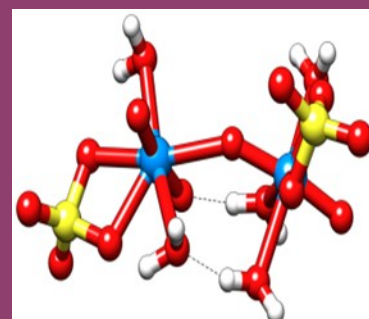
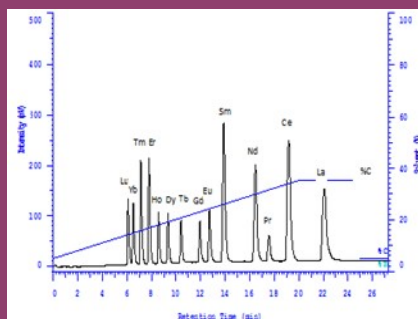




# ASSET Bulletin on Separation Science



Separation Science in Health, Environmental  
and Nuclear Technology

**Editor: Dr. S. Jeyakumar**

***Editorial***

Separation methods and techniques, an enabling science, emerging with new trends in all fields of science. As you have witnessed, for the benefits of students, academicians and young researchers of other arena, ASSET has been bringing out bulletins of a particular theme. This bulletin is a special issue to be released on the occasion of e-SESTEC-2020. However, this one is different from the other bulletins. There are six articles narrating the role of separation science in some specific achievements in the field of health, environment and nuclear technology.

Separation of radioisotopes with required radiochemical purity from the fission products, their applications in radio pharmaceuticals /radionuclide therapy, separation processes associated with the synthesis of nano-materials used for the sorption of toxic pollutants, individual separation of actinides and lanthanides, a prime requirement in nuclear fuel cycle, are the highlights of these articles. An interesting article from computational chemistry is included which reports how efficient extractants for heavy metals were designed with the support of computational chemistry.

I wish to record my heartfelt thanks to all the contributing authors for their efforts in submitting the articles in a short span of time. I thank Dr. Sumit Kumar, Dr. Vijay Telmore and Dr. P.G. Jaison for their kind support. My special thanks to Mr. M.K. Das for his untiring efforts in preparing this bulletin.

**Contents**

|  |    |
|--|----|
| President's Message  |    |
| Development of $^{106}\text{Ru}$ Plaques for the Treatment of Eye Cancers: A Make in India Initiative towards Atmanirbhar Bharat | 01 |
| <i>D. Banerjee, G. Sugilal and C.P. Kaushik</i>  |    |
| Use of nanomaterials for sorption of toxic species   | 09 |
| <i>Jayshree Ramkumar and S.Chandramouleeswaran</i>   |    |
| Speciation and Separation of Fission Products in Different Environments: A Quantum Chemical Perspective                          | 17 |
| <i>M. Sundararajan</i>   |    |
| Individual Separation of Lanthanides and Actinides using High performance Liquid chromatography                                  | 23 |
| <i>Vijay M. Telmore, Pranaw Kumar and Jaison P.G.</i>  |    |
| Preparation of $^{177}\text{Lu}$ -Trastuzumab for Cancer Care: Role of Separation Sciences                                       | 30 |
| <i>Mohini Guleria &amp; Tapas Das</i>  |    |
| Radiation grafted functional polymers for water purification   | 35 |
| <i>Virendra Kumar</i>  |    |

## President's Message



Prof. Pradeep Kumar Pujari  
President, ASSET

Dear Members,

It is a pleasant opportunity to address and greet you all. Keeping pace with the current developments in the field of Separation Science and Technology, ASSET has been making efforts in disseminating information on emerging trends in separation science to its members as well as to the scientific community through various means of communications including special bulletins, ASSET-Lectures, symposia etc. Indeed, ASSET gained reputation and recognition among the Indian Scientific Community.

Radioactive isotopes, or radioisotopes, are highly valuable in medicine, particularly in the diagnosis and treatment of diseases. A number of formulations involving radioisotopes are getting evolved to meet the demand of nuclear medicines. Indigenous development of  $^{106}\text{Ru}$  plagues at BARC, which turned to be a low-cost viable treatment for eye-cancer and preparation of  $^{177}\text{Lu}$ -Trastuzumab for cancer care, became feasible due to the separation process employed in separating radioisotopes either from the target or from fission products with required radiochemical purity.

The role of separation science in the synthesis of radiation grafted polymeric supports for removing toxic pollutants in industrial effluents and in the synthesis of nanoparticles for the sorption of toxic species is significant. Similarly, with the aid of computational chemistry the extractants are designed to achieve better separation factors. Conventional separation procedures are replaced with modern separation techniques such as HPLC etc., in realising individual lanthanide and actinide elements, a prime requirement in the nuclear fuel analysis. ASSET is presenting this bulletin on the theme, role of separation science in health care, environment and nuclear technology.

I am sure the members will find this bulletin interesting, informative and beneficial to the separation scientists.

***Separation Science in Health,  
Environmental and Nuclear technology***

## ***Development of $^{106}\text{Ru}$ Plaques for the Treatment of Eye Cancers: A Make in India Initiative towards Atmanirbhar Bharat***

**D. Banerjee, G. Sugilal and C.P. Kaushik**

Nuclear Recycle Group  
Bhabha Atomic Research Centre, Mumbai-400085, India  
Corresponding Author: *D. Banerjee*  
Email: [daya@barc.gov.in](mailto:daya@barc.gov.in)

### **Introduction**

Though eye cancer is an uncommon disease and its represents only about 0.5 % of total number of cancer cases, the numbers eye cancer cases reported in India every year are quite significant. It can affect all age groups including newborns, children, adults and older individuals. In fact, children of age groups < 5 years are badly affected by the disease, retinoblastoma [1]. India alone accounts for around 25% of world retinoblastoma cases with about 1,500 new cases each year. It is the fact that a large number of cases go undetected during early days or unreported because of the lack of awareness. Fortunately, eye cancer is totally curable if diagnosed early. Therefore, increase of awareness about the symptoms of eye cancers and facilities available for the treatment of the ailment can save many lives. Symptoms, like white cat's eye, squint, any mass on the eyelid, unexplained decrease in vision, etc., warrant for eye checkup. Ophthalmologists in India together with NGOs and civil society are dedicatedly working for better public awareness about eye cancer and its cure.

Various contemporary modalities for the treatment of eye cancers are laser therapy, brachytherapy, radiotherapy, enucleation, chemotherapy, etc [2]. Among others, plaque

brachytherapy is very simple to use and very effective for restoring the vision and salvaging the eye. Presently, three radioisotopes viz.,  $^{106}\text{Ru}$ ,  $^{125}\text{I}$  and  $^{90}\text{Sr}/^{90}\text{Y}$  are used for treatment of various forms of eye cancer. In fact,  $^{106}\text{Ru}$  plaque brachytherapy was established in 1993 by Prof. Bertil Damato, who was an ophthalmic surgeon in Liverpool. Thereafter, it is being used extensively in Europe with excellent eye and vision salvage track record. Indian doctors are also using the plaques procured from M/s Eckert & Ziegler BEBIG, who has been supplying the plaques all over the world over last three decades. Very high cost of imported plaques restricts accessibility of the treatment to a small section of society. Recently, Bhabha Atomic Research Centre (BARC), Mumbai, India has developed  $^{106}\text{Ru}$  plaques of two different configurations (round and notched) utilizing entirely indigenous technology [3]. Plaques have been used successfully for treatment of patients at different hospitals. The present indigenous development will now allow greater penetration of the treatment and positively impact more lives. Highlights of the development are reported in this paper.

### **Characteristics of $^{106}\text{Ru}$**

The unique decay characteristics of  $^{106}\text{Ru}$  are presented in Figure 1.  $^{106}\text{Ru}$  has a half-life of

about one year and it is a low energy beta emitter. However, its daughter,  $^{106}\text{Rh}$  emits high energy beta radiation (3.54 MeV) which is used for the treatment of eye cancer. Further, the limited range of beta radiation helps in delivering a sufficient dose to the tumor while minimizing collateral damage to healthy parts of the eye.

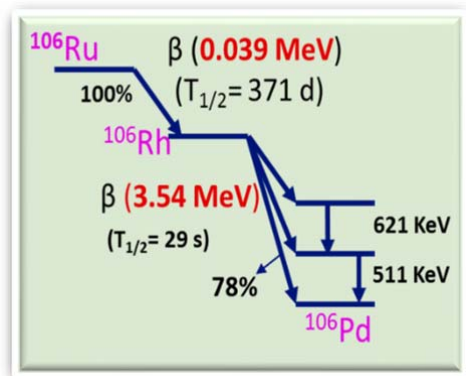


Figure 1: Decay characteristics of  $^{106}\text{Ru}$

**$^{106}\text{Ru}$  Source**

$^{106}\text{Ru}$  is produced in nuclear fission reaction of  $^{235}\text{U}$  with a fission yield of around 0.4%. Closed fuel cycle adopted by India enables recovery of valuable radionuclides from the high level wastes generated while reprocessing of the spent fuel.

**Process steps for the preparation of  $^{106}\text{Ru}$  based plaques**

The overall process steps for the production of  $^{106}\text{Ru}$  plaque is represented in Figure 2. The major steps include (i) separation of the radioelement in radiochemically pure form, (ii) electrodeposition of Ru on silver substrate and (iii) sealing of the source. The sealed source is then subjected to extensive quality control tests which will be discussed in later part of the manuscript.

**Process for the separation of Ru from radioactive waste**

For management of high level waste generated from reprocessing plants, India follows partitioning of long lives minor actinides and

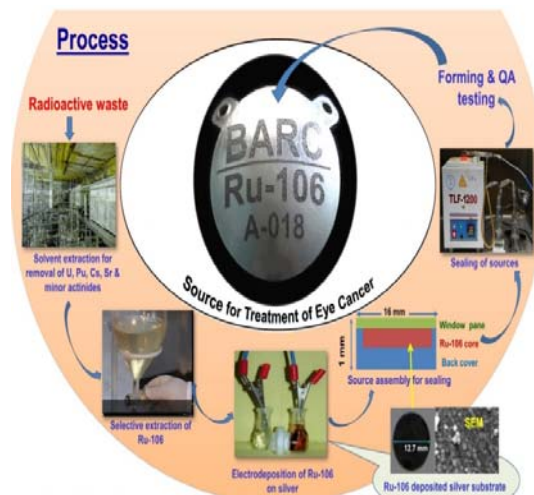


Figure 2: A thumbnail view of the process for production of Ru Plaque

high yields fission products such as  $^{137}\text{Cs}$  and  $^{90}\text{Sr}$ . Adaptation of this innovative scheme not only helps in effective management of the high level waste but also opens up the possibility to use several recovered radionuclides in various medical and industrial applications. The low active solution generated from the partitioning process is relatively clean and has substantial amount of  $^{106}\text{Ru}$ . It is to be noted that the  $^{106}\text{Ru}$  solution required for brachytherapy applications should be radiochemically pure.

For the recovery of Ru from HLW, oxidation of the nitrosyl Ru species to volatile  $\text{RuO}_4$  followed by collection of the generated gas either by distillation or extraction in  $\text{CCl}_4$  is being practiced [4]. The optimized process flowsheet for the recovery of Ru is given in Figure 3.

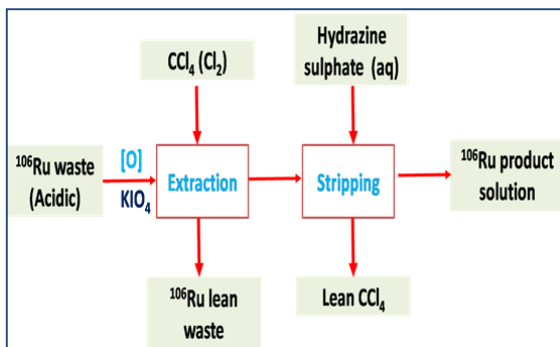


Figure 3: Flow sheet developed to purify  $^{106}\text{Ru}$  from high level waste

Figure 4 confirms the radiochemical purity of  $^{106}\text{Ru}$  product solution, analyzed using HPGE detector for gamma emitting radionuclides and ZnS for alpha.

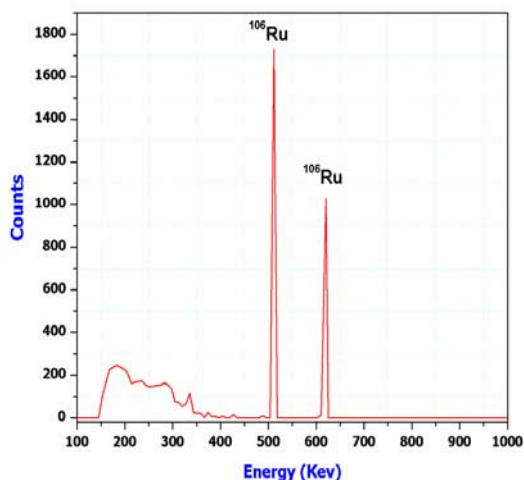


Figure 4:  $\gamma$  spectrum of Ru(III) solution obtained after stripping

#### Electrodeposition of $^{106}\text{Ru}$

$^{106}\text{Ru}$  in product solution was dried and the residue dissolved in 1 % sulphamic acid was used as catholyte. The  $^{106}\text{Ru}$  was electrochemically deposited on Ag cathode using Pt anode and sulphamic acid as anolyte. Typical electrolysis conditions involve passing of DC current of 10 – 20 mA for a period of 30 min to 4 hours for deposition of around 0.5-1 mCi of  $^{106}\text{Ru}$  activity on the disk. Optimum

conditions for electrodeposition were ascertained from the study of SEM micrograph of the electrodeposited disk with inactive Ru solution. Figure 5 presents the X-ray elemental mapping of the sample (Ru in shown in red and Ag in blue colors) in the SEM image, confirming reasonably uniform deposition on Ru on Ag sheet. The inset of the Figure 5 representing elemental profile of the sample obtained from EDX analysis.

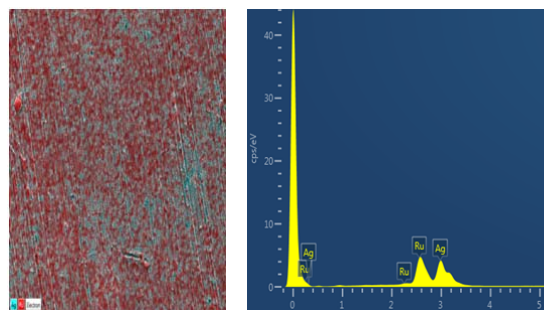


Figure 5: X-ray elemental mapping of the sample (Ru in shown in red and Ag in blue colors) in the SEM image, inset represents elemental profile of the sample.

#### Fabrication of Plaque

The Ru deposited cathode is used for plaque preparation. The plaque consists of a 0.9 mm thick Ag backing plate, the 0.2 mm thick Ru coated Ag substrate and a 0.1mm thick Ag window. The entire assembly was sealed by brazing. Post brazing, the plaque was bent to the required radius using a die.

#### Quality assurance tests

Each fabricated plaque is subjected to stringent quality controlled tests as per the list given in Table 1. All the tests are carried out as per the AERB SS3 guidelines [5]. Good manufacturing practices (GMP) are followed in all stages of source fabrication and in all quality assurance test. Adaptation of GMP ensures its quality as medical products. Table 1 gives a list of quality

assurance tests carried out for each <sup>106</sup>Ru plaque.

**Plaque configurations**

Employing above mentioned procedures, plaques of two different configurations, as shown in Figure 6, have been developed and deployed for the treatment of eye cancers. The round plaque is useful for the treatment of retinoblastoma, uveal and choroidal melanomas. Almost 40% of eye cancer patients can be treated using this plaque design. The notched plaque is useful for treatment of eye cancers located near the optical nerve. Unique design of the plaque facilitates selective dose delivery to the tumor while sparing the optical nerve, which is the most important part of the eye. The plaques are available with a wide range of activities, with low dose rates chosen for smaller tumors, typically prevalent in children. The high active sources are useful for treatment of larger tumors up to 6 mm in height. Almost 50% of eye cancer patients can be treated with this plaque. Each plaque can treat multiple patients over a period of one year.

