When a hydrocarbon

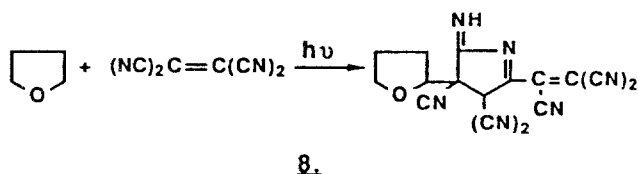
fuel containing ferrocene was mixed with fuming nitric acid the mixture ignited spontaneously [19]. Such a hypergolic mixture was of potential value as a rocket fuel so it was of great interest to the U.S. government.

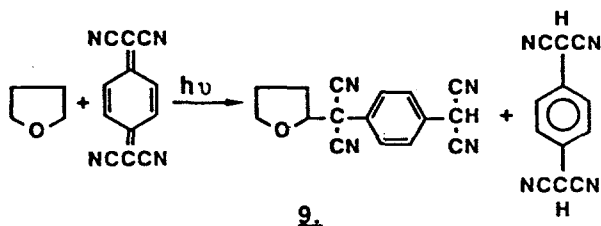
In 1957, our Organic Chemicals Department was divided to form a new Elastomer Chemicals Department with Carter and me as Research Directors. With our strong encouragement Pedersen chose to join us. Although we never tried to influence his programs, he somehow seemed to feel he should work on subjects he deemed of interest to us. This included elastomers, elastomer chemicals, and isocyanate and urethane chemistry. He soon made an important contribution in a well studied area. We were trying to find ways of increasing the use of neoprene in light colored stocks, particularly for tire side walls where its ozone and age resistance are outstanding. But, since white neoprene stocks discolored on light exposure, its use was largely restricted to black stocks. Pedersen showed by the simplest of experiments (exposing neoprene to light in the presence and absence of water and air) that the goal was attainable, but with practical difficulties. On photolysis, neoprene liberates hydrogen chloride which in turn catalyzes color-forming condensation reactions involving the aldehyde and ketone products of oxidation. If water or bases are present to dilute or neutralize the acid, no color is formed. Unfortunately, impractically large amounts of basic oxides would be required to protect the neoprene completely over the life of a tire.

His next endeavors involved the chemistry of peroxyurethanes **7** which he synthesized by reaction of hydroperoxides with isocyanates or carbamoyl chlorides. They were found to decompose smoothly both homolytically and by intramolecular



reactions and were of interest as polymerisation catalysts [20]. After a brief excursion into photochemical addition reactions of tetrahydrofuran to tetracyanoethylene and tetracyanoquinodimethan [21] **8**, **9**, he shifted his attention toward elastomeric polymers. He prepared for the first time novel functionally substituted ethylene/propylene copolymers with pendant amino and sulfide groups which had many very interesting properties [22-23].



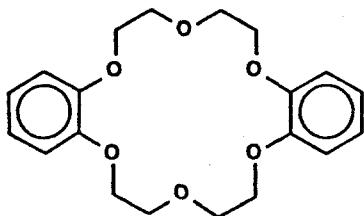


Despite the obvious practical possibilities of these studies, I felt that this simple chemistry was not the best use of Pedersen's unusual capabilities, so I encouraged him to return to his beloved coordination chemistry, still of great interest to him. To convince him that there were good subjects of importance to us in that field I suggested that the chemistry of transition elements like vanadium might be worthy of attention. We were then using vanadium in a coordination catalyst system to make a very important polymer whose microstructure depended on the vanadium ligands. When polymerization was completed, we used an acid extraction to remove the vanadium residues from the elastomer since vanadium catalyzed its oxidative degradation. So I asked him if he would like to study vanadium to see if he could develop an understanding of why it was so fine a polymerization catalyst in one oxidation state and so strong an oxidation catalyst in another. I also wondered whether he could think of any substances from his earlier work with metal deactivators which might deactivate the vanadium so that the costly extraction would not be necessary.

Pedersen jumped in enthusiastically. He suggested that it would be interesting to study polydentate oxy structures derived from various polyhydric phenols since these had not been examined. A few months later he told me he enjoyed the catalyst ligand chemistry but that the various complexing agents all *enhanced* the pro-oxidative behavior of vanadium except for tetrasalicylal pentaerythrityltetraamine which was not practical for manufacture. He also planned synthesis of a new pentadentate ligand for possible use as a catalyst [24]. (It later turned out to be ineffective.)

4. Crown Ether Discovery

This is when the lightning struck! From one of his reactions he isolated the first of the *Crown Ethers*, which he later called dibenzo-18-crown-6, **10**. His first person account of his discovery and his reaction thereto written for the 1987 Symposium



10.

on Macrocyclic Chemistry commemorating the 20th anniversary of his first publication on 'crown' ethers is found elsewhere in this volume [25]. His account is truly a remarkable story! Intuitively and almost immediately he recognized the significance of his find and he pursued it the way a bird dog goes after his game.

