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A tribute to Sidney Loeb –The pioneer of reverse osmosis desalination research

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The technical viability of RO desalination technology was demonstrated in the late 1950's by the pioneering work of Sidney Loeb and Srinivasa Sourirajan and a team of researchers at the University of California, Los Angeles (UCLA) led by Professors Joseph McCutchan and Samuel Yuster. Today Reverse osmosis (RO) membrane desalination is a mature process for the production of potable water from seawater and inland brackish water. RO membranes are also now widely used as part of the overall process for the treatment of wastewater for reclamation and reuse for irrigation, industrial, and groundwater recharge applications. RO desalination technology is used worldwide and has made it possible to develop new potable water sources in areas of the world where freshwater water sources are scarce.

The establishment of the Office of Saline Water (OSW) in the early 1950's marked the beginning of organized interest in desalination in the U.S. This was marked by the opening of the "Sea Water Conversion Laboratories" at the Richmond Field Station adjacent to the UC Berkeley Campus. The new program was under the direction of Professor Everett Howe, the Statewide Coordinator of "Saline Water Conversion Projects", and was supported primarily by the State of California. Shortly afterwards, a program known as the "Pilot Plant Group" was established at UCLA, focusing on addressing California's water shortage problems. This program involved faculty and students from the mechanical, chemical, and civil engineering departments. Researchers and faculty at UCLA, under the direction of Prof. J. W. McCutchan, involved in early RO membrane research included Edward Selover, Serop Majikian, James S. Johnson, F. Milstein, Gerald Hassler, Julius Glater, and Mary Justice. It is important to note that, during the above period and until the early 1980's, the UCLA engineering school followed unified curricula, where all engineering students develop a significant common engineering and science background.

Desalination research at the University of California (UC) actually dates back to the 1940's. At that time, Professor W. Langelier and associates carried out their classical work on the mechanisms of scale formation in saline water. This work at UC Berkeley established the now-famous Langelier Index, widely used for the prediction of calcium carbonate scaling limits. The first considerations of water desalination at UCLA date to the early 1950's and described in two School of Engineering Reports authored by Gerald Hassler [1,2]. Hassler contemplated the use of membranes and some believe was the first to coin the term "reverse osmosis". By the mid 1950's, Hassler was experimenting with the concept of membrane desalination, but was diverted into other areas including membrane-based narrow gap distillation process. At the same time, Samuel Yuster and his students were pursuing the idea of "surface skimming" with fine capillaries or bubbles, believing that the presence of a "fresh water" layer (of ~7 Å) at the water/air interface could be harvested by various surface skimming techniques. This idea was then extended to include cellophane and cellulose acetate membranes expecting that, with little pressure, it would be possible to "push" the thin water layer through a thin polymeric film while rejecting the salt ions. In parallel with the efforts at UCLA, Professor Reid at the University of Florida [3] was also experimenting with the use of cellulose acetate membranes to achieve separations in a process he also coined as "reverse osmosis". Reid and Berton [4] were apparently the first to demonstrate that it is feasible to desalt saline water using a synthetic semipermeable membrane. However, the water flux obtained

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by their membranes and in the various processes at UCLA did not yield a practical level of permeate water flux.

The above efforts, while yielding important theoretical understanding of the thermodynamics of mixed-electrolyte systems and water properties near and at interfaces, were unsuccessful in producing desalinated water at levels of practical interest. The work at Florida and UCLA, however, has inspired Srivasa Sourirajan, who joined Professor Samuel Yuster's research group in the late 1950's. In 1958, Sidney Loeb joined the group to develop the celebrated Loeb–Sourirajan (L–S) cellulose acetate RO membrane [5].

Sidney Loeb received his B.S. in chemical engineering from the University of Illinois in 1941. Prior to joining UCLA as a graduate student, he worked in the Los Angeles area in the fields of petrochemicals, rocket engines, and nuclear reactors. He received his M.S. and Ph.D. degrees from UCLA in 1959 and 1964, respectively. Loeb's entry into the RO research area and the path that his life took in connection with RO desalination is best described in his own words [6]:

> "In looking for a particular research project, I was attracted to desalination and in particular to a California state-sponsored project and fellow student, Srinivasa Sourirajan, who invited me to partner with him. He was working with professor Samuel Yuster on a project called "surface-skimming". However, after a time, it appeared more appropriate to call it reverse osmosis. Sourirajan and I worked [for] about two years together to make the process practical, i.e., producing fresh water from saline water such as seawater at an adequate permeation rate through the membrane without the use of excessive hydrostatic pressure."