**Table 1: List of quality assurance tests carried out for each plaque <sup>106</sup>Ru**

| Sl. No. | Test Name          | Conditions                    | Objective                       |
|---------|--------------------|-------------------------------|---------------------------------|
| 1       | Bubble tests       | In hot glycerin.              | Sealing integrity of source     |
| 2       | Homogeneity test   | By exposing radiochromic film | Activity distribution on plaque |
| 3       | Leak testing       |                               |                                 |
| 3.1     | Immersion tests in | Water (100 mL)                | Sealing integrity of            |

|     |                                     |  |   |
|-----|-------------------------------------|--|---|
|     | boiling liquid                      | at boiling conditions for 10 min, 3 times          | source                                  |
| 3.2 | Immersion tests in hot liquid       | Water (100 mL, 50 °C) for 4h                       | Sealing integrity of source             |
| 3.3 | Immersion tests at room temperature | Water (100 mL) at room Temp, for 48 h              | Sealing integrity of source             |
| 4   | Activity measurement                | Radiometric counting of <sup>106</sup> Ru          | Quantification of deposited activity    |
| 5   | Dosimetry                           | Exposing EBT3 films keeping at different distance. | Determination of the dose depth profile |
| 6   | Sterilization                       | Autoclave at 121° C, 14.5 Psi pressure, 20 min     | Sealing integrity of source             |

**Performance evaluation of <sup>106</sup>Ru plaques**

Presently, 10 plaques are in use for treatment of eye cancers at different hospitals of our country. The first use of the round plaque was carried out by Dr Santosh Honavar at the Centre for Sight Hospital, Hyderabad in treating a patient with ocular surface squamous neoplasia. The results of the intervention was very encouraging, no evidence of local tumor recurrence, while complete vision was maintained. Thereafter,



sources have been used in multiple occasions at that centre and also in other hospitals of country



**Round Plaque  
(Type A)**  
Diameter: 15.8 mm)  
Activity: 20-30 MBq



**Notched Plaque  
(Type N)**  
Diameter:21.0 mm  
Activity: 30-50 MBq

Figure 6: Different configurations of  $^{106}\text{Ru}$  plaques: (a) Round and (b) Notched

namely Sankara Eye Hospital, Bangalore; Dr. Rajendra Prasad Eye Hospital, AIIMS, Delhi; Hinduja Hospital, Mumbai; and Fortis hospital, Gurgaon. More than 15 patients have been treated so far with excellent post treatment results in all cases.

### Conclusions

Bhabha Atomic Research Centre (BARC), Mumbai, has developed BARC Ru-106 plaques of two different configurations (round and notched) and successfully deployed for the treatment of eye cancers. The stringent quality control measures and good manufacturing practices implemented for plaque production ensure medical grade quality of the plaque. Extensive performance evaluation of the plaques by the leading ophthalmologists in India qualifies the  $^{106}\text{Ru}$  plaques for eye cancer treatment. This is a significant achievement as

thousands of eye cancer cases are reported annually in India, requiring intervention by plaque brachytherapy. Previously, plaques were imported to meet these requirements at very high cost, restricting accessibility for the treatment to a small section of the society. The present indigenous development will allow greater penetration of eye cancer treatment and positively impact more lives.

### Acknowledgements:

The work presented in this paper is the result of dedicated work of many scientists and engineers of BARC. Authors wholeheartedly thank each of them for their contributions. Authors also gratefully acknowledge the contribution of Doctors and Radiation Physicists who were involved at different stages of plaque development and performance evaluation process. Special thanks to Dr. Santosh Honavar, Director Centre for Sight Hospital, Hyderabad; Dr. Atul Kumar, Chief, Dr. R P Centre, AIIMS Delhi, Dr. N. Lomi, Ophthalmologist Dr. R P Centre, Dr. Mahesh Sanmugam, Sankara Eye Hospital, Bengaluru, Dr. Vivekanand, Hinduja Hospital, Dr. S. Laskar, TMC, Mumbai and Dr. Tamil Selvan, for their valuable contributions.

### References

1. H. Mishra et al., A review on retinoblastoma: Most common intraocular malignancy in childhood, *Int. J. Sci. Res.*, 2017, 6(9), 197 – 199
2. B. Chawla et al., Conservative treatment modalities in retinoblastoma. *Indian J Ophthalmol.* 2013;61(9):479–485. doi:10.4103/0301-4738.119424.

***Separation Science in Health, Environmental and Nuclear technology***

3. P. Sinharoy et al., Development of  $^{106}\text{Ru}$  bearing sealed source for eye cancer treatment applications, BARC Newsletter, 1-4, 2018.
4. P Sinharoy et al., Separation of radio-chemically pure  $^{106}\text{Ru}$  from radioactive waste for the preparation of brachytherapy sources: an insight of process development study, Separation Science and Technology, 1-7, 2020
5. AERB safety standard no. AERB/SS/3 (Rev. 1) Approval Date October 5, 2001.



Dr. D. Banerjee obtained M.Sc. (Chemistry) from Burdwan University (West Bengal) and joined BARC in 1998. After graduating from 42<sup>nd</sup> batch of BARC Training school, he joined Process Development Division of Nuclear Recycle Group. He obtained Ph.D. degree in Chemistry, from Homi Bhabha National Institute (HBNI), Mumbai in 2012.

His research interests include development of processes for the treatment of radioactive liquid waste, recovery of valuable radionuclides from radioactive waste and fabrication of sealed sources for radiation technology and brachy therapy applications. He is a recipient of Scientific and Technical Excellency award 2008 and Group Achievement Award 2009 for contribution in the treatment of technetium and ruthenium rich alkaline intermediate level waste. He has about 90 publications to his credit in various international journals and symposia.

## ***Use of nanomaterials for sorption of toxic species***

**Jayshree Ramkumar\* and S.Chandramouleeswaran**

Analytical Chemistry Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400085, India

\* Corresponding Author: *Jayshree Ramkumar*

Email: [jrk@barc.gov.in](mailto:jrk@barc.gov.in)

### Introduction

The increasing rate of anthropogenic activities and industrialization causes great apprehension regarding the effect on environment. Environment is defined as the sum total of all the living (animals, birds, plants) and non-living elements (water, soil, air) and their effects which influence human life. The technological advancements result in the contamination of various environmental media like ground water. The removal of these unwanted species is known as remediation. The unwanted species discharged into the media can be referred to as contaminants or pollutants and it is to be understood that there is a slight difference between the two terms. Contaminant is a substance (biological, chemical, physical, or radiological which is otherwise absent in the environment) found under certain natural or man-made conditions while pollutant is the contaminant which causes adverse effects to human health which can be long- or short-term. Hence it is clear that “not all contaminants are pollutants but all pollutants are contaminants”. Thus one can realize contaminant is any substance present at wrong place and wrong time. But however, it is present in wrong quantity, and then it becomes a pollutant. This can be understood by the famous quote of Paracelsus which says “All substances are poisonous, there is none that is not a poison; the right dose differentiates a poison from a remedy”[1]. The different pollutants may be of different nature namely inorganic (heavy metal / radioactive cations, anions), organic

(dyes) or biological (bacteria, virus). Since these species are toxic in nature, there is limit to their concentration in ground water as specified by regulatory boards like WHO [2]. There are several techniques like membranes separation [3] which have been used to remove the species of interest. Speciality polymers like Nafion have excellent applications including separation due to their unique properties [4]. Of all the protocols, sorption using various types of materials are found to be attractive as it is economic and easy to prepare [5]. Nanomaterials are a class of materials with unique properties and have varying applications due to their small sizes in the range of 1-100 nm. Nanoxides show excellent applications due to their well defined crystalline structures and shape [6]. Since the nanomaterials have large surface area, their applications for sorption of toxic species seems quite viable [7]. There are other criteria that the nanomaterials should satisfy for their use as sorbents for environmental remediation. The first requisite is that these materials themselves should not be toxic and it is more beneficial if the nanomaterials have multifunctional properties (antimicrobial).

Another important aspect is the recyclability and reuse of the nanomaterials which plays a great role. This enables the use of highly exotic materials as sorbents. The removal of pollutants from the environment can be either through sorption or degradation, based on the reactivity of the nanomaterial used and the pollutants. The main advantages of nanosorbents

is the ability to fine tune the properties by changing the various characteristics (shape, size, morphology etc) of the nanomaterial. Magnetic sorbents have an additional advantage of being easily separated from aqueous solution after use. Nanomaterials can be used as such or have their surfaces suitably modified.

The main problem associated with nanosorbent is its recyclability from the aqueous solution (due to the small particle size and superior dispersive properties) and this limitation can be circumvented by nanocomposites. Nanocomposites possess properties that are amalgamation of those of individual components (two nanomaterials or nanomaterial/polymer or membrane) resulting in enhanced applicability of the composite due to excellent stability and sorption or permeability properties.

In this overview, the results of our studies on the use of nanosorbents for the removal of various toxic species have been discussed.

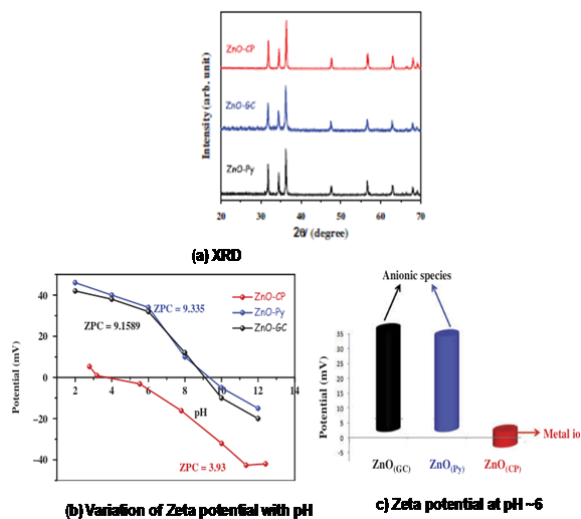
**Studies using nanosorbents**

The removal of fluoride ion from aqueous solution was studied using nanocrystalline magnesia-alumina mixed oxide ( $Mg_{0.80}Al_{0.20}O_{1.10}$ ) prepared by combustion synthesis method. It was seen that sorption was achieved at near neutral conditions within a period of 1h with a capacity of 10mg/g [8].

Nanooxides of manganese, iron and mixed oxide of cobalt/iron were used for the removal of lead ions from solution [9]. Nanocrystalline ferrites were prepared by combustion synthesis while alkaline hydrolysis of  $KMnO_4$  was carried out to synthesize  $MnO_2$ . The sorption was found to be maximum at pH of 6 and time period required was 3h using 0.1 g of oxide. However, with  $MnO_2$ , the sorption was maximum

at the same pH (~ pH 6) but the sorption was completed with 0.5h using 0.05g of sorbent [9]. Manganese oxide was further evaluated for the sorption studies of uranyl ion and other transition metal ions at room temperature [10]. It was found that the maximum sorption of individual ions was achieved at different pH values and with varying times of equilibration. Thus it is seen that the separation could be achieved based on the pH and kinetics.

Zinc oxide nanoparticles (ZnO NPs) are multifunctional in nature and therefore are associated with large number of applications. In the use of ZnO NPs as sorbents, it was seen that the surface charge of the ZnO NPs could be fine tuned by changing the synthesis protocol adopted [11]. In this study, ZnO NPs were synthesized using three different methods namely pyrolysis, gel combustion and coprecipitation method and nanoparticles produced are designated as ZnO (PY), ZnO (GC) and ZnO (CP) respectively.



*Fig.1: Characterization studies of different ZnO NPs*

The XRD patterns shown in Fig 1(a) confirmed that all the three protocols resulted in pure crystalline ZnO NPs with same crystalline structure. The average crystallite size in the range

of 20-46nm. The surface charge is a very important factor in deciding the nature of the applications. The effect of pH on surface charge shows that with increase in pH, there values decrease towards negative value through zero. The pH at which surface charge is zero is known as the point of zero charge (pHpzc) and the values are 3.93, 9.1 and 9.3 for ZnO(CP), ZnO(GC) and ZnO(Py) respectively (Fig.1b). It is also crucial to know about the surface characteristics in near neutral conditions. It is seen that at this pH of ~6, the negative surface of ZnO(CP) makes it suitable for sorption of metal ions while the positive surface of ZnO (GC) and ZnO (Py) makes it suitable for anionic species (Fig1(c)). However prior to this work, the ZnO NPs were synthesized independently and had been evaluated for their sorption behaviour. But it was in the present study, a correlation between the surface charge and the actual application could be understood completely.

ZnO NPs synthesized using co-precipitation method was found to have a very highly selective sorption with respect to  $\text{Cu}^{2+}$  ions with a capacity of 400mg/g [12]. It was also seen that the sorbent could be recycled to five cycles without a significant decrease in its sorption capacity (Fig.2).

ZnO NPS synthesized by pyrolysis (ZnO(PY)) and gel combustion (ZnO(GC)) were used for sorption of chromate [13]. The results are given in Fig.3. This is understandable that the surface charge was positive and so could take up anionic species. However it was interesting to note that these NPs showed uptake of cationic rhodamine 6G also. This could be explained as follows. One possible reason could be the change of cationic dye into neutral species with lactam structure and this

could fit within the porous structures of the ZnO NPs.

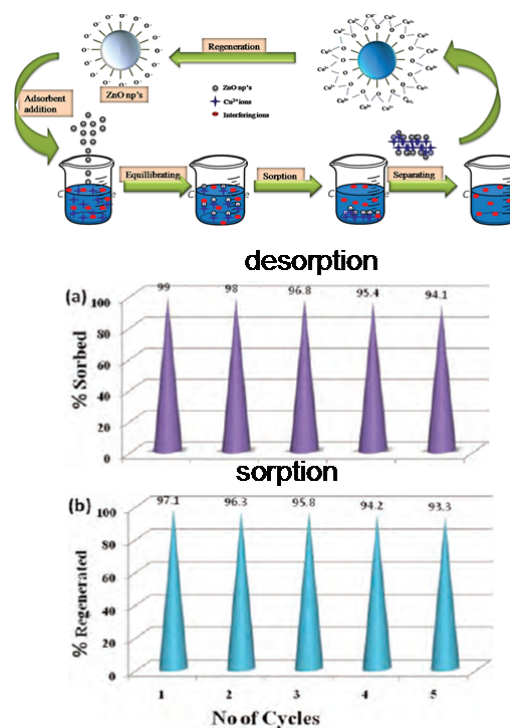


Fig.2: Sorption studies using ZnO (CP)

Further structural elucidation indicate the presence of very small amounts of organic precursors on the surface of nanoparticles which could combine with cationic dye due to hydrogen bonding. Since the amount of precursor on surface is very low, the amount of cationic dye sorbed was very low as compared to anionic chromate.

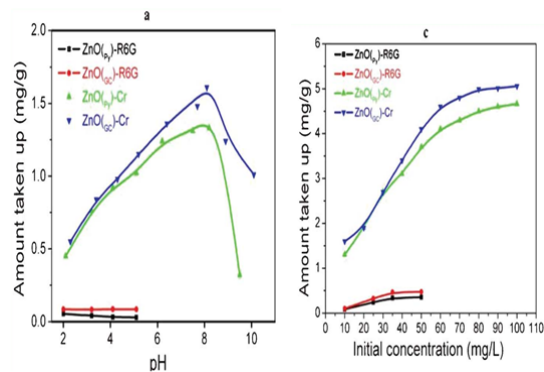


Fig.3: Sorption studies with ZnO (GC) and ZnO (PY)

The possible presence of precursor and its effect on sorption gave a clue to the fact that the surface modification of ZnO NPs using organic ligands could be carried out to make it selective towards heavy metal ions [14]. The thiourea and silanol group functionalized ZnO NPs designated as TU-ZNPs and S-ZNPs respectively were synthesized by a simple one pot-co-precipitation method followed by a facile ligand introduction onto the surface. The thiol-functionalized silica-capped ZnO nanoparticles (TFS-ZNPs) composite was also synthesized and compared for its sorption property. This technique could tailor the surface chemistry to impart the specificity and affinity toward the target analytes (Pb and Hg) depending on the ligand incorporated. It was seen from XRD that the process of functionalization does not alter the structure or size of ZnONPs but reduces the crystallinity. It was further observed that functionalization was restricted to the surface only. It was seen that the complete and highly selective sorption could be achieved within 15 mins. The high degree of selectivity can be seen from the results given in Fig 4.