Pedersen first described his research at the International Conference on Coordination Chemistry in Nikko, Japan in September 1967 (see paper in this issue by D. Busch) and in his beautiful 1967 note and paper in the *Journal of the American Chemical Society* [26] which describes about 50 crown ethers with from 9- to 60-membered oligoether rings. This was an amazing accomplishment for a single chemist assisted by one technician. Charlie's description of events leading to the discovery has been published [27, 28].

Reaction to his work was fast and enthusiastic. *Angewandte Chemie* noted it in the hot news section of their July 7, 1967 edition and in early 1968 it won the American Chemical Society Delaware Section award for best paper of 1967. Now everyone wanted a talk or paper from him! Knowing full well the unusual nature of his discovery Pedersen spent the rest of his career with du Pont on the chemistry of the crown ethers until he retired in 1969. After that, at the invitation of the late Sir Ronald Nyholm, he spent three months collaborating with Professor Mary Truter (University College, London). Their work was concerned mainly with the crystal structures of crown ethers and their metal derivatives [29].

His own further studies greatly broadened the scope of the discovery and included syntheses of new crown ethers, factors governing inclusion of other metal ions, products with sulfur and nitrogen in the rings, extensions of the preparation and characterization of crystalline salt complexes, ionic complexes, and unusual thiourea complexes. He made many suggestions for uses of the crown ethers, especially for catalysis and separations, which have proved to be prophetic. He was fully aware of the potential of these substances for carrying various metal ions into organic media to effect reactions. They are described in six papers and ten patents [30–37] and in the publications of some of his colleagues. In the course of this work he also studied reactions of crown ethers as organic chemicals and their utility as catalysts and as agents for effecting ionic reactions in organic media.

While the complexation of transition-metal cations is a commonplace phenomenon, practically no alkali-metal ion complexes were known before the advent of the crown compounds. Thus, the discovery of a large variety of easily synthesized alkali-cation-complexing agents represented a real breakthrough. This complexing property is far more than a laboratory curiosity; in fact, it is the key to the importance of the crown ethers. The complexes are soluble in a variety of organic solvents in which the uncomplexed salts are at best sparingly soluble. Moreover, the inter-ionic forces are considerably reduced by the oligoether ring which surrounds the cation, so that there is far less ion pairing and 'naked cations' are available in much higher concentration for reaction.

5. Impact of Crown Ether Discovery on the Scientific World

The major impact of Pedersen's discovery is shown by the frequency of citation of his crown ether papers and even more strikingly by the many new directions of research it has opened up in which many groups have been engaged. These include:

cryptates, J. M. Lehn; host-guest chemistry, D. J. Cram; naked-ion chemistry, C. L. Liotta; phase-transfer catalysis, C. L. Liotta; solubilization of alkali metals, J. L. Dye; ion pairing in non-polar solvents, J. Smid; X-ray structure of complexes, M. J. Truter; crown ethers as ionphores, G. Eisenman; and many others.

As Professor D. J. Cram described it [38]:

Pedersen's discoveries illustrate organic synthesis and the organic chemist at their best. Using a simple Williamson ether synthetic procedure and simple starting materials, he synthesized in good yields a new family of cyclic polyethers. He noted that these 'crown compounds' complex and lipophilize metal guest cations whose diameters are similar to the diameters of the host crown compounds. He attributed the good yields of the crown compounds in part to templating effects during the ring closures. He varied the ring sizes over a wide range by appropriate selection of starting materials and the orders in which the molecular parts are assembled. The anions of salts lipophilized by the crown compounds have in many cases never been brought into non-polar organic media before, and show greatly enhanced reactivity over what they have shown in polar media.

Charles Pedersen's discovery of the crown compounds has had a major impact in a variety of investigative fields: inorganic chemistry (the crowns are ligand assemblies); organic chemistry (the crowns are commercial synthetic aids); physical organic chemistry (crown compounds greatly affect ion pair organization); biological chemistry (crowns are important ion transport agents); and analytical chemistry (analytic reagents and ion selective electrodes are based on crown compounds). Pedersen's discoveries were not the usual result of the efforts of a group of competitors that he led or beat into print. Nor are they those of a large group of scientists under a director; they were his alone.

Professor D. J. Cram added:

He had no competition – he was alone – he was original – he did something important – he knew it was important – and he knew what to do with his discovery... It is my belief that Pedersen's demonstration of the feasibility for synthesizing multiheteromacrocycles is leading to the development of a whole new synthetic field of organic host-guest chemistry.

The man who did all this was not after riches, glory, or status. He loved the thrills and problems of research and in his heart he most wanted his work to be worthwhile and so recognized. We could not find so deserving nor more modest and unassuming a person to honor than my dear friend and associate Charles Pedersen.

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