



Dr D.R. Nagaraj

Flotation chemicals constitute a most powerful tool in enhancing mineral separation performance, affecting overall economic and environmental impacts of the process. Dr D.R. Nagaraj (Nag) has more than 35 years of outstanding and innovative achievements in the design, development and commercialisation of numerous families of novel flotation reagents (collectors, depressants, dispersants, etc.) and in advancing the art and science of flotation agents for sulphide and non-sulphide mineral separations. His seminal 1987 paper^[1] titled The chemistry and application of chelating or complexing agents in minerals separations formally introduced the donor-acceptor model, which paved the way for rational design of flotation reagents. During his entire career he has been involved in a bridge building exercise between academic research and practical applications.

However, his persistence at requiring knowledge to be useful has made him sought after by both communities. His holistic approach^[2] to reagent selection and flotation optimisation is one example of his devising a rational and practical scheme for dealing with real, complex ores. His pioneering work in the use of SIMS surface analytical technique^{[3],[4]} for determining the disposition of collectors on mineral surfaces started a trend in the academic community and is an example of the high quality work for which he is known.

In addition to devising schemes to optimise chemical usage, Nag has developed and patented many organic and polymeric materials for flotation and toxic metal removal. Here are a few examples:

- **Alkyl and Aryl monothiophosphates as acid circuit sulphide collectors:** Nag pioneered the use of alkyl and aryl monothiophosphates (modifications of existing dithiophosphates) as acid circuit sulphide collectors^[5]. Under alkaline conditions the monothiophosphates are excellent collectors for precious metals such as Au and Ag. The largest mines in North America and Asia currently use the monothiophosphates to improve their gold and silver recoveries.

- **Synthetic functionalised polymers as depressants in sulphide flotation:**^[6] Using insights from his donor-acceptor model, Nagaraj *et al*

conceptualised and synthesised polymeric depressants containing mineral-specific functional groups for use in enhancing sulphide flotation. The most important application for these depressants has been for Cu-Mo separation, where they can greatly reduce the use of inorganic Cu sulphide depressants such as NaSH, Na₂S, and Nokes. These inorganic reagents are known to have serious safety, health and environmental (SHE) concerns such as stench and H₂S formation. Mitigation of those SHE issues through the use of polymeric depressants protects operators and also improves economics and logistics as a result of greater reagent efficiency. A number of mines around the world currently use these depressants.

- **Alkoxy carbonyl thionocarbamates as collectors for mildly alkaline circuits:**^[7] A major gangue mineral present in sulphide copper ores is pyrite, which readily responds to sulphide collectors at pH <10, resulting in results in significant grade dilution of the concentrate. In order to deal with this problem, plants typically use large amounts of lime to raise the pH to greater than 10.5 to depress pyrite. Lime consumptions can be quite high, and most plants run multiple lime kilns in order to generate enough lime, even though they are notoriously energy inefficient. The collectors developed by Nag allow for the flotation of copper ores at pH 9.5, resulting in significant energy savings. These reagents, now in use at multiple mining operations around the world, also brought unprecedented dose-efficiency, leading to significantly reduced reagent footprint at mining operations. Plants in Africa are known to use as little as 1ppm of this family of reagents to achieve desired performance, as compared to 20-30ppm of other reagents.

- **New Collectors for PGMs and gold: Nag developed a new family of modified dithiocarbamates**^[8]. When using these reagents by themselves, the recovery of metallics improved considerably, and in combination with existing reagents, overall Au and sulphide recovery could be improved. As a result these reagents are now in use at multiple Au operations around the world.

Nagaraj's productive career has been characterised by the application of good fundamentals to the solution of practical problems in flotation, elevating both the academic and industrial communities.

Nag obtained his Doctorate from Columbia University in Mineral Engineering & Applied Surface Chemistry in 1979; M.Sc in Electro-hydrometallurgy and B.Eng (Metallurgy) from Indian Institute of Science in 1974 and 1972; and B.Sc (Chemistry) from Bangalore Univ, India in 1969. He joined American Cyanamid (then becoming Cytec Industries and now Solvay) in 1979. His main focus at Solvay is Research and Development of new



reagents for the mineral industry. He has received many special recognition awards and three major awards, most notably the Mining Lantern Award for outstanding career contributions at Cytec, and twice the Circle of Excellence awards for specific scientific achievements. In 2015 he was promoted to the position of Principal Research Fellow in recognition of his long time achievements as a scientist and a technologist.

He has a strong background in organic/analytical/coordination chemistry, minerals processing, hydrometallurgy, water-soluble polymers, surface and colloid chemistry, applied electrochemistry, and statistics/experimental design. He is well known in the industry for his expertise in the area of flotation reagents, plant process diagnostics and problem solving, and in fundamental chemistry aspects of mineral separations. He holds 23 patents and has published 85 papers. Nag has mentored over 30 summer interns and university exchange students and is well known in both the industry and the academic world. He has successfully transferred fundamental knowledge to practice. He has served on several doctoral dissertation committees. In addition to presenting his work in the academic circles, he has lectured extensively in most of the major mineral processing companies around the world.

Nag has more than 35 years of outstanding and innovative achievements in the design, development and commercialisation of numerous families of novel flotation reagents and in advancing the art and science of flotation agents. The reagents developed by him brought unprecedented dose-efficiency, and are now in use at multiple mining operations around the world. This has led to significantly reduced reagent footprint at mining operations. He has also developed many organic and polymeric complexing agents for the removal of toxic metals from effluents and process streams.

He has conducted many workshops in the industry on a variety of minerals processing topics, and particularly on the fundamental and practical aspects of flotation reagent chemistry and applications. One of his notable contributions to the field of flotation reagents has been in bringing a rational scientific basis for reagent design for

mineral separations. He is well known for his pioneering work in the use of SIMS surface analysis technique to solve many long-standing problems in minerals processing plants. He used the Insights gained from these studies to develop new flotation reagents. Nag has also written several popular papers with a highly critical analysis, and these have served to dispel the myriad misconceptions in flotation practice and to provide practical guidelines for plant operators. Recently he developed a holistic approach to reagent selection and optimisation in flotation. The concepts developed are applicable to many complex mineral processing systems.

He has been an active member of SME since 1974. He was a member of the MPD Executive Committee and served as committee chair in 2009. He has actively served in the MPD Fundamentals Committee for 15 years; was Chairman of this committee in 1998; has presented papers, organised and chaired sessions regularly at SME, and in International conferences. Nagaraj was invited to present keynote lectures at the 2008 *International Mineral Processing Congress* in Brisbane and 2015 Flotation Conference in Cape Town. He has also participated in many regional SME meetings. He introduced many new sessions in the SME annual meetings with a view to bridge the gap between fundamental research and practice. He served on the Taggart Award committee. He is a recipient of the Gaudin Award of the Mineral Processing Division of the SME in 2005, and the Frank. F. Aplan Award of the AIME in 2005. Nagaraj served as the Co-Editor in Chief of the *International Journal of Mineral Processing* (IJMP) from 2007-2014, and continues to be a regular reviewer of papers for *Minerals and Metallurgical Processing*, *IJMP*, *Minerals Engineering*, *Colloid and Surface Science*. Nag was a regular contributor for many years to the Annual Review issue of *Mining Engineering*.



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