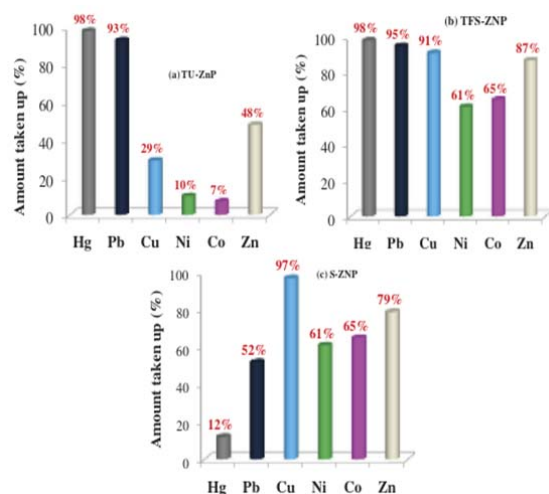


Fig 4: Sorption of different toxic metal ions by (a)TU- (b) TFS-and (c) S-ZNPs.

Studies using polyoxometalate (POM) nanostructures have been carried out for evaluation of their sorption capacity.

Super adsorbent properties of sonochemically synthesized nano BaWO<sub>4</sub> had been serendipitously discovered [15]. Flower shaped aggregates (~250 nm) of BaWO<sub>4</sub> (average size of ~10–15 nm) with a high surface area of ~148 m<sup>2</sup> g<sup>-1</sup>, could result in complete removal of cationic dyes (Rhodamine B (RhB) and methylene blue (MB)) within a short time span. Similarly barium molybdate (BaMoO<sub>4</sub>) nanoparticles synthesized via a simple sonochemical technique showed excellent sorbent properties with respect to toxic dyes like Rhodamine B (RhB), Malachite green (MG) and Methylene blue (MB) [16]. Regeneration of the sorbents is easily possible through simple thermal treatment and similar adsorption efficiency up to five consecutive cycles has been demonstrated [16]. The tungstate and molybdate nanostructures of manganese synthesized by sonochemical methods were found to show excellent sorbent characteristics with respect to dyes and copper ions from aqueous solution [17] due to very high surface area. Complete removal of dyes like Rhodamine B and Methylene blue was possible within 2–10 minutes. However the complete removal of copper is achieved within 15 mins using manganese tungstate while manganese molybdate could achieve this in 300 mins. Fig.5 shows the representation of the results of all these sorption studies. CeVO<sub>4</sub> nanostructures were studied with an aim to understand the formation of solid solution formation [18]. The effect of Mo substitution on the structures and the possible implications on sorption behavior was evaluated.

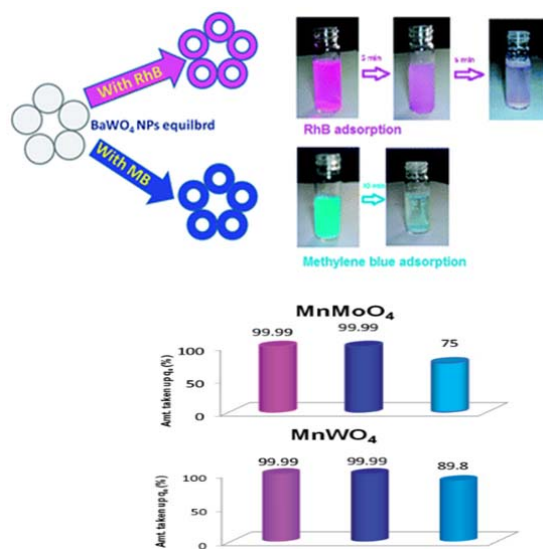


Fig.5: Sorption with tungstate / molybdate

It was seen that the introduction of Mo into the anionic framework yielded hierarchical mesoporous structures with substantial increase in surface area from 76 to 147 m<sup>2</sup>/g. These structures showed excellent uptake capacity of about 100mg/g for lead ions. In addition, the presence of Mo in CeVO<sub>4</sub> resulted in enhancement of kinetics of sorption (Fig.6).

Iron oxide silica nanocomposites have been used to evaluate the sorption efficiency with respect to different metal ions and cationic dyes[19,20]. The synthesis of magnetic nano-composites was carried out by simple co-precipitation iron in basic medium followed by in situ coating of SiO<sub>2</sub> using tetraethyl orthosilicate (TEOS). The detailed characterization of morphology showed that the Fe<sub>3</sub>O<sub>4</sub> nanoparticles was coated with amorphous silica of a shell thickness of 2–3 nm. These nanocomposite could be easily removed from solution after equilibration using external magnet. The sorption of transition metal ions like Zn<sup>2+</sup>, Co<sup>2+</sup>, Ni<sup>2+</sup> and Cu<sup>2+</sup> were evaluated [19]. In addition to transition metal ions, the nanocomposite was tested for the uptake of metal ions like uranyl ion also cationic dyes like Rhodamine 6G and

methylene blue [20]. The zeta potential measurements of surface charge helped in assessing the applicability of the sorbents.

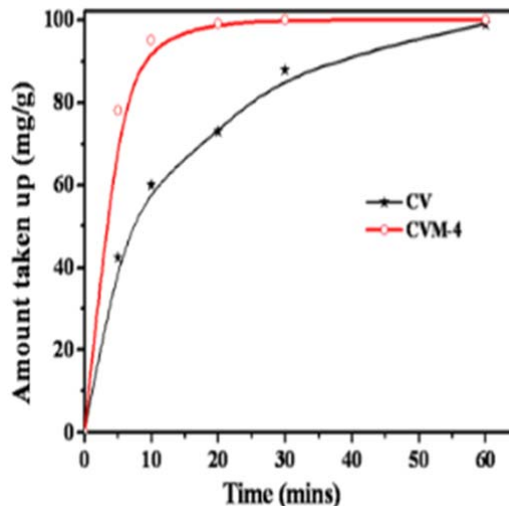
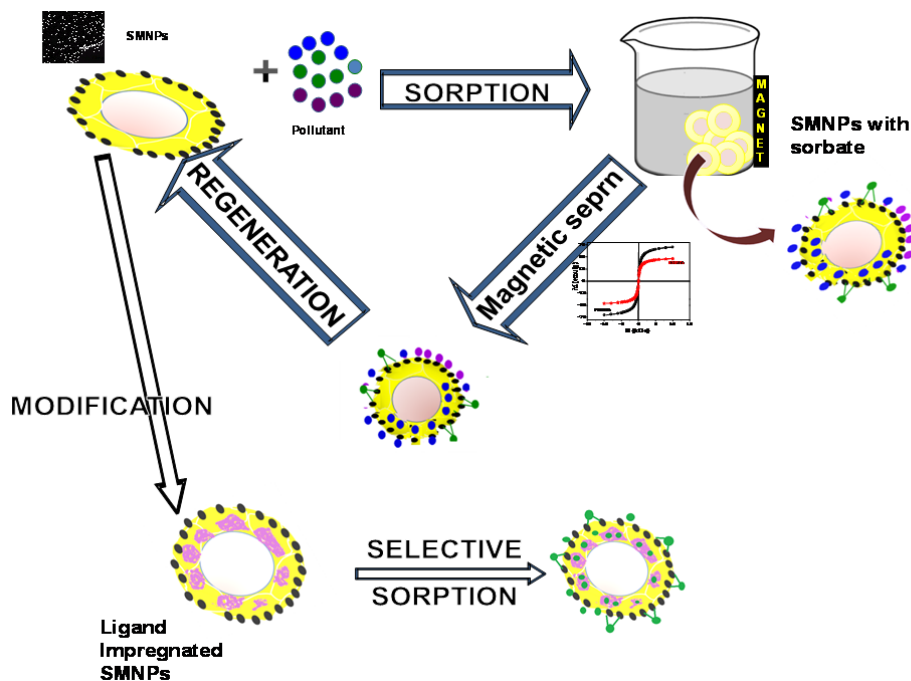


Fig.6: Effect of Mo substitution on sorption kinetics

The high porosity and large surface area of sorbent contributed to its excellent sorption efficiency. The selectivity towards uptake of Methylene Blue (MB) as opposed to that of Rhodamine 6G (R6G) was quite intriguing and detailed studies were carried out to understand this. Detailed investigations of sorption mechanism showed that both uranyl and zinc ions form complexes with silanol groups and can be present both on the surface and also within the pores of the mesoporous silica shell. Methylene blue is taken up by electrostatic interactions and a pore-filling mechanism operates. Copper, nickel and cobalt ions are taken up by electrostatic interactions with the surface silanol groups. Since the bare nanosorbent showed no selectivity in sorption of metal ions, modification was carried out to enhance selectivity with respect to uranyl ion by ligand impregnation. Fig.7 gives a schematic representation of the sorption process.



It also gives an idea of the surface modification carried out to make the nanocomposite selective towards uranyl sorption.



*Fig.7 : Schematic representation of sorption using magnetic nanocomposites*

**Conclusions**

In all these studies it was seen that the surface charge and structure of the nanomaterials plays a great role. It is seen that the surface charge can be fine-tuned using different synthesis protocols. Surface modification of nanoparticles improved the selectivity of sorption with respect to heavy metal ions like lead and mercury. Super sorption efficiency with excellent sorption kinetics with respect to cationic dyes could be achieved using exotic nanostructures. The use of magnetic nanocomposites and its subsequent modifications could be useful for achieving selective separation. From these studies it can be seen that for some species sorption is a surface phenomena while for other, pore-filling mechanism also plays a great role. Thus applicability of these nano-materials could be easily envisaged in a variety of applications.

**Acknowledgements**

The authors are thankful to Dr.A.K. Tyagi, Associate Director, CG, BARC for his constant support and technical interactions and Dr.C.N.Patra, Head ACD, CG, BARC for his support.

**References**

1. Jayshree Ramkumar, (2013). Cost Effective Sorbents for Environmental Remediation. Advanced Functional Polymers and Composites: Materials, Devices and Allied Applications. Volume 2., Chap 9
2. V. Geissen, H. Mol, E. Klumpp, G. Umlauf, M. Nadal, M. van der Ploeg, S.E.A.T.M. van de Zee, C.J. Ritsema, Int. Soil Water Conserv. Res. 3 (2015) 57-65
3. Jayshree Ramkumar, BARC NEWSLETTER 315 (2010) 39-42

4. Jayshree Ramkumar In book: Functional Materials, 2012 Eds: Banerjee and Tyagi, Elsevier, pp.549-577
5. S.Chandramouleeswaran, Jayshree Ramkumar, J.Hazard. Mater. 280 (2014) 514-523.
6. R.Shukla, Dimple P. Dutta, Jayshree Ramkumar, Balaji P. Mandal, Avesh K. Tyagi, In Springer Handbook of Nanomaterials, Ed: Robert Vajtai, 517-552
7. Jayshree Ramkumar, Arch. Nanomed. 1 (2018) 71-74,
8. R. Shukla, Jayshree Ramkumar, A.K. Tyagi, Int.J. Nanotech. 7 (2010) 989-1002
9. Jayshree Ramkumar, R. Shukla, S. Chandramouleeswaran, T. Mukherjee, A. K. Tyagi, Nanosci. Nanotech. Lett. 4 (2012) 693-700
10. J.Mukherjee, Jayshree Ramkumar, S. Chandramouleeswaran R.Shukla, A.Tyagi, J. Radioanal.Nuc.Chem. 297 (2013). DOI: 10.1007/s10967-012-2393-7
11. J.Majeed, Jayshree Ramkumar, S. Chandramouleeswaran, A. K. Tyagi, Sep.Sci.Technol. 50 [2015] 404-410,
12. Jerina H. Zain, Jayshree Ramkumar, S. Chandramouleeswaran, A. Tyagi, Adv. Por.Mater. 2 (2014) 69-78.
13. Jerina H. Zain, Jayshree Ramkumar, S. Chandramouleeswaran, A. Tyagi, RSC Adv. 3 (2013) 3365-3373.
14. Jerina Majeed, Jayshree Ramkumar, S. Chandramouleeswaran, A. K. Tyagi, Sep.Sci.Technol. 55 (2020) 1922-1931
15. A. Singh, Dimple P. Dutta, Jayshree Ramkumar, Kaustav Bhattacharya, A.K.Tyagi, M. H. Fulekar, RSC Adv., 3 (2013) 22580-22590
16. Dimple P Dutta, A.Singh, Jayshree Ramkumar, Kaustava Bhattacharya, A.K. Tyagi, M.H.Fulekar, Adv.Por.Mater. 2 (2014) 237-245
17. Dimple P. Dutta, Aakash Mathur, Jayshree Ramkumar and A.K. Tyagi, RSCAdv. 4 (2014) 37027
18. J.Hisham Zain, V.Grover, Jayshree Ramkumar, et al., J Mater Sci 55 (2020) 5690-5704
19. Jerina Majeed, Jayshree Ramkumar, S.Chandramouleeswaran, A.K.Tyagi, AIP Conf. Proc. 1591, 605 (2014); <https://doi.org/10.1063/1.4872690>
20. Jayshree Ramkumar, Jerina Majeed, S. Chandramouleeswaran, Micropor. Mesopor. Mater. 314 (2021) 110858.

## ***Separation Science in Health, Environmental and Nuclear technology***



Dr. Jayshree Ramkumar joined BARC through the 1 year orientation program (37th Batch of Training School) after the completion of MSc from University of Madras, Chennai. Subsequently she joined the Analytical Chemistry Division in 1994. Since then, she is involved in the development of new separation procedures for toxic species using a wide range of materials from bulk matrices to nanomaterials. She has also developed analytical sensors / methodologies for determination of metal ions like Uranium, Lead and cobalt in aqueous solutions. Her PhD was on the work on ion exchange and related studies using Nafion membrane. She was awarded the MANA Research Fellowship to carry out postdoctoral research at National Institute of Materials Science (NIMS), Ibaraki, Japan in 2009. She is Associate Professor of HBNI, Mumbai. She has more than 60 publications and three book chapters to her credit. She has given talks in various International and national conferences and also served as chairpersons in different conferences.



Shri. S.Chandramouleeswaran is presently working as SO/D in ACD, BARC., Mumbai His research interest includes Separation science using different matrices using like nanomaterials and membranes for removal heavy metal ions and various dyes and developing new analytical methodologies for trace and ultra trace characterisation in alloys, high purity material, environmental and geological samples. He has about 40 publications in international peer-reviewed journals and a book chapter to his credit.

## ***Speciation and Separation of Fission Products in Different Environments: A Quantum Chemical Perspective***

**M. Sundararajan**

Theoretical Chemistry Section, Chemistry Division, Bhabha Atomic Research Centre, Trombay, Mumbai  
400085, India

Email: [smahesh@barc.gov.in](mailto:smahesh@barc.gov.in)

### **Introduction**

With limited fossil fuel supply and an increasing population, the urge to satisfy their energy demands is a humongous task. Several alternate energy sources derived from Solar and good but remain insufficient and inefficient due to several technical issues. The discovery of nuclear fission reactions and the associated energy release can be efficiently used in the power generation. The Indian nuclear technology is well established and tested to be safe for more than 50 years. The beauty of the nuclear fission reaction is unique in a way that more than 30 elements are generated as fission products in a single reaction. These fission products are extremely valuable and it is foolish to dispose it as such. Particularly with limited uranium as fuel source and efficient reprocessing, we can selectively recover several radionuclides that are useful for societal applications. Several ligands are designed to selectively extract a metal ion from a mixture of fission products. For instance, calix-crown ether and TBPs are used for the extraction cesium ion and uranyl ion.