These early studies were carried out using a high pressure desalination cell (Fig. 1). Loeb and Sourirajan succeeded in developing a practical cellulose acetate RO membrane. As Loeb describes:

> "The most singular and unique feature of the Loeb–Sourirajan [L–S] membrane, specifically [is] a very thin active salt separation layer surmounting a relatively thick support layer. This thin separation layer holds back the salt but allows the permeation & water into and through the support layer... In the fall of 1960, after two years of work together, Sourirajan had to leave the U.S. because of visa termination problems."

The development of successful L-S membranes is credited to the anisotropy of the membrane. Tests with membranes demonstrated reasonable performance at

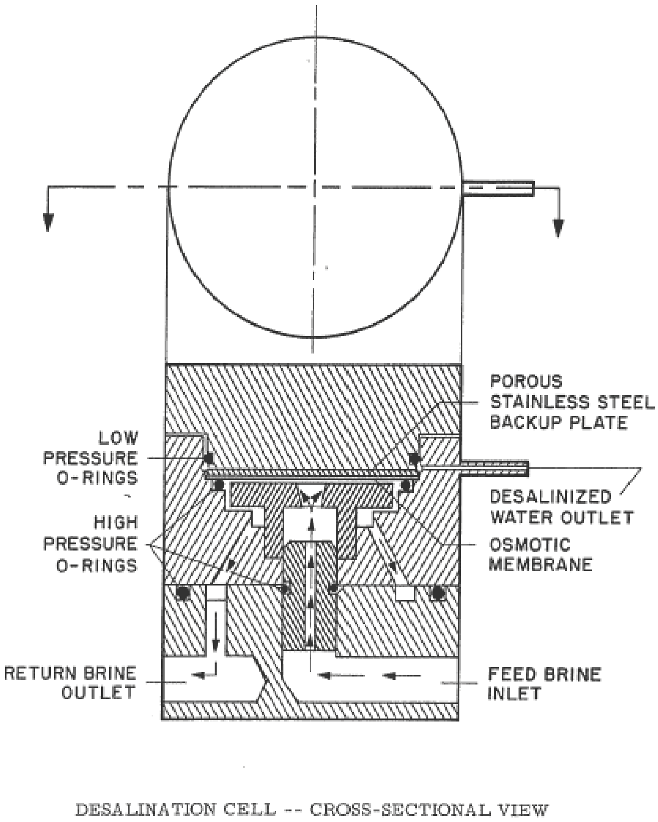

Fig. 1. The first high pressure RO cell used at UCLA for testing cellulose acetate membranes.

times and sometimes the performance was poor. Loeb and Sourirajan observed that when the side facing the air during the casting on a glass plate was in contact with the saline solution, reasonable permeate flux was obtained. As Loeb once said [6]:

> "I sometime wonder if I would have continued testing that membrane sheet if the first test had been a failure."

The main variables for a successful membrane were: (1) cold casting of the membrane, (2) air-drying for a short period of predetermined time, (3) sudden immersion in ice water for a specific period, and (4) heating of the membrane in hot water at a temperature of 71–82°C. Improvements to the L–S membranes were sought by Loeb in his Ph.D. work (with Professor T.E. Hicks as his academic advisor) in which he focused on the role of electrolytic additives to produce high performance cellulose acetate membranes from the casting solutions (Fig. 2). Although magnesium perchlorate was the found to be the optimal salt, the systematic study concluded that the special requirements of the additive were derived chiefly from the anion, although a predictive generalization for the anion utility could not be derived [7].

As Loeb's Ph.D. work was reaching its conclusion, interest in the L–S membrane was attracting significant interest in education and commercial circles. As Loeb noted [6]:

> "...This interest increased exponentially, especially after installation in 1965 of a highly successful municipal RO plant in the little town of Coalinga, California supplying about 1/3 of the their freshwater. The plant was situated in the firehouse garage and was operated by the fireman when he was not putting out fires. He also took care of an experimental electrodialysis plant and the town sewage disposal plant."

The Coalinga plant was the first "commercial" reverse osmosis plant, based on the L–S membrane. The plant, designed by McCutchan and Loeb at the UCLA School of Engineering and Applied Science, consisted of an array of one-inch tubular cellulose acetate membranes inserted into titanium support tubes (Fig. 3). This newly developed reverse osmosis membrane plant (Fig. 4) provided a breakthrough in desalination technology by demonstrating the first large-scale production of potable water by reverse osmosis. The UCLA Water Desalination Research Group collected data and supervised operation of this facility for 3½ years at which time the plant was turned over to the city of Coalinga [8]. The plant remained on-line operated by the city of Coalinga for a total period of seven years.