Designing novel ligands for the complexation of various actinide species has gained significant attention due to their importance in nuclear waste management.<sup>1</sup>The toxic radionuclides can pollute several environments from aquatic species, soil environment, etc. One possible way to control

their release into groundwater is to take advantage of the differing solubility of their different oxidation states. Strategies for reducing the mobility of these species usually center on their reduction to less soluble, lower oxidation state species, which in the case of uranium, for example, involves reduction of soluble U(VI) to insoluble U(IV). This process is facilitated by Multi-heme cytochromes in Bacteria and Iron containing mineral surfaces.<sup>2</sup> Thus, to design an efficient extractant, it is mandatory to know the speciation of the heavy metal ions in different environment at the molecular level. In this article, we showcase few examples from our computational laboratory on the speciation and design of extractants for heavy metal ions.

### **Computational Tools**

Performing experiments on toxic and or radionucleisuch as uranyl, chromate needs well equipped laboratories with high-safety standards are generally expensive. Additionally, some species are short lived intermediates with short half-life are often not identified in experimental time scale.The speciation of heavy metal ions can be studied at the molecular level using molecular modeling methods which is a four way challenge.<sup>3</sup> First, the accuracy and cost of performing computational modeling are inversely proportional.The most accurate and doable quantum chemical methods CCSD(T) methods are

considered as benchmarking quality methods for single reference wavefunctions. In the case of truly multi-configurational, a Complete Active Space Self Consistent Field (CASSCF) should at least be used to treat the ground state degeneracy, and the remaining dynamic correlation can be treated within the framework of MP2 methods such as CASPT2 and NEVPT2. [5]. Second, the heavy metal ions contain large electrons which should be handled with basis set. Both all-electrons and effective core potentials are available that should be carefully chosen to manage the computational cost.



*Fig.1. Four way Computational challenge.*

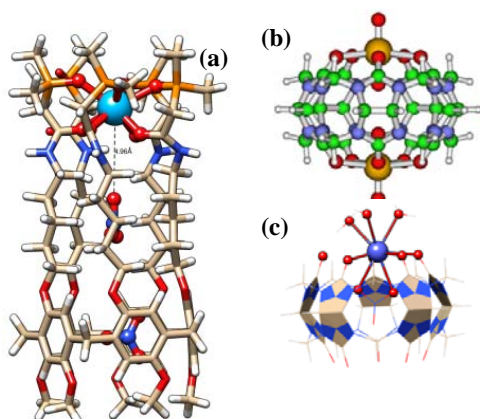
Third, most of the heavy metal ions are often charged species such as tris-nitrato-uranyl ( $[\text{UO}_2(\text{NO}_3)_3]^{1-}$ ). Either, the species is highly solvated or exist in the presence of counter-ions. In addition to the methods chosen above, one needs to take care of solvation as well. In this regard, either explicit solvation or implicit solvation with continuum models is often used. Last but certainly not the least, to some extent relativistic and multiplet effect should be considered approximately. In this regard, scalar relativistic ZORA and DKH methods often predict results at least semi-quantitatively. In fact, due to the large number of electrons in the heavy metal ions such as uranyl and the inner core electrons are often not involved in bonding, an effective core potential (ECP) is often used to model the inner core electrons. In this regard, a small core

(SC) ECP is superior over large core ECP due to the better description of valence electron in SC-ECP. It should be noted that some portion of relativistic effects are also incorporated in the ECPs which should predict ground state properties such as geometries and vibrational frequencies fairly well.

### **Supramolecular Separation of Heavy Metal Ions**

Supramolecular containers are versatile often mimic the enzyme. The rigid cavity of macrocycles modulates the speciation and binding of heavy metal ions that are similar to those of protein backbones. Typically, these host molecules are used to tune the photophysical and photochemical properties of host molecules. Upon functionalization, the host molecules become efficient ligands for the extraction of heavy metal ions. Pillar-arenes (PA) are largely hydrophobic in nature and upon functionalization with carbamoylmethylphosphine oxides (CMPO), they can be used for the selective extraction of Th(IV) ion in nitric acid and room temperature ionic-liquid medium.<sup>4</sup> DFT calculations are carried out to understand the speciation. DFT calculations clearly suggest the binding is stronger and the nitric acid weakly interact with Th(IV) ion (**Fig. 2a**).

Unlike PA, Cucurbiturils (CB[n]) are classic host molecule that can bind cations with large association constant ( $\log K_a$ ). In a theory inspired study, we have shown that uranyl ion can bind strongly with CB-[5] host molecule.<sup>5</sup> We have studied the binding in several conformers and we note that  $\mu$ -5 binding is the most favorable one (**Fig. 2b**). Experiments are conducted in parallel and surprisingly, X-ray data was released that our conclusions matched nicely.<sup>6</sup>



**Fig.2.** Optimized structures of (a) Th(IV) binding to functionalized PA[5], (b) uranyl and (c) Am(III) binding to CB-[5].

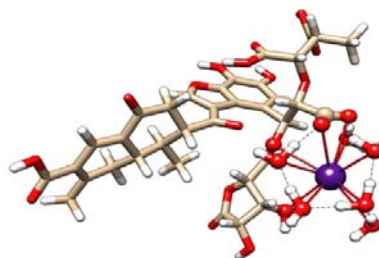
We have also provided the structure and binding affinities of several functionalized CB-[5] with [UO<sub>2</sub>]<sup>2+</sup>, [NpO<sub>2</sub>]<sup>2+</sup> and [PuO<sub>2</sub>]<sup>2+</sup> species. Experiments are yet to be conducted on these radionuclides with functionalized CB-[5].

We have also studied the Lanthanide/actinide separation with CB-[5] host molecule.<sup>7</sup> The portal oxygens of CB-[5] are hard-donors favorably bind Eu(III) ion compared to the soft-nature of Am(III) ion. The counter-anions dictate the binding energies that are elucidated from electronic structure calculations (**Fig. 2c**). Our calculations are later experimentally proved by Tomar and co-workers.<sup>8</sup>

### Computational Modeling of Geochemical Speciation of Heavy Metal Ions

Cesium (Cs<sup>137</sup>) and Strontium (Sr<sup>90</sup>) radionuclides are one of the high level wastes generated from the back end of nuclear fuel cycle. The migration of these radionuclides in soil largely depends on chemical and biological reactivity of soil

components. Soil Organic matter (SOM) is one of its essential component which is known to alter the mobility of radionuclide cations like Cs<sup>+</sup> and Sr<sup>2+</sup>. Shedding light on the possible interaction mechanisms at the atomic level of these two ions with SOM is thus vital to explain their transport behavior and, for the design of new ligands for the efficient extraction of radionuclides. We have performed state-of-the-art multi-scale model approach using metadynamics (MtD), molecular dynamics (MD) simulations and density functional theory (DFT) based calculations to understand the binding mechanism of Sr<sup>2+</sup> and Cs<sup>+</sup> cations to fulvic acid (FA), a model for SOM.<sup>9,10</sup>

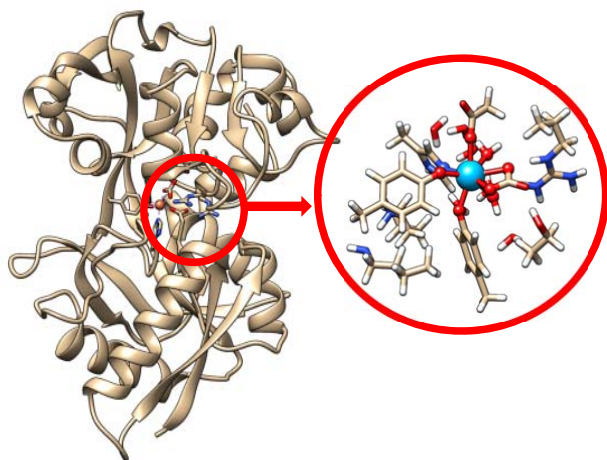


**Fig.3.** Optimized structures of Cs(I) binding to fulvic acid.

Our studies predict that interaction of Cs<sup>+</sup> to FA is very weak as compared to Sr<sup>2+</sup>. The water-FA interaction is largely responsible for the weak binding of Cs<sup>+</sup> to FA, which leads to the outer sphere complexation of the ion with FA. For Sr<sup>2+</sup>, the interaction between Sr<sup>2+</sup> and FA is stronger and thus can surpass the existing secondary non-bonding interaction between coordinated waters and FA leading to inner sphere complexation of the ion with FA, akin to the uranyl binding to FA.<sup>8</sup> We also find that entropy plays a dominant role for Cs<sup>+</sup> binding to FA, whereas Sr<sup>2+</sup> binding is an enthalpy driven process. Our predicted results are found to be in excellent agreement with the available experimental data on complexation of Cs<sup>+</sup> and Sr<sup>2+</sup> with SOM.

### **In Silico Design and Development of Decorporating Agents**

The possibility of plutonium (Pu) intake by radiation workers cannot be ruled out. Transportation of Pu(IV) to various organs/cells is mainly carried through iron-carrying protein, serum transferrin (sTf) (**Fig. 4**).<sup>11</sup> Understanding the Pu-sTf interaction is a primary step toward future design of its decorporating agents. Due to the obvious experimental difficulties, such as, handling of radionuclides associated with health and safety concerns, we have explored the use of multi-scale computational techniques to understand the Pu(IV) binding with sTf and look out for its decorporation at extracellular pH using suitable ligands. Our computational predictions unravel several key features that are necessary for the successful design of decorporating agents.



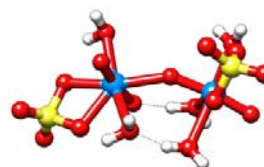
**Fig.4.**Optimized structures of Pu(IV) binding to blood serum transferrin.

Until now, we have screened two decorporating agents for Pu(IV); hydroxypyridinone (HOPO) and catechol (CAM)-based ligands. Pu(IV) at protein binding site (BS) is found to be strong that it was not detached with the docked HOPO, whereas CAM is found to facilitate dislodging the heavy ion from the protein's binding influence. Alternative

competing mechanisms are being explored in our computational laboratory.

### **Reduction Mechanism of U(VI) to U(IV) ion**

Reduction of  $\text{UO}_2^{2+}$  ions to  $\text{U}^{4+}$  ions is difficult due to involvement of two axially bonded oxygen atoms, and often requires a catalyst to lower the activation barrier. The noble metal nanoparticles (NPs) exhibit high electrocatalytic activity, and could be employed for the sensitive and rapid quantifications of  $\text{UO}_2^{2+}$  ions in the aqueous matrix. The mechanism of the electroreduction of  $\text{UO}_2^{2+}$  by the RuNPs/GC was studied using density functional theory calculations.<sup>12</sup>



**Fig.5.**Optimized structures of U(VI)-U(V) species.

The reduction pathway can be initiated through the electron transfer from the electrode to U(VI) species to form the reduced  $[\text{UO}_2\text{SO}_4(\text{H}_2\text{O})_3]^{1-}$  species. Upon reduction, the U=O bond length is elongated from 1.80 (in U(VI)) to 1.88 Å. Alternatively, the  $[\text{UO}_2\text{SO}_4(\text{H}_2\text{O})_3]$  species can dimerize through the formation of T-shaped complex (denoted as U(VI)-U(VI). In the T-complex, one of the uranyl is coordinated to the second uranium through the displacement of one water molecule. Although the formation of such dimeric species is slightly unfavorable (by 4.77 kcal mol<sup>-1</sup>), this weak complex can be anchored by two strong hydrogen bonding which can reduce to form U(VI)-U(V) species (**Fig. 5**). The formation of this species is favorable by -22.9 kcal mol<sup>-1</sup>. Of the two uranium centers, the added electron is delocalized between the two centers. As compared

to U(VI)-U(VI) species, the reduced U(VI)-U(V) species is strongly bound which are firmly held through hydrogen bonding interactions.

The U(VI)-U(V) can further reduced to U(V)-U(V) species which can undergo disproportionation which can be formed in two different pathways. In the first case, the two individually reduced U(V) species can form a T-shaped complex which is -32 kcal mol<sup>-1</sup> more favourable as compared to the two individual U(V) species. In this case, each uranium center has one unpaired electrons (~1.10e-) which are firmly held by hydrogen bonding interactions. However, in the second case, the reduced U(V) species can form a T-shaped complex with the U(VI) species, thus forming U(VI)-U(V) species. Finally, due to the acidic pH condition, protonation at the 'yl' oxygen is indeed feasible which can trigger the electron transfer from first uranyl center to the second center leading to the formation of U(VI) and U(IV) species (U(VI)-U(IV)). The proton affinity of U(V)-U(V) species is favorable by more than 300 kcal mol<sup>-1</sup> is approximately more than 40 kcal mol<sup>-1</sup> as compared to the hydration free energy of the proton(-265 kcal mol<sup>-1</sup>).

### Conclusions

In this article, we have shown several examples on the separation and speciation of several heavy metal ions in different chemical environments. We believe that Electronic structure calculations are extremely useful and can be truly predictive in nature if proper care is taken and not purely black-box type.<sup>13</sup>

### References

1. J. L. Sessler, P. J. Melfi, G. D. Pantos, Coord. Chem. Rev. 250 (2006) 816.
2. M. Sundararajan, R. S. Assary, I. H. Hillier, D. J. Vaughan, Dalton Trans. 40 (2011) 11156.
3. M. Sundararajan, BARC NewsLetter, (2016) 109.
4. A. Sengupta, M. Singh, M. Sundararajan, L. Yuan, Y. Fang, X. Yuan, W. Feng, M. S. Murali, Inorg. Chem. Commun. 75 (2016) 33.
5. M. Sundararajan, V. Sinha, T. Bandyopadhyay, S. K. Ghosh, J. Phys. Chem. A. 116 (2012) 4388.
6. S. Kushwala, S. A. Rao, P. P. Sudhakar, Inorg. Chem. 51 (2012) 267-273.
7. B. Sadhu, M. Sundararajan, T. Bandyopadhyay, Inorg. Chem. 55 (2016) 598.
8. N. Rawat, A. Kar, A. Bhattacharyya, A. Rao, S. K. Nayak, C. Nayak, S. N. Jha, D. Bhattacharyya, B. S. Tomar, Dalton Trans. 44 (2015) 4246.
9. B. Sadhu, M. Sundararajan, T. Bandyopadhyay, J. Phys. Chem. B 119 (2015) 10989.
10. M. Sundararajan, G. Rajaraman and S. K. Ghosh, Phys. Chem. Chem. Phys. 13 (2011) 18038.
11. L. Mishra, M. Sundararajan, T. Bandyopadhyay, J. Biol. Inorg. Chem. 25 (2020) 213.
12. R. Gupta, M. Sundararajan, J. S. Gamare, Anal. Chem. 89 (2017) 8156.
13. S. Ahn, M. Hong, M. Sundararajan, D. H. Ess, M.-H. Baik, Chem. Rev. 119 (2019) 6509.





Dr. M. Sundararajan is an experienced researcher who has completed his Bachelors (University second rank) and Mastersdegree (University third rank) in India. In this 5 years period, he received training in several advanced synthetic (JNCASR Bangalore, India) and computational chemistry laboratory (Bharathidasan University, Tiruchirappalli) in India. In 2002, he has received ORS (Overseas Studentship award) and URS (University research studentship) awards to pursue his doctoral studies at the University of Manchester with Prof. Ian H Hillier. During his PhD he studied the structure function relationship of iron and copper containing proteins. He has developed semi-empirical parameters for iron to incorporated with the multi-scale modeling methods to understand the redox properties of electron transfer proteins. After the completion of his PhD, he worked on more challenging topic which is relevant to bio-remediation of toxic heavy metal ions using metalloproteins. The bio-reduction mechanism of uranyl and chromate using electron transfer proteins is proposed by the applicant which is now widely recognized through the formation of dimeric uranyl species. The applicant also received an Alexander von Humboldt Fellowship to pursue post-doctoral research at the University of Bonn, Germany in the group of Prof. Frank Neese. In this two year stint, he calibrated the density functionals for low spin iron nitro species and he explored the use of advanced spectroscopic properties of metalloproteins such as Myoglobin and copper proteins. In 2010, he joined the present institute through K. S. Krishnan Research Associateship and latter adsorbed as Scientific officer. Presently his research interests are centered towards modeling the speciation of heavy metal ions in different environments which is directly relevant to nuclear waste management processes, a trust area of research within department of atomic energy. He is actively involved in solving complex chemical problems relevant to back-end-of the nuclear fuel cycle. As India follow the open-nuclear cycle policy unlike the western world, the reprocessing is spent nuclear fuel is one of the key areas of research in the institute. Due to the health and safety requirements, the use of computational chemistry techniques to model such toxic radionuclides become very hand. He has published over 60 research articles in international journals which includes two book chapters. Further, he has published over twenty articles as corresponding authors in reputed international journals. The applicant also has strong collaboration within the institute (such as Prof. S. Kannan, Prof. H. Pal), nationally (Prof. G. Rajaraman, IIT Bombay, Prof. M. Jaccob, Loyola College, Prof. A. Dutta, IIT Bombay) and internationally (Prof. F. Neese, MPI-Mulheim, Germany Prof. C. A. Morgado, Universidad Técnica Federico Santa María, Av., Valparaíso, Chile.) Since joining the present institute, the applicant has guided more than 10 students though summer research fellowship. The research work carried out from the present institute is cited and received well by national and international community. For designing novel nanomaterials for nuclear waste management, he received the young scientist award of chemical sciences in 2012. In 2015, he was conferred with Department of Atomic Energy Young Scientist Award for outstanding contribution in theoretical and computational chemistry.

## ***Individual Separation of Lanthanides and Actinides using High Performance Liquid Chromatography***

**Vijay M. Telmore, Pranaw Kumar and Jaison P.G.**

Fuel Chemistry Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400085, India

(Corresponding Author: *Jaison P.G.*; Email: jaipg@barc.gov.in)

### **Introduction**

The understanding that the use of small particles and high pressures is essential to improve the separation efficiency in chromatography, has paved the way for the establishment of high performance liquid chromatography (HPLC) [1]. Improvements in instrumentation, column technology and theory led to rapid and high resolution LC separations. Application of HPLC with on-line detection has reduced the analysis time from days to a few minutes because of its speed and sensitivity [2]. Separation and determination of lanthanides and actinides are of great importance in nuclear technology, geochemistry, environmental sciences, material science, etc [3]. High resolution separation of lanthanides is important in nuclear technology for the burn-up determination of irradiated fuels and for the characterization of nuclear fuels with respect to trace constituents [4,5]. Separation of Th, U and Pu is required to minimize the isobaric/spectral interferences during the quantitation or atom ratio measurements by mass spectrometry [6].

Individual separation of lanthanides is a challenging task in view of their similar electronic configuration and nearly same ionic radii. The use of complexing agents as eluents in the ion exchange chromatography helps to amplify the slight differences in the stability constants of the Ln-eluent complexes and leads to better separations. Ion interaction chromatography (IIC)

was employed for the separation of individual lanthanides in view of the fast mass transfer and the flexibility to modify the column capacity.

### **Instrumentation**

The HPLC system consisted of a low-pressure quaternary gradient pump and a diode array detector. C<sub>18</sub> monolith RP column, C<sub>18</sub> particulate RP column and C<sub>8</sub> particulate reversed-phase (RP) column were used as the stationary phases. Solutions were injected into the column using a Rheodyne injector with 20  $\mu$ L or 100  $\mu$ L sample loops. The eluted components were monitored after post-column reaction with a metallochromic reagent, which was added with a reciprocating pump into a low dead volume-mixing tee.

### **Individual Separation of Lanthanides**

It is well established that mobile phase parameters such as eluent concentration, complexing agents, pH, etc. play significant role in influencing the separation of lanthanides by IIC. Work was therefore carried out to bring out the significance of the nature of ion interaction reagent (IIR) on the resolution of lanthanide separations. Another objective was to identify a suitable IIR offering long term adsorption onto the reversed phase (RP) column and thereby obviating the need to introduce the IIR in the mobile phase during the separation. Hence, comparative study of IIRs was carried out under identical experimental conditions. IIRs viz. n-octane sulphonate, n-octane sulphate, n-

octadecane sulphonate and eicosyl sulphate were selected for the study. Separation efficiency was assessed on the basis of resolution, which is related to the number of theoretical plates. Volume and composition of the IIR required for the proper equilibration of the column were optimized for each IIR. Separation of lanthanide mixtures was carried out using a concentration gradient of eluent, viz.  $\alpha$ -hydroxy isobutyric acid (HIBA). The long term adsorption of these IIRs onto the stationary phase was also studied. Among different IIRs studied, n-octadecyl sulphonate showed the highest resolution for the 14 lanthanides (Fig. 1) and provided good long term adsorption stability.

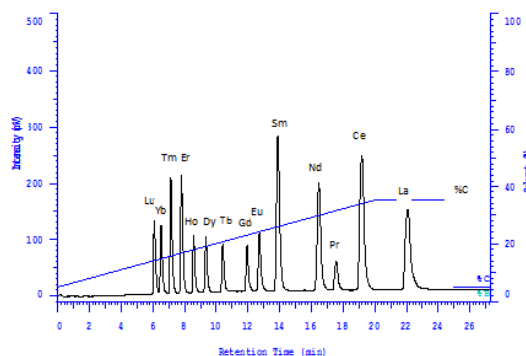


Fig.1. Separation of 14 lanthanides on a  $C_{18}$  column coated with  $C_{18}$ -sulphonate

In view of their similar chemical and physical properties, determination of rare-earth elements in bulk of a rare-earth element is a difficult task. Hence effect of important chromatographic parameters were studied simultaneously to bring out the best conditions for the separation. For this study, two different stationary phases i.e.  $C_{18}$  and  $C_8$  of same dimensions were compared. It was found that the resolution among lanthanides was better when  $C_8$  RP column was used with n-octanesulphonate as IIR. Studies were also undertaken to optimize the conditions for holding large amounts of Dy without affecting the

resolution so that the method can be applied to real life samples with significant Dy/Ln amount ratios. Under the optimized conditions, separation between Dy and Y was possible with a resolution of  $> 2.5$ , using HIBA as a single eluent. It may be noted that the problem of co-elution of Dy and Y is well documented in the literature [7] and combination of different ligands were used for achieving the separation between Y and Dy. Fig. 2 shows the separation of lanthanides present in the  $Dy_2O_3$  sample. Concentrations of lanthanides and Y in the sample were determined by standard addition method.

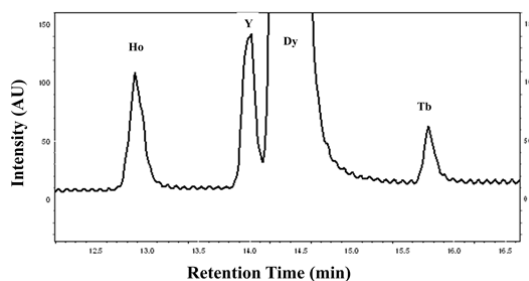


Fig.2. Separation of minor lanthanides in  $Dy_2O_3$  sample using a  $C_8$  column.

The methodology for the separation of lanthanides was also adopted for the dissolved spent fuel samples for the determination of burn-up. Burn-up is defined as the atom percent fission of heavy element ( $mass \geq 225$ ) during its life time in the reactor. Mass spectrometric method for the determination of burn-up requires the isolation of the La and Nd fractions for the analyses based on  $^{139}La$  and  $^{148}Nd$  fission monitors, respectively. However, the presence of large amounts of actinides in these samples can mask the lanthanide peaks. This necessitates prior separation of lanthanides as a group by conventional ion exchange. This multistage separation makes the process tedious and also vulnerable for the loss of analyte. The possibility of separating the lanthanides without involving

any pre-separation of the matrix elements was thus explored. The pH of the eluent and concentration of IIR were found to play a vital role in deciding the capacity of the column to retain Th and U. A dual gradient elution condition was employed for the direct determination of lanthanides in presence of large amounts of Th or U using single column. A concentration gradient of  $\alpha$ -HIBA (pH 6) was used for separating individual lanthanides while retaining Th and U onto the stationary phase. After their separation, another gradient with  $\alpha$ -HIBA of pH 2.5 was introduced for the elution of Th and U. Since the elution of matrix elements takes place after the elution all the lanthanides, the method allows the use of a minor fission product (Tb) as an internal standard for the quantification of fission monitors viz. La and Nd (Fig. 3).

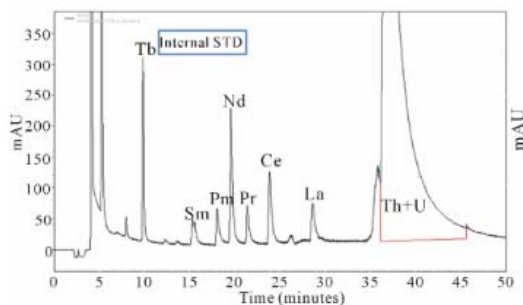


Fig.3. Separation of lanthanide fission products from dissolved (Th,Pu)O<sub>2</sub> spent fuel sample using dual gradient elution.

The methodology exploits the advantages of the internal standard approach as well as direct injection method. Since no preliminary separation is involved, analysis is faster and is less prone to loss of analyte. Since internal standard was used for quantification, it takes care of majority of the fluctuations and uncertainties during the sample handling.

IIC was also explored to carry out selective pre-concentration of lanthanides in presence of

zirconium. Zirconium is expected to undergo hydrolysis or polymerization under the typical condition employed for the individual separation of lanthanides. Thus high concentrations of zirconium pose a challenge for the separation of lanthanides using HPLC. Chromatographic behaviours of lanthanides and zirconium were studied using  $\alpha$ -HIBA as a complexing agent. Under the optimized conditions, bulk of zirconium was found to elute out from the column whereas lanthanides were quantitatively retained onto the column. The pre-concentration conditions were later optimized for maximizing the recovery of lanthanides. Subsequently, pre-concentrated lanthanides were separated on an analytical column of the same nature as the pre-concentration column. Since bulk of zirconium has no interaction with stationary phase, a low capacity column could be used to achieve pre-concentration. Further, on-line pre-concentration procedure minimizes the analyte loss and cross-contamination. Figure 4 shows a chromatogram obtained for the separation of lanthanides and zirconium mixture.

In order to examine the nature of the species formed between zirconium and the eluent, studies were carried out using a C<sub>18</sub> column separately modified with n-octante sulphonate and trimethyloctylammonium chloride. The study indicated that major zirconium species must be anionic in nature and hence showed very little retention on cation exchange based pre-concentration column. This postulate was later corroborated by carrying out the speciation study of zirconium-HIBA system using electrospray ionisation mass spectrometry.

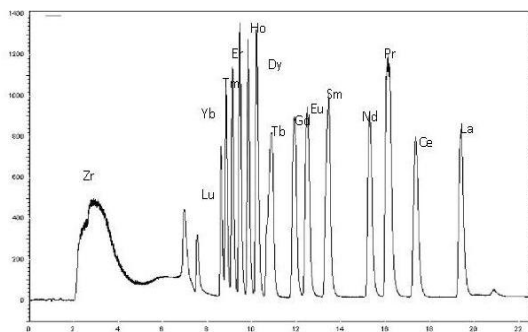


Fig.4. Separation of a mixture of lanthanides in presence of Zr using dual column HPLC method.

### Separation of Thorium, Uranium and Plutonium

Separation and determination of thorium, uranium and plutonium in presence of each other has drawn much attention because of their importance in nuclear energy related applications. HPLC method based on the hydrophobic interaction of hydroxycarboxylic acid complexes of these elements with RP stationary phase were developed. Presence of methanol in the mobile phase was found to improve the peak shape as well as sensitivity of the method. pH of the mobile phase was found to be an important factor as it significantly influences the retention capacity of the column. It is seen that Th is eluted prior to U when most of the hydroxycarboxylic acids are used as eluents [8]. However, when mandelic acid is used as the eluent, the elution pattern was found to reverse which is beneficial for the determination of U in samples containing bulk of Th [9]. Figure 5 shows the chromatogram obtained by injecting a mixture with Th/U amount ratio 106300 using mandelic acid and methanol as the mobile phase. U peak is separated from Th peak with a time gap of almost 1 min indicating that the determination of the former would not be interfered by the latter peak.

In order to understand the reason for the change in the elution pattern, the retention of Th and U were monitored as a function of two IIRs viz. n-octane sulphonate and of tetra-n-butyl ammonium bromide. It was found that the retention of both Th and U decreases as concentration of n-octane sulphonate increased. However, retention of U was found to increase with increase in concentration of the tetra-n-butyl ammonium ion and thereby indicating the anionic nature of uranyl-mandelate complex. On the other hand, retention time of thorium-mandelate complex decreased steadily with the increase in concentration of this IIR and this shows the charge neutrality of this complex. Thus on RP stationary phase, Th is retained as neutral thorium mandelate complex whereas U is adsorbed as anionic uranyl-mandelate complex. The presence of these major species explains the distinct elution pattern observed when mandelic acid is used as an eluent.

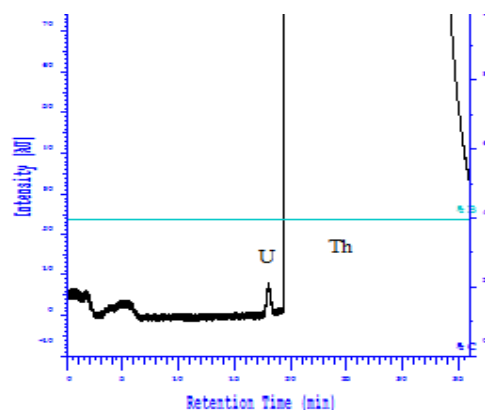


Fig.5. Separation of U and Th in a mixture with Th/U amount ratio >1,00,000.

The method was later modified for the separation of Th, U and Pu(IV). The optimized parameters were employed for the separation and determination of Th, U and Pu(IV) in a dissolved solution of spent (Th,Pu)O<sub>2</sub>. Figure 6 shows the separation of Th, U and Pu(IV) after directly

injecting the irradiated  $(Th,Pu)O_2$  sample by employing mandelic acid as the eluent. Prior to injection, the dissolver solution was subjected to redox treatment to convert all the Pu species into IV state.

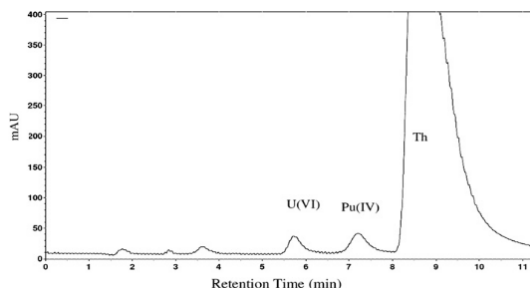


Fig.6: Separation of Th, U and Pu(IV) from irradiated  $(Th,Pu)O_2$  sample.

Since plutonium possesses multiple oxidation states which can coexist in solution, another HPLC method for the separation of Pu(III), Pu(IV) and Pu(VI) was developed. Studies were carried out to compare the chromatographic behaviour of different oxidation states of Pu in presence of the eluent, HIBA and mandelic acid, separately. The order of retentions seems to be in accordance with the degree of hydrophobicity exhibited by the resultant Pu-ligand complexes. Retention of Pu(III) did not show any significant influence by the eluent concentration or its pH. It was seen that the retentions of Pu(IV) and Pu(VI) species decreases steadily with the increase in concentration of eluent. Retentions of both these species increased as a function of pH of the mobile phase. Figure 7 shows that the different oxidation states of Pu could be separated by HPLC using HIBA as an eluent.