Following the Coalinga plant demonstration, in 1971, the desalination group at UCLA was assigned the task of designing a reverse osmosis pilot plant to be installed at Firebaugh, California [9]. A one-inch tubular plant, similar in design to the Coalinga facility, began operation in November 1971 and was managed by the UCLA desalination research group for a period of four months with continuing involvement in the analysis and optimization of the facility [10]. Operation of the above plant was taken over by the California Department of Water Resources and it remained "on line" until 1980.

It is important to note that prior to installation of the first L-S/UCLA tubular RO membrane plant, short-term

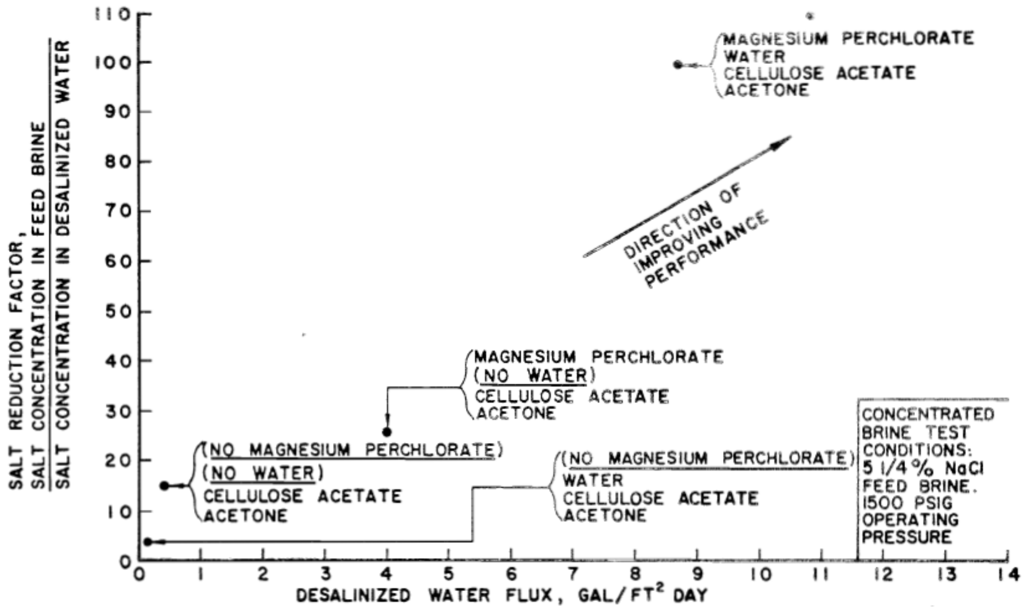

Fig. 2. A summary of the impact of various salts used on the casting solution on the performance of celulose acetate membranes.