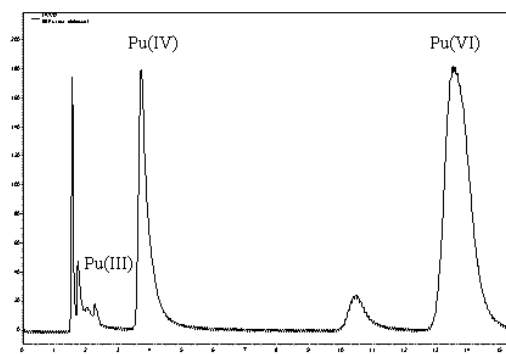


Fig.7. Chromatogram showing the separation of different oxidation states of Pu.

It was seen that the concentration and pH of the complexing agent influences the equilibrium of Pu(III)-Pu(IV) as well as Pu(IV)-Pu(VI) systems. pH and concentration of eluent were found to play an important role in the conversion rates. e.g. a high pH and high concentration of HIBA facilitates the conversion from Pu(III) to Pu(IV) whereas a relatively low pH and high concentration of HIBA is helpful for the conversion from Pu(VI) to Pu(IV).

### Conclusions

The studies demonstrated the versatility and efficiency of IIC for the separation of lanthanides in different types of samples. The developed dual gradient elution methods allow for direct injection of the samples with no pre-separation of the matrix. Since no preliminary separation procedure is involved, analysis is faster and is less prone to contamination. Methods were also developed for the separation of Th, U and Pu using RP-HPLC. Methods were also investigated for the separation of different oxidation states of Pu using HPLC. The study shows that though the eluents are capable of separating different oxidation states of Pu, they can contribute to the inter-conversion among the oxidation states and thereby altering the actual equilibrium present in the original sample.

**References**

1. S. Sudev, V. S. Janardhanan. *Int. J. Pharm. Sci. Rev. Res.*, **56** (2019) 28. .
2. A. Datta, N. Sivaraman, T.G. Srinivasan, P.R.V. Rao, *Radiochim. Acta* **98** (2010) 277.
3. X. Yin, Y. Wang, X. Bai, *Nature Communications*, **8** (2017) 14438.
4. N.L. Elliot, L.W. Green, B.M. Recoskie, R.M Cassidy, *Anal. Chem.* **58** (1986) 1178.
5. N.N. Wanna, K.V. Hoecke, A. Dobney, M. Vasile, T. Cardinaels, F. Vanhaecke, *J. Chromatogr. A* **1617** (2020) 460839.
6. V.M. Telmore, Pranaw Kumar, S. Jagadish Kumar, Preeti Goswami, K. Sasi Bhushan, Raju V. Shah, Sumana Paul, R.M. Rao, P.G. Jaison, S. Kannan BARC Report, BARC/2020/E/005
7. L.V. Tsakanika, M.O. Petropoulou, L.N. Mendrinou, *Anal Bioanal Chem* **379** (2004) 796.
8. P.G. Jaison, N.M. Raut, S.K. Aggarwal, *J. Chromatogr. A* **1122** (2006) 47.
9. P.G. Jaison, V. M. Telmore, Pranaw Kumar, S.K. Aggarwal, *J. Chromatogr. A* **1216** (2009) 1383.



P.G. Jaison obtained his M.Sc. degree in Chemistry from Cochin University of Science and Technology. After graduating from 41<sup>st</sup> batch of BARC Training School, he joined Fuel Chemistry Division of Bhabha Atomic Research Centre in 1998. He obtained his Ph.D. degree from Homi Bhabha National Institute in 2014. His fields of interest are mass spectrometry and liquid phase separation techniques. He has developed different liquid chromatographic methods for the separation and determination of lanthanides and actinides. He is also interested in the electrospray ionisation mass spectrometric studies on the complexation of actinides and lanthanides with the ligands used in their separation.



## ***Preparation of $^{177}\text{Lu}$ -Trastuzumab for Cancer Care: Role of Separation Sciences***

**Mohini Guleria & Tapas Das**

Radiopharmaceuticals Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400 085, India

(Corresponding Author: *Tapas Das*; Email: [tdas@barc.gov.in](mailto:tdas@barc.gov.in))

### **Introduction**

'Radioimmunotherapy' (RIT) is a special class of radionuclide therapy where radiolabeled monoclonal antibodies are used for targeted therapy for various diseases, predominantly cancers. Although the use of only a couple of radiolabeled monoclonal antibodies have been approved by the regulatory authorities for therapeutic intervention of human cancers till date, efforts are underway to develop a wide-variety of radiolabeled antibodies for the RIT of various types of cancers. Separation sciences and technologies play a pivotal role in the development of radiolabeled antibodies for cancer care. As these radiolabeled preparations will be administered in human patients, such preparations must fulfill the stringent requirements with respect to both chemical purity as well as radiochemical purity. To ensure the suitability of final radiolabeled preparation for clinical application, such preparations undergo purifications in different stages of their preparation and in all such stages, separation technologies play a crucial role which is exemplified by discussing the preparation methodology of  $^{177}\text{Lu}$ -Trastuzumab in the present article.

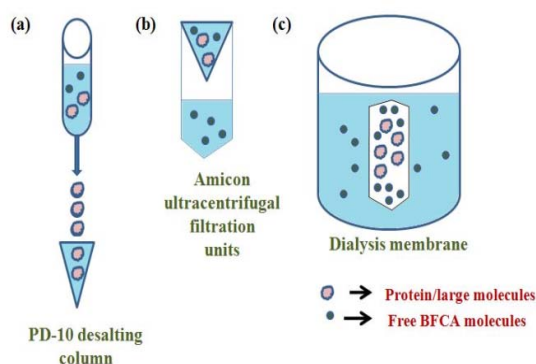
Trastuzumab (Herceptin®), a humanized monoclonal antibody, is an US-FDA (Food and Drug Administration of United States of America) approved drug, used for the treatment of patients suffering from metastatic breast cancers over-

expressing Human Epidermal Growth Factor Receptor 2 (HER2) antigen receptors [1]. Monoclonal antibodies are proteins bearing high molecular weight of the order of ~150 kDa and are employed as tumor markers owing to their high degree of specificity towards antigen receptors over-expressed on cancer cells. 'RIT' is a special class of immunotherapy which exploits the affinity of immune proteins towards the tumor-associated specific antigens or antigen receptors for delivering a therapeutic radionuclide to the target of interest in order to provide a lethal dose of cytotoxic radiation to the cancerous lesions [2-4]. Prime advantage of using radiolabeled antibodies in place of unlabeled ones for cancer treatment lies in the fact that by targeting a limited number of cancer cells in the tumor mass, a large number of such cells can be destroyed owing to the cross-fire effect exerted by the particulates (beta/alpha/Auger electron) generated due to the decay of the associated radionuclide [2-6]. As the destruction of the cancer cells are predominantly achieved owing to the cytotoxic effect exerted by the associated radionuclide, role of monoclonal antibodies is simply reduced to a carrier vector to deliver the radioactivity to the target cells and this essentially minimizes the requirement of costly antibodies and also reduces the chemotoxic dose burden of the treatment.

For developing a RIT agent for the treatment of HER2 receptor positive breast cancer patients, Trastuzumab can be radiolabeled with a suitable particulate emitter, which decays by emission of either  $\beta^-$  or  $\alpha$  particle or by release of Auger electrons [2]. In the last decade,  $^{177}\text{Lu}$  has emerged as one of the most useful radionuclides for the development of endo-radiotherapeutic agents, particularly for the treatment involving small or medium-sized tumorous lesions, owing to its suitable nuclear decay characteristics and easy production feasibility using medium flux research reactors [1,7-9]. Lutetium-177 decays to stable  $^{177}\text{Hf}$  by release of  $\beta^-$  particles having maximum energy of 497 keV along with the emission of gamma photons of suitable energy [ $E_\gamma = 113$  keV (6.4%), 208 keV (11%)] which helps in theranostic intervention enabling simultaneous scintigraphy and dosimetric evaluations [7-9]. The comparatively longer half-life ( $T_{1/2} = 6.73$  d) of the radionuclide helps in transporting  $^{177}\text{Lu}$  or  $^{177}\text{Lu}$ -based agents to the remote places from its production site without significant loss of activity due to radioactive decay. Additionally, the large thermal neutron capture cross-section of  $^{176}\text{Lu}$  ( $\sigma = 2100$  b) helps in economic and large-scale production of the radionuclide with high radionuclidic purity and adequate specific activity using medium flux research reactors [7-9].

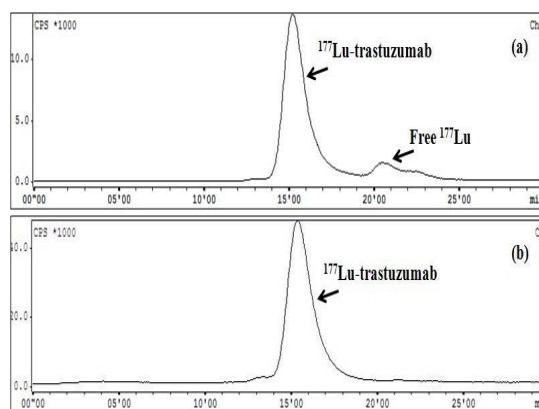
Direct incorporation of  $^{177}\text{Lu}$  in Trastuzumab moiety is not viable owing to the non-availability of suitable functional groups in the antibody framework, which are capable of forming stable complex with the radiolanthanide [10]. To circumvent this problem, antibodies are first conjugated with a suitable bi-functional chelating agent (BFCA); which attaches itself covalently with the antibody moiety from one end, whereas the other end is utilized for engaging

with radio-metal ion ( $^{177}\text{Lu}$  in the present case). Post-conjugation, it is necessary to completely remove the un-reacted/free BFCA molecules from the reaction mixture, which can be materialized using different separation techniques viz. membrane filtration, size exclusion chromatography and dialysis (Fig. 1) [11]. While developing  $^{177}\text{Lu}$ -Trastuzumab for patient care, *p*-NCS-benzyl-DOTA (2,2',2''-(10-(1-carboxy-4-((4-isothiocyanatobenzyl)amino)-4-oxobutyl)-1,4,7,10-tetraazacyclododecane-1,4,7-triyl)triacetic acid) was chosen as the BFCA and the un-conjugated BFCA was separated from the antibody-BFCA conjugate by using commercially available Amicon® ultra-centrifugal filtration units (molecular weight cut off 10 kDa). Significantly higher molecular weight of Trastuzumab compared to that of *p*-NCS-benzyl-DOTA allowed selective removal of non-conjugated BFCA from the reaction mixture after 6-7 cycles of filtration using ultra-centrifugal filtration units. The complete removal of free BFCA molecules was ascertained by recording HPLC profile of the residual solution using HPLC system employing size exclusion chromatography column.



*Fig.1: Pictorial representation of purification techniques employed to separate free BFCA molecules from antibody-BFCA conjugate*

Once the purified Trastuzumab-*p*-NCS-benzyl-DOTA conjugate was obtained, the antibody-BFCA conjugate was radiolabeled with  $^{177}\text{Lu}$  by incubating the conjugate dissolved in HEPES buffer with  $^{177}\text{LuCl}_3$  at 37 °C temperature. The percentage radiochemical yield of the radiolabeled preparation was determined using paper chromatography ( $R_f$  for  $^{177}\text{Lu}$ -Trastuzumab = 0.0-0.1;  $R_f$  for free  $^{177}\text{LuCl}_3$  = 0.9-1.0) as well as by HPLC studies ( $R_t$  for  $^{177}\text{Lu}$ -Trastuzumab =  $15.5 \pm 0.5$  min;  $R_t$  for free  $^{177}\text{LuCl}_3$  =  $21.5 \pm 0.85$  min) and was found to be  $(91.08 \pm 2.54)$  %. Attempts were made to further purify the preparation by removing the un-complexed or free  $^{177}\text{Lu}$  from the preparation, which was achieved by using pre-packed PD-10 desalting columns, which work on the principle of size exclusion chromatography. Although, ultra-centrifugal filtration process results greater recovery of purified product, it is not utilized for the purification of  $^{177}\text{Lu}$ -Trastuzumab; primarily due to the longer time required for achieving separation by this method, which essentially increases the radiation exposure of the working personnel [1]. This process helped to prepare  $^{177}\text{Lu}$ -Trastuzumab with a radiochemical purity of  $>95\%$ , which is considered suitable for human administration. However, purification of the  $^{177}\text{Lu}$ -Trastuzumab using PD-10 column was associated with the loss of radioactivity due to the trapping of the activity in the column matrix as well as in the loading vial. On an average,  $(72.8 \pm 1.2)$  % of the loaded activity could be retrieved after purification through the PD-10 column. The HPLC profiles of  $^{177}\text{Lu}$ -Trastuzumab, before and after purification through PD-10 column are shown in Fig. 2 (a) and (b), respectively.  $^{177}\text{Lu}$ -Trastuzumab, thus obtained, was finally subjected to Millipore filtration ( $0.22 \mu\text{m}$ ) prior to the administration in patients to ensure the sterility of the product.

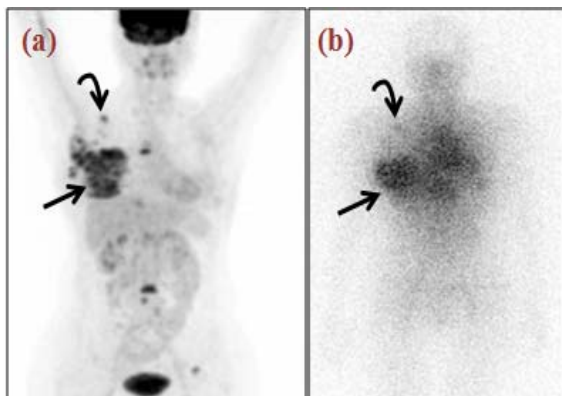


*Fig. 2: Typical HPLC profile of  $^{177}\text{Lu}$ -Trastuzumab (a) before and (b) after purification through PD-10 column*

$^{177}\text{Lu}$ -Trastuzumab, prepared by the method mentioned above, was administered to immunohistochemically proven HER2 positive metastatic breast cancer patients for studying biological distribution of the agent. Clinical studies showed that  $^{177}\text{Lu}$ -Trastuzumab gets selectively accumulated in the cancerous lesions, detected previously in diagnostic PET (positron emission tomography) scans of the same patient (Fig. 3) indicating the target-specificity of the developed product [12]. Treatment of breast cancer patients with the administration of therapeutic dose of  $^{177}\text{Lu}$ -Trastuzumab is expected to be initiated in the near future.

It is evident from the above-discussion that proper separation of antibody-BFCA conjugate (Trastuzumab-*p*-NCS-Benzyl-DOTA) from BFCA (*p*-NCS-Benzyl-DOTA) and radiolabeled antibody ( $^{177}\text{Lu}$ -Trastuzumab) from uncomplexed radioactivity ( $^{177}\text{LuCl}_3$ ) is crucial for the successful formulation of  $^{177}\text{Lu}$ -Trastuzumab. Additionally, the quality control procedures, required to be performed for ensuring the purity of the radiolabeled preparation, prior to its

administration in patients, are also solely based on the principles of separation technology.

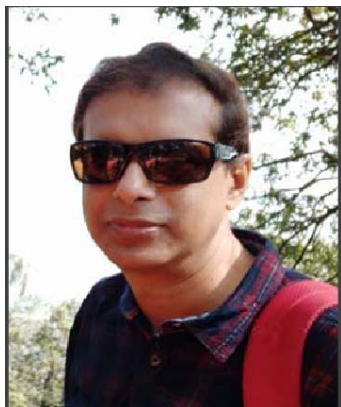


*Fig. 3: Whole-body scans of a patient detected with HER2 positive metastatic breast cancer, obtained using (a)  $^{18}\text{F}$ -FDG (fluorodeoxyglucose) and (b)  $^{177}\text{Lu}$ -Trastuzumab, respectively.*

Therefore, it can be safely concluded that separation sciences and technologies play an important role in the development of radiolabeled antibodies required for cancer care.

### References

1. G. L. Ray, K. E. Baidoo, L. M. M. Keller, P. S. Albert, M. W. Brechbiel, D. E. Milenic, *Pharmaceuticals* **5** (2012) 1-15.
2. M. R. Chamrathy, S. C. Williams, R. M. Moadel, *Yale J. Biol. Med.* **84** (2011) 391-407.
3. S. M. Larson, J. A. Carrasquillo, N. K. V. Cheung, O. W. Press, *Nat. Rev. Cancer* **15** (2015) 347-360.
4. H. Kawashima, *Sci. World J.* **2014** (2014) 1-10.
5. T. E. Schmid, G. Multhoff, *Front. Oncol.* **2** (2012) 1-4.
6. H. Zhou, G. R. Pehrson, C. A. Waldren, D. Vannais, E. J. Hall, T. K. Hei, *Proc. Natl. Acad. Sci.* **97** (2000) 2099-2104.
7. A. Dash, M. R. A. Pillai, F. F. Knapp, *J. Nucl. Med. Mol. Imaging* **49** (2015) 85-107.
8. M. R. A. Pillai, S. Chakraborty, T. Das, M. Venkatesh, M. Ramamoorthy, *Appl. Radiat. Isot.* **59** (2003) 109-118.
9. S. Banrjee, T. Das, S. Chakraborty, M. Venkatesh, *Raiochim. Acta* **100** (2012) 115-126.
10. H. Mohsin, F. Jia, G. Sivaguru, M. J. Hudson, T. D. Shelton, T. J. Hoffman, C. S. Cutler, A. R. Ketring, P. S. Athey, J. Simón, R. K. Frank, S. S. Jurisson, M. R. Lewis, *Bioconjug. Chem.* **17** (2006) 485-492.
11. W. Wojdowska, U. Karczmarczyk, M. Maurin, P. Garnuszek, R. Mikoajczak, *Curr. Radiopharm.* **8** (2015) 62-68.
12. M. Guleria, R. Sharma, J. Amirdhanayagam, H. D. Sarma, V. Rangarajan, A. Dash, T. Das. *RSC Med. Chem.* **12** (2021) 263-277.



Dr. Tapas Das is presently working as Head, Radiopharmaceutical Chemistry Section in Radiopharmaceuticals Division of Bhabha Atomic Research Centre, Mumbai. He had joined Department of Atomic Energy (DAE) in 1998 after completing his post-graduation in Chemistry and one year Orientation Course in Nuclear Science and Engineering (OCES) from BARC Training School. He had obtained Ph.D. from University of Mumbai in 2004 for his studies on radiopharmaceutical sciences. His research field of interest includes production of radioisotopes and development of radiopharmaceuticals for diagnostic and therapeutic applications. Dr. Das has received several awards such as, Prof. H. J. Arnikar Best Thesis Award (2005), DAE Young Scientist Award (2008), DAE Group Achievement Awards (2009, 2017, 2018), Tarun Datta Memorial Young Scientist Award (2010) and DAE Scientific and Technical Excellence Award (2015). He has served as Technical Co-operation Expert of International Atomic Energy Agency (IAEA) to Republic of Korea (2006), Kazakhstan (2010) and Indonesia (2017). He has also served as a consultant to the Agency (2018). He is an 'Associate Professor' and recognized Ph.D. guide of Homi Bhabha National Institute (HBNI), Mumbai. He has more than 90 publications in various peer-reviewed international journals.

## Radiation grafted functional polymers for water purification

Virendra Kumar

Radiation Technology Development Division, Bhabha Atomic Research Centre, Trombay, Mumbai-400085

\*Email: [vkumar@barc.gov.in](mailto:vkumar@barc.gov.in)

### Introduction

In the past few decades, with steep population growth and the ever-expanding industrial sector, large scale wastewater generation has emerged as a serious environmental concern. Consequently, the need for more efficient and affordable wastewater treatment technologies has become paramount. Although, majority of the polymers exhibit good thermo-mechanical properties, their inert nature require certain modifications in their properties according to tailor-made specifications designed for target applications. Radiation technologies based on ionizing radiation (gamma rays, electron beams, plasma) offer environment friendly, efficient and versatile tools for modification of polymeric materials, wherein new functionality and novel characteristics can be imparted to polymers. Radiation graft polymerization, being an efficient process for functionalization of exiting polymers, can play important role in remediation of some of the water pollutants [1-4]. This article will cover some of the recent advances made in the field of development of radiation grafted functional polymeric adsorbents and recyclable catalytic systems for water purification applications.

### Radiation grafting process

Radiation grafting is a co-polymerization process wherein polymer chains of desired monomers are grown (covalently bonded) onto the existing polymer substrates using ionizing radiation.

Mechanism of radiation grafting process involves the formation of free radicals on existing polymer due to breaking of bonds caused by ionizing radiation. These free radicals initiate the graft copolymerization chain reaction from the monomers, leading to formation of functional grafted chains attached to the base polymer. Radiation graft polymerization process offers advantages over other conventional grafting processes, such as room temperature processing conditions, better control over reaction parameters and the absence of any harmful chemical initiators [1-5]. Fig. 1 presents the schematic of a typical radiation grafting process.

Radiation graft polymerization reaction can be performed by two different methods: i) Simultaneous irradiation grafting and ii) Post-irradiation grafting method.

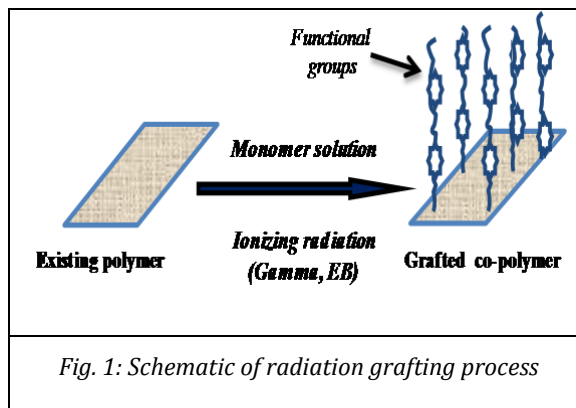


Fig. 1: Schematic of radiation grafting process

**i. Simultaneous irradiation grafting:** In this method, grafting reactor containing an existing polymer substrate, dipped in the monomer solution, was exposed to ionizing radiation. The

radicals generated on polymer backbone lead to the graft copolymerization reaction

**ii. Post-irradiation grafting:** In this method, the polymer backbone is first exposed to ionizing radiation to generate free radicals on it, and subsequently brought in contact with the monomer solution to initiate the graft copolymerization reaction.

The radiation grafted samples is characterized by grafting yield (G.Y.).

$$G.Y. (\%) = \frac{(\text{Weight after grafting} - \text{Initial weight})}{\text{Initial weight}} \times 100 \quad (1)$$

**Radiation grafted functional adsorbents for treatment of dye waste water**

The uncontrolled disposal of colored dyes effluents from industries (textiles, leather, paper, printing, etc.) into water streams adversely affects the quality of water bodies. This causes environmental pollution and poses serious health risks to human population as well as aquatic life [6,7]. Of late, increased public concern and strict regulation enforcement have forced these industries to treat dye effluents before discharging to the environment, and to look for more efficient and viable options to treat these effluents. Physico-bio-chemical methods, such as adsorption, coagulation, precipitation, filtration, ozone treatment, chemical oxidation, photocatalytic processes, biological treatment and ionizing radiation degradation have been proposed for dye effluent treatment [8]. Due to very complex nature of textile waste water no universal method is available yet and therefore, combinations of different processes are being used for this purpose. However, adsorption has been found to be a comparatively simple, effective and efficient process that avoids generation of toxic secondary degradation by-products. A range

of functional adsorbents (cationic and anionic) have been synthesized via mutual irradiation grafting process for removal of ionic dyes from textile waste water systems.

**Radiation grafted anionic adsorbent for separation of cationic dyes:**

Anionic vinyl monomers namely, 4-vinylbenzenesulfonic acid sodium salt (VBSA) was used to fabricate anionic types of cellulose adsorbents via gamma radiation induced simultaneous irradiation grafting process. Different grafting parameters were studied and grafting process was optimized. Fig. 2 shows the effect of total dose and monomer concentration on the grafting yield. The dose of 4.0 kGy and [VBSA]=20% was optimized for further studies.

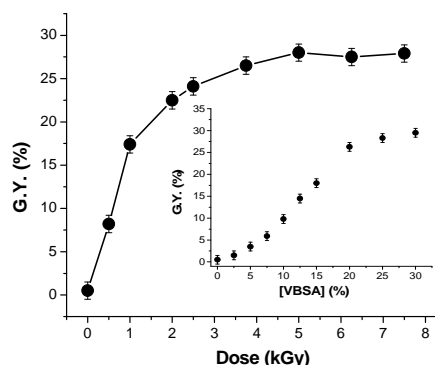


Fig. 2: G.Y as a function of absorbed dose. (Dose rate=1.5kGy.h<sup>-1</sup>, [VBSA] = 20%). Inset: G.Y as a function of monomer concentration (Dose= 4.0kGy)

The grafted samples were characterized by FTIR and TGA (Fig. 3). The VBSA-g-Cellulose adsorbent (G.Y=25%) was tested for removal of basic dyes (Basic Red 29; BR29) from water in batch as well continuous flow operation mode [1].

The adsorbent could be reused for multiple cycles with minimal attrition losses. Fig. 4 presents the Schematic of lab scale fixed bed packed column

system and breakthrough curve for BR29 (Adsorbent=1g, [BR29]= 200ppm, flow rate= 60mL/h).

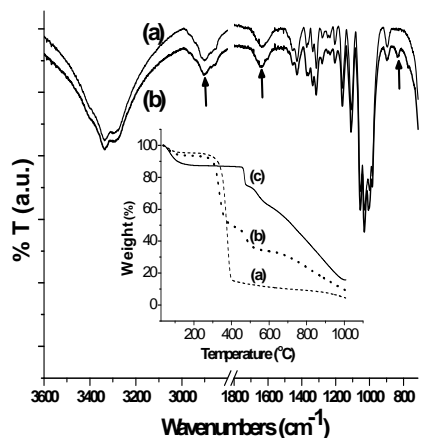


Figure 3: FTIR spectra of (a) Cellulose (b) PVBSA-g-cellulose. Inset: TGA plot of (a) Control Cellulose (b) PVBSA-g-cellulose (G.Y. = 25%) (c) PVBSA.

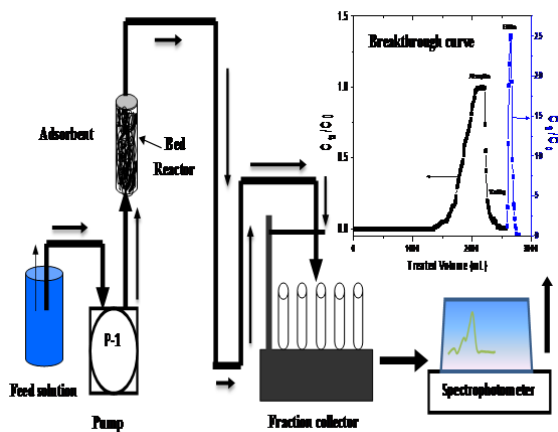


Fig. 4: Schematic of fixed bed packed column system (PVBSA-g-Cellulose) and breakthrough curve for BR29

**Radiation grafted cationic adsorbent for separation of anionic dyes:**

Cationic cellulose adsorbent was also synthesized via simultaneous radiation grafting of Quaternary ammonium salt containing monomers (QAS),

namely 2-(Methacryloyloxy) ethyltrimethyl ammonium chloride (MAETC) and Vinylbenzyl trimethylammonium chloride (VBT) on to cotton cellulose fabric (low cost and abundant biopolymer). [2,9]. The cationic cellulosic adsorbents were employed for removal of anionic acid dyes (AB25, AB193, etc.) from synthetic and real dye waste water in batch as well as column process. Equilibrium adsorption and adsorption kinetic data were analyzed using different adsorption isotherms and kinetic models. Breakthrough curves were established for textile dyes using lab scale fixed bed column system packed with radiation grafted cellulose adsorbent. The MAETC-g-Cellulose adsorbent based process was successfully upscaled and demonstrated at a semi pilot scale treatment of acid dye waste water. (Fig. 5). Large scale field trials are in progress to establish the technology.



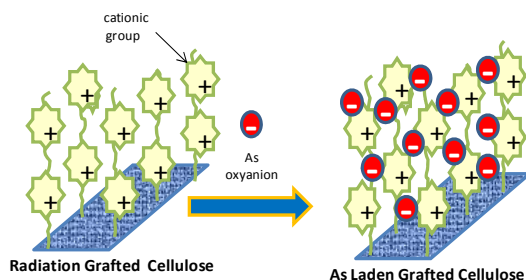
Fig. 5: Radiation grafted cellulosic adsorbent based semi pilot plant for dye waste water treatment

**Radiation grafted adsorbent for separation of Arsenic from drinking water:**

Arsenic pollution in drinking water has evolved into a critical environmental hazard in several parts of India, such as Chhattisgarh, West Bengal, Uttar Pradesh, Bihar and the northeastern region. To mitigate this problem, Radiation grafting has been employed for the first time, to the best of our



knowledge, as a facile tool for tailoring a novel, recyclable functionalized cellulose (MAETC-*g*-Cellulose) based adsorbent for remediation of Arsenic from water (Fig. 1). The optimized adsorbent system was demonstrated to efficiently remove Arsenic from aqueous streams (Fig. 6).



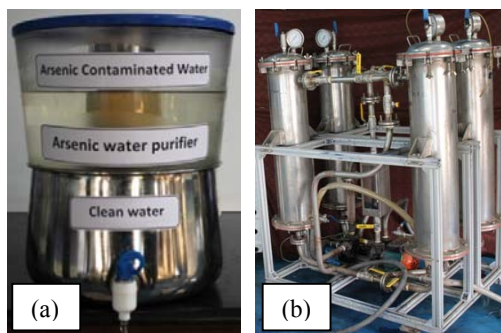
*Fig. 6: Removal of Arsenic from water using Radiation grafted cationic adsorbent.*

Arsenic contaminated groundwater samples collected from different affected areas were successfully treated to reduce contamination level below the WHO permissible limits of 10 ppb in drinking water. Post successful field trials and semi pilot scale treatment, the scope of the work was subsequently expanded to conceptualize and materialize a unique water treatment technology for Arsenic remediation at both domestic and community levels.

Technology Readiness Levels (TRLs) method was followed to quantify the technical maturity of the technology. Figure 7a and 7b shows a radiation grafted Cellulose fabric based gravity driven domestic water purifier and a community scale water purifier, respectively. The technology has been successfully transferred to licensees in a concerted effort towards disseminating this technical knowhow for the benefit of the people residing in regions afflicted with high Arsenic water contamination.

**Radiation grafted functional adsorbents for removal of toxic metal ions:**

In some parts of the country, ground water has been reported to be contaminated with toxic metal ions, such as Uranium, Cadmium, etc. [10].