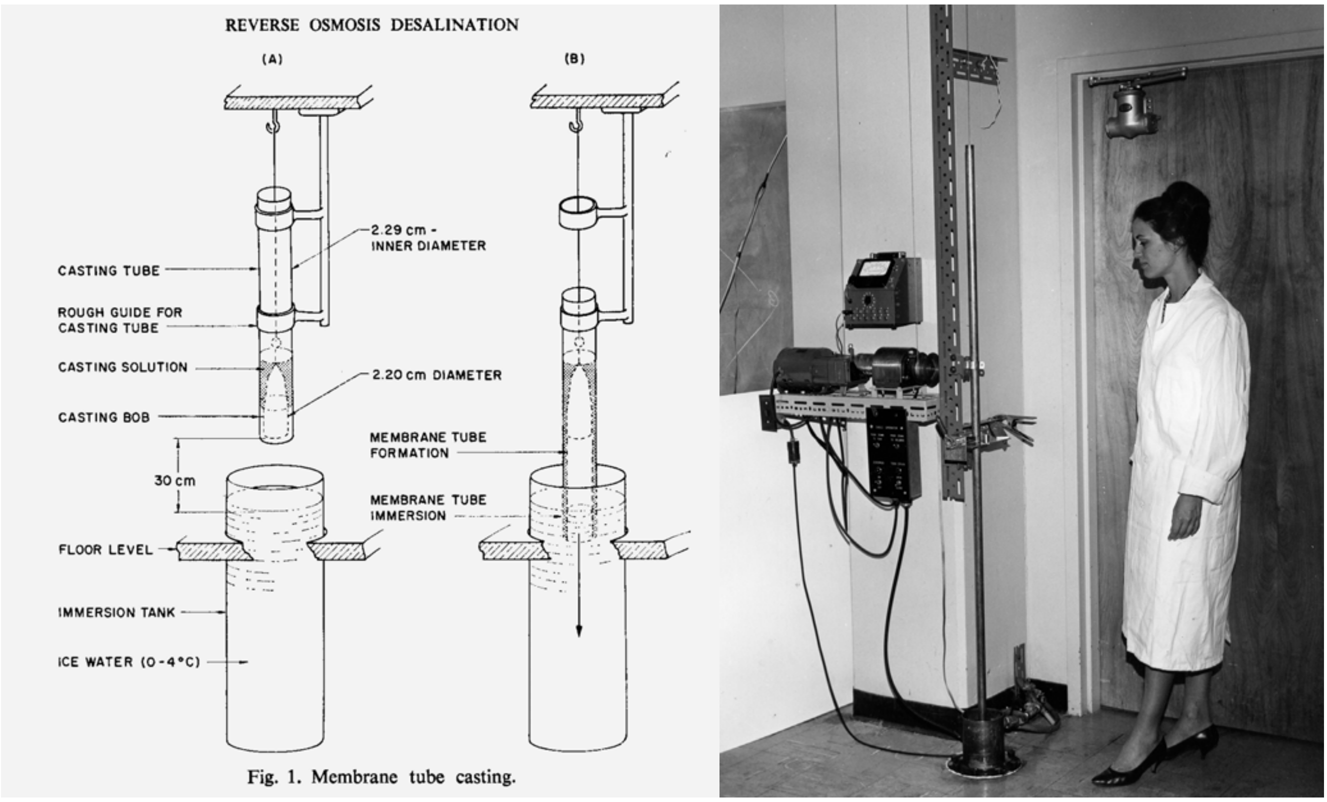

Fig. 3. A schematic of the approach to casting tubular cellulose acetate RO membranes (left), and experimental system (right) at UCLA (the well assembly that is is still intact on the fifth floor of Boelter Hall at the UCLA School of Engineering and Applied Science).

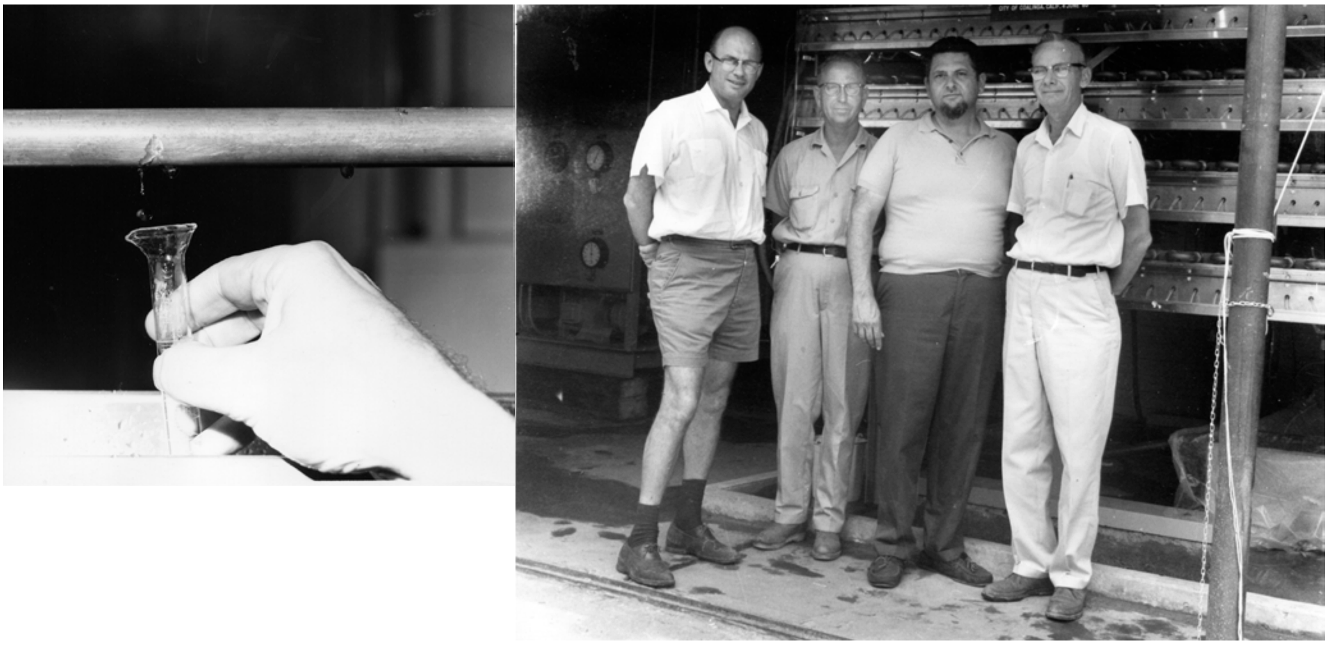

Fig. 4. The tubular membrane (left) showing peremate flow from a hole drilled in the membrane and the Coalinga RO plant in which the tubular L–S membrane were first used (right).