*Fig. 7: Radiation grafted cellulose adsorbent based water purifier for Arsenic removal (a) domestic water purifier and (b) community scale water purifier.*

Polymeric adsorbents, functionalized with suitable chemical groups (ionic or chelating) have potential applications in removal of the toxic metal ions from water bodies. For example, Amidoxime (AO) functionalized polymer adsorbent was found to be more suitable for uranium removal [11-13]. AMO-*g*-PP adsorbent has been synthesized via electron beam induced post irradiation grafting process, wherein polyacrylonitrile (PAN) chains were grafted to non-woven polypropylene matrices, followed by chemical conversion of nitrile groups to amidoxime groups (AMO) by reacting with hydroxylamine under optimized conditions [12,13]. Amidoxime-*g*-polypropylene adsorbent was employed for recovery of uranium from seawater. The schematic of the fabrication of amidoxime-*g*-polypropylene adsorbents via EB induced post-irradiation grafting process is presented in fig. 8 [12,13]. The adsorbent could be

regenerated and recycled for several cycles without significant attrition losses. The adsorbent was also employed for removal of heavy metal ions including  $\text{Co}^{2+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Mn}^{2+}$ , and  $\text{Cd}^{2+}$  from aqueous solutions [12-14].

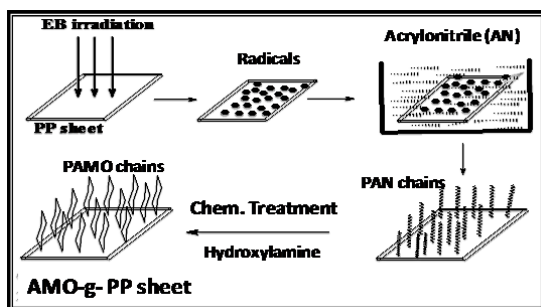


Fig. 8: Amidoximated PP adsorbents via EB induced post-irradiation grafting process

**Metal nanoparticles-immobilized-polymer catalytic system for Cr(VI) remediation:**

Cr(VI) contamination has been found to be one of the serious water pollution caused mainly due to the discharge from leather and dye industries. One of the novel approaches adopted to deal with Cr(VI) toxicity is the catalytic reduction of highly toxic Cr(VI) to less toxic Cr(III) form using metal nanoparticles based catalysts. A facile, reusable and robust Pd nanoparticles immobilized catalytic reactor (Pd-NiCaR) system was developed using green, environment friendly plasma polymerization followed by gamma radiolytic processes [15]. Schematic of fabrication of Pd-NiCaR system and mechanism for formic acid mediated catalytic reduction of Cr(VI) to Cr(III) is presented in fig. 9.

Briefly, a room temperature, RF powered plasma polymerization process was employed to functionalize a Polyethylene-Polypropylene (PE-PP) non-woven matrix with epoxy group containing monomer 2,3-epoxypropyl methacrylate (EPMA).

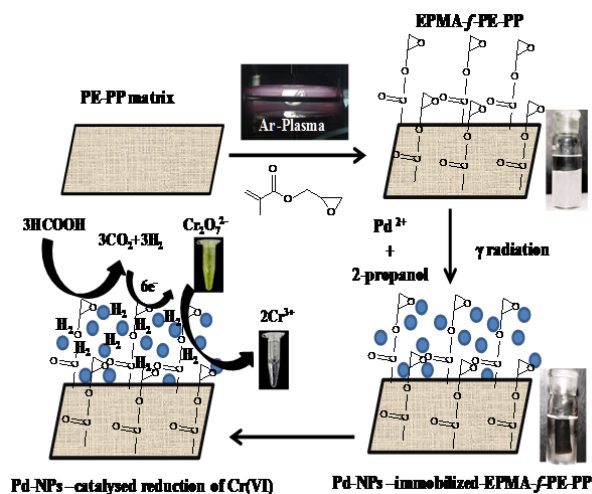


Fig. 9: Schematic of fabrication of Pd-NiCaR system and catalytic reduction of Cr(VI)

EPMA functionalized PE-PP (EPMA-f-PE-PP) substrate was subsequently used as a template for in-situ generation and immobilization of Pd NPs via gamma radiolytic route. The catalytic efficacy of Pd-NiCaR towards Cr(VI) reduction, in presence of formic acid as a reductant, was investigated spectrophotometrically. The system showed excellent reusability (>20 cycles) and storage stability (>30 days) without substantial loss (~11%) of activity. Practical applicability of the robust catalytic system towards Cr(VI) toxicity mitigation was also established in continuous flow mode using a fixed-bed column reactor.

**Enzyme-immobilized-radiation grafted polymer biocatalytic system:**

Enzymes are the biocatalysts bearing excellent properties, such as high selectivity and specificity that may facilitate them performing the most complex chemical processes under the most benign experimental conditions. However, the use of free and soluble enzyme system suffers from issues related to their reusability, cost, stability, sensitivity to various denaturants and applications in continuous reaction mode [16]. To overcome these limitations, use of immobilized

enzyme systems has now taken precedence over free enzyme systems. Immobilization of enzymes leads to enhanced thermal stability of the enzyme and broader pH range of enzyme activity. At the same time, reusability and separation of the enzyme from the product becomes feasible, which is extremely essential when using expensive or scarcely produced enzymes for high end products [17]. The immobilization strategies include physical adsorption, entrapment, and covalent binding [18]. One of the approaches used to achieve covalent immobilization of enzymes is the use of functionalized polymer support matrices. In order to achieve covalent immobilization of enzymes, radiation induced grafting of desired functional groups onto polymer surfaces has been carried out to introduce functionality to the otherwise inert polymer surfaces [5,19].

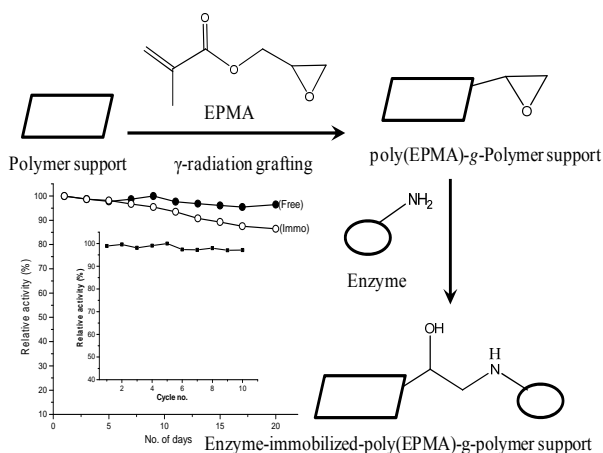


Fig. 10: Radiation induced epoxy functionalization of polymer and covalent immobilization of enzyme on to poly(EPMA)-g-polymer support. (Inset: Storage stabilities and repeatability of laccase immobilized- PES system)

Briefly, epoxy functionalized polymer supports have been synthesized via mutual irradiation grafting of EPMA on to polymer (PES, PP) supports. Subsequently, environmentally and industrially relevant enzymes, namely Laccase

and Horseradish peroxidase (HRP) were covalently immobilized on to poly(EPMA)-g-PES/PP supports via single step-room temperature coupling reaction of amine group of enzyme with the epoxy group of grafted poly(EPMA) chains (Fig. 10) [5,19].

The immobilization of laccase on poly(EPMA)-g-PES beads showed improved storage stability. In addition, the immobilized laccase system could be used repeatedly without significant compromise on the activity of the enzyme up to 10 cycles over a period of 5 days (Inset fig.10). The laccase immobilized EPMA-g-PES bead system could be employed to degrade acid Red 1 (AR1) dye in aqueous solution. Room temperature incubation of the immobilized laccase system with of AR1 dye (~10ppm) resulted in ~88% degradation of the dye over a period of 15 days, and could be repeatedly used [19]. Similarly, a recyclable catalase-immobilised-poly(EPMA)-g-Cellulose based biocatalytic system have also been fabricated using radiation grafting process [20].

### Conclusion

Radiation induced grafting is an efficient process for the design of highly efficient advanced functional polymeric support for range of environmental applications. Different functional adsorbents have been developed by radiation grafting process and demonstrated successfully for efficient removal of toxic pollutants, including dyes, Arsenic and toxic metal ions, from water bodies. Radiation grafted epoxy functionalized polymer supports have also been synthesized and employed for fabrication of robust and recyclable catalytic system by covalently immobilizing enzymes (Laccase, HRP, Catalase) and metal nanoparticles. Improved operational, storage and thermal stability along with reusability of immobilized catalysts makes them efficient

biocatalytic systems for potential environmental applications. Practical applicability of developed water treatment systems was established by upscaling it from lab to pilot scale in continuous flow mode operation.

#### **Acknowledgement**

Author express his sincere thanks to everyone who has been involved and helped directly or indirectly in the activities reported.

#### **References**

1. N. Misra, S. Rawat, N. K. Goel, S. A. Shelkar, V. Kumar, *Carbohydr. Polym.*, 241 (2020) 116902
2. N. K. Goel, V. Kumar, N. Misra, L. Varshney, *Carbohydr. Polym.*, 132(2015) 444.
3. V. Kumar, N. Misra, N. K. Goel, R. Thakar, J. Gupta, L. Varshney, *RSC Adv.*, 6(2016) 2974.
4. V. Kumar, Y. K. Bhardwaj, K. P. Rawat, S. Sabharwal, *Radiat. Phys. Chem.*, 73(2005) 175.
5. V. Kumar, N. Misra, J. Paul, B. R. Dhanawade, L. Varshney, *Polymer*, 55(2014) 2652.
6. K. Klemola, J. Pearson, A. V. J. Liesivuori, P. L. Seppä, *Autex Res. J.* 7(2007) 224.
7. S. A. Figueiredo, R.A. Boaventura, J.M. Loureiro, *Sep. Purif. Technol.*, 20(2000) 129.
8. H. S. Rai, M. S. Bhattacharyya, J. Singh, T. K. Bansal, P. Vats, U. C. Banerjee, *Crit. Rev. Env. Sci. Tec.* 35(2005) 219.
9. V. Kumar, N. K. Goel, Y. K. Bhardwaj, S. Sabharwal, L. Varshne, *Sep. Sci. Technol.*, 47(2012) 1937.
10. C. Srinivas, P. Ravi Shankar, C. Venkateshwar, M. S. Satyanarayana Rao, R. R. Redd, *Poll. Res.*, 19(2000) 285.
11. S. Katragadda, H. D. Gesser, A. Chow, *Talanta*, 45(1997) 257.
12. V. Kumar, Y. K. Bhardwaj, K. Tirumalesh, C. V. Chaudhari, N. K. Goel, J. Biswal, S. Sabharwal, *Sep. Sci. Technol.*, 41(2006) 3123.
13. S. Das, A. K. Pandey, A. Athwale, V. Kumar, Y.K. Bhardwaj, S. Sabharwal, V. K. Manchanda, *Desalination*, 232(2008) 243.
14. A. Zhang, T. Asakura, G. Uchiyama, *React. Funct. Polym.*, 57(2003) 67.
15. N. Misra, V. Kumar, S. Rawat, N. K. Goel, S. A. Shelkar, Jagannath, R. K. Singhal, L. Varshney, *Environ. Sci. Pollut. Res.*, 25(2018) 16101
16. J. L. Gomez, A. Bodal, E. Gome, J. Bastida, A. M. Hidalgo, M. Gomez, *Enzyme Microb. Technol.* 39(2006) 1016.
17. S. Datta, L. R. Christena, Y. R. S. Rajaram, *Biotechnology*, 3(2013)1.
18. C. Mateo, J. M. Palomo, G. Fernandez-Lorente, J. M. Guisan, R. Fernandez-Lafuente, *Enzyme Microb. Technol.*, 40(2007)1451.
19. N. Misra, V. Kumar, N. K. Goel, L. Varshney, *Polymer*, 55(2014) 6017.
20. N. Misra, N. K. Goel, S. A. Shelkar, L. Varshney, V. Kumar, J. *Mol. Catal. B Enzym.*, 133(2016)S172.



Dr. Virendra Kumar is presently serving as Head, Advanced Material Section, Radiation Technology Development Division, BARC & Assoc. Prof. HBNI, Mumbai. He obtained his Masters and PhD degrees from Indian Institute of Roorkee and Mumbai University, respectively. He completed his Post-doctoral research (2007-2009) from Université Pierre et Marie Curie, Paris, France. His research activities include Radiation and plasma functionalized polymers for wastewater remediation, purification of drinking water, recyclable catalytic systems, antifouling, antibacterial & super-hydrophobic surfaces, biosensors, smart hydrogels, etc. He is the recipient of *DAE-Scientific & Technical Excellence Award- 2016*, *DAE-Group achievement award- 2016*, *IANCAS-Dr. Tarun Dutta Memorial Award-2016* and *ISRAPS- Dr. P. K. Bhattacharya Memorial Young Scientist award -2006*. He has about 250 publications, including international journal, conferences, book chapter, technical reports and invited talks in his credit. He has been actively involved in Board of Research in Nuclear Sciences (BRNS) and International Atomic Energy Agency (IAEA) activities in the field of radiation processing of polymers for societal applications.

## Product Profile

### **GR SCIENTIFIC, UK:-**

Aquamax KF Plus

### **THERMOFISHER SCIENTIFIC, USA:-**

GC, GCMS, ICPMS, IC, AAS

### **BECKMAN COULTER, USA:-**

Particle Size Analyzer, Ultra Centrifuge

### **HANON**

Microwave digestion System, Auto Melting Point Apparatus  
Recirculating Chiller

### **SKYRAY INSTRUMENTS CO. LTD., USA AND CHINA:-**

XRF, ICPHPLC, GC, ICPMS, GCMS, LCMS

### **TESCAN BRNO, S.R.O. M CZECH REPUBLIC :-**

Conventional & Variable Pressure Scanning Electron  
Microscope High Resolution Schottky Field Emission  
Scanning Electron Microscope Ultra - High Resolution  
Schottky Field Emission Scanning Electron Microscope  
Combined Focused Ion Beam - Scanning Electron  
Microscope Systems Integrated Mineral Analyzer

### **CHEMICALS & REAGENTS. :**

Mitsubishi, Fimar Chemicals

### **SHINE - CHINA**

ION Chromatography

### **INESA ANALYTICAL INSTRUMENT CO. LTD. CHINA.**

UV-VIS Spectrophotometer  
Flame Photometers

### **GAS EQUIPMENTS / GAS GENERATORS**

GAS Purification control system.  
GAS Piping & Utility Projects

### **SINEO**

Microwave Digestion System

### **SERVICE / SPARE SUPPORT**

Microwave Digestion System  
UV Spectro - Photometer  
ICP, ICP-MS, GC, GC-MS, HPLC, LC-MS

### **AMP TEKNO SERVICES**

406, Devika Tower, 4 A & B, Chander Nagar, Ghaziabad 201 011 INDIA

Email: [neeraj@amptekno.com](mailto:neeraj@amptekno.com), [info@amptekno.com](mailto:info@amptekno.com)  
[contact@amptekno.com](mailto:contact@amptekno.com), [vikas@amptekno.com](mailto:vikas@amptekno.com)  
<http://www.amptekno.com>

Ph. +91 - 120 - 4119585

Mob. +91 - 9311026060, 9310176060

**FTIR, UV-Spectrophotometer  
Nano Drop Spectrophotometer**

**Automatic Kjeldahl Analyzer  
Automatic Polarimeter  
Automatic Titrator**

**FLUORESCENCE SPECTROPHOTOMETER  
GAS CHROMATOGRAPHY, AAS**

**GAS Generator (high Purity)  
For Air, Nitrogen & Hydrogen**

**ION CHROMATOGRAPHY  
AAS**

 **AMP TEKNO  
SERVICES**  
Bringing the World Closer

# Metrohm India Private Limited

Comprehensive solutions for chemical analysis



New generation of potentiostat/galvanostat

from Metrohm Autolab

VIONIC powered by INTELLO



Ion Chromatography



Performance on a whole new level

Omnis - Titrator



Socorex - Pipette



pH Meter - 913

Valid till 31st Dec'21

Metrohm is one of the world's most trusted manufacturers of high precision instruments for laboratory and process analysis. The company was founded in 1943 by engineer Bertold Suhner in Herisau, Switzerland, where it is headquartered to this day.

In India Metrohm India Pvt. Ltd. is serving Indian market for more than 2 decades. At Metrohm, We offers a comprehensive portfolio of analytical technologies ranging from titration and ion chromatography to near-infrared and Raman spectroscopy, as well as several other techniques.