desalination efforts at Firebaugh were conducted by several industrial firms including DuPont, Aeroget-General, and Ionics. These commercial desalination systems involved hollow fine fibers, plate-and-frame RO membrane units, and electrodialysis. Serious technical problems were encountered in these early studies in each of these pilot facilities. In contrast, the L-S/UCLA tubular membrane plant operated continuously for an extended period of time with minimum of maintenance.

Shortly after the installation and successful operation of the Coalinga plant, Dr. Loeb began his work in Israel as he recalls [6]:

> "In 1966 I went to Israel under UNESCO auspices to teach RO at Ben-Gurion University in Beer-Sheva. A pilot plant was setup in the south of Israel at a Kibbutz called Yotvata situated in the desert. Probably because this was the first publicly available RO plant in Israel, the inhabitants refused to drink the water. However, the women did bring buckets to the plant for the allegedly soft water to wash their hair. Then an outspoken doctor came down to the plant (from Beer-Sheva) and informed the Yotvata residents that they were all going to get rigid spines if they continued to drink the saline ground water. Then, they began to drink our RO water. Later a full-scale plant was installed in Yotvata...Well, I was offered a University Professorship in Israel. More importantly, I met Mickey (Miriam) ...and decided to stay."

Although much of the recognition that Sid Loeb received is for the celebrated L–S membrane, his impact on the field of RO desalination is much broader than this singular material. For example, already in the early days of RO desalination, Loeb and his collaborators demonstrated the limitations on reverse osmosis due to mineral scaling and the passage of organics through RO membranes. In the early 1970's he invented an energy-producing process called pressure-retarded osmosis (PRO) for the generation of energy by exploiting the osmotic pressure difference between two liquid streams. Loeb has devoted considerable effort to promoting the idea of generating power from the PRO process in which, as he described, "...reverse osmosis run[s] backwards... [and] PRO is possible wherever in the world a river runs into the sea." This technology is now attracting significant attention and it is also the foundation for the so-called forward osmosis or as Loeb would have probably said simply "osmosis" for desalination.

Sid Loeb was a dedicated researcher who devoted most of his professional life toward solving the world's water problems. His pioneering work was during an exciting era of the 1960's with the U.S. racing to land a man on the moon (man landing on the moon occurred on July 20, 1969), while he was racing to find a practical way to desalt saline water. Desalination efforts were recognized as a task of immense importance to humanity by President John Kennedy who declared that "In this administration, we will put a man on the moon and make the desert bloom." The president asserted that "If we could ever competitively, at a cheap rate, get fresh water from saltwater, that would be in the long-range interests of humanity and would dwarf any other scientific accomplishments (April 12, 1961)." One could argue that the accomplishment of such a feat would deserve two Nobel prizes: one for science and one for peace.

The successful development of the L–S RO membrane and field demonstration of the RO technology for water desalination by Loeb and his colleagues were remarkable achievements by this unique individual. This work has provided the basis for tremendous industrial development of reverse osmosis technology. It is doubtful that this multi-faceted multi-billion industry would exist today were it not for these pioneering academic efforts in the early 1960's. Yet, Sid Loeb did not bask in the glory. His passion for moving forward and seeking to solve real-world problems is exemplified by a letter he sent to his colleague Bud Glater in February 12, 1992, in which Sid Loeb wrote:

> "I am involved with one invention after another without success. Still, I keep trying. Maybe the road to success is paved with failures."

The above statement by a man who has changed the world is humbling as most of us would be thrilled to have a positive impact on just one soul.

Acknowledgements

The material for this article was based on the collection of historical documents at the Henry Samueli School of Engineering and Applied Science, recollections of Julius Glater from the early years of desalination research at UCLA, and a number of conversations with Sid Loeb during his visits to UCLA, the 2002 North American Membrane Society Meeting (Long Beach, CA), the 1999 ICOM Meeting (Toronto, Canada), and the Fourth Mediterranean Chemical Engineering Conference (Israel, 1999).

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