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A Journey of Translational Research in Engineering Physics

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I was born in 1933 in Chahal Kalan- a small village near Gujranwala in Pakistan. I used to walk about 4km to my school, and read in the light of an oil lamp. My favorite sports were kabadi, wresling and playing free-for –all hockey on a dirt road, and I learned to swim in the village pond. My dream was to become an Aeronautical Engineer. The partition of India brought our family to Delhi where I completed my tenth grade in DAV school in a camp near the Golemarket. With a few career options open even to a topper in those days, Physics was the most preferred choice which is what I did to graduate with BSc (Hons) and MSc (1954) in Physics from Delhi University. We were taught a lot of physics by some of the best known teachers in India in those days. But, sadly, I neither learned much nor I was inspired partly because Physics as taught to us was never related to anything around us which I could appreciate, and partly because the physics laboratory experiments we had to perform as a part of the curriculum were neither exciting nor innovative. This led me to look for opportunities elsewhere.

Inspirational Experience :

When I arrived in the University of British Columbia, Canada in September 1954 to pursue my PhD programme on a World University Fellowship, I suggested to my proposed supervisor that I wanted to learn physics by doing things with my own hands and that I enjoyed doing so and thus I would like to start with learning workshop skills. Shocked to see me in a brand new suit and tie asking to be first trained in workshop practice, he took me to the Workshop and asked someone to put me through the drill of learning the use of various tools, lathes, glass blowing, etc. Subsequently, I designed my own glass vacuum system with a mercury diffusion pump (which is what vacuum technology was at that time), silvered large glass dewars for storing liquid nitrogen and liquid helium, and wired electronic circuits to measure and maintain very low temperatures of a fraction of a degree Kelvin obtained by adiabatic demagnetisation. We had to learn how to liquefy He gas, and recycle it after the evaporation of liquid. Observing the superfluid liquid helium (a macroscale scale quantum fluid) getting out of its container against gravity (a quantum phenomenon) was akin to a spiritual experience for me. Sometimes, such experiments lasted up to 48 hours. My supervisor stayed with me all the time and brought packed food for both of us. This experience of conducting exciting experiments in collaboration with a supervisor as a coworker and mentor left a deep impact on me. Then and there, I made up my mind that, given an opportunity, I would like to set up a laboratory where students and faculty would work together like colleagues, learn to work with their own hands, learn to learn from experiences,

and above all appreciate the need to translate the knowledge so obtained into an asset for society at large. Little did I know at that time that my dream would be fulfilled eventually in the form of an Institution came to be known as "Thin Film Laboratory "(TFL) at IIT Delhi.

Thin Film Research: A New Frontier

As a postdoctoral Research Fellow of the Defense Research Board of Canada at the Royal Military College, I set up facilities to verify the latest BCS theory of superconductivity by measuring ultrasonic absorption in superconductors. This was followed by a stint as a Max Planck Fellow in Fritz Haber Institute, Berlin where I established a low temperature XRD facility from scratch to determine any asymmetry in electron density distribution in hexagonal metals

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In the early 60's, a dramatic change took place in my scientific career. Based on remarkable electronic and optical properties of thin-films,. vacuum deposited ultrathin films of several materials showed great promise of emerging as a new frontier of science and technology Unfortunately, the properties of such films were not reproducible which led some to call it "5th state of matter" (besides solid, liquid, gas, and plasma) I chose to work with two leading industry research laboratories in USA which provided me with a challenging opportunity to establish what thin-films really were and why they showed anomalous properties. Of course, this gave me an opportunity to work in a new, exciting and evolving field of Thin Film Research for microelectronic and photonic applications. As a senior scientist, I was given a free hand to conduct research in any direction which could be of interest to the industry. First of all, many workers set out to find out why thin-film properties were so temperamental. After numerous studies, we all came to the conclusion that properties of thin-films (and similarly nanomaterials created abintio) depended strongly on the way atomic species were created, transported and assembled to create nanomaterials of different dimensions. That is, the birth stages of nucleation and growth of a thin-film or nanomatter determined the nanostructure and thus the properties. This meant that controlled and reproducible deposition parameters were essential for obtaining reproducible properties of thin-films.

I published my research findings extensively and was granted 4 US patents. As early as 1962, I published a paper, the first of its kind, on Thin Film Photocell (solar cell as it is now called) in IEEE Journal. I discovered current controlled negative resistance switching in thin oxide films (a topic which is being revived for commercial applications) Our pioneering work on structural, electrical and optical changes in GeTe thin films at elevated temperatures led private companies (such as Moser Baer) to develop writable CDs. I developed and patented a duoplasmatron ion beam source for vacuum sputter-deposition of hard optical films/coatings. Two decades later, this patent came to the rescue of a US based multinational which was dragged to court with an over one billion dollar legal suit by a rival company for violating their patent for depositing durable laser mirrors used in laser guided weapons for defense. By citing my patent as an evidence of an existing knowledge in the field, the company won the court battle. The news attracted headlines in New York newspapers.

The exciting ecosystem of research in industry oriented research laboratories in US pushed me further to challenge myself to author the very first book in the field. At the age of 32, I spent the next three years in my spare time to write a Treatise "Thin Film Phenomena". Published in 1969, the book was a grand success. The book is globally respected as the "Bible" for newcomers to the field even today. Learning about my work in the new area of Thin-Films, the Director, IIT Delhi inquired if I would be interested in joining IITD. Before long, the Institute offered me a very attractive position of a Senior Professor of Solid State Physics and also offered to pay all my relocation expenses by air for the family. Such a generous offer by a premier institution in India was unthinkable in those days. I could hardly refuse this golden opportunity to fulfill my dream of setting up a research laboratory in India with a paradigmatic difference. We arrived in Delhi on August 23, 1970. My wife and I met the director of IITD on the 24th morning. Warmyly welcoming me to IIT Delhi, the Director handed over personally the keys of the bungalow at 10, West Avenue, IITCampus bungalow which became our future residence for 17 years. This warm welcome and reception led me to resolve to burn the bridge to my attractive US position (from which I had taken leave), and, come what may, justify the trust posed in me by IITD.

The Birth of the Thin Film Laboratory (TFL):

I was shown around the Physics department and, in particular, two large empty rooms where I was supposed to set up my research laboratory. A PhD student, who had decided to join me even before I joined IIT, was keenly waiting to talk with me. I told him that if he was prepared to accept the rough and tough role of a pioneering scientist, he was welcome as my student. Thus, both of us started together to clean the floors of what would become the globally famous Thin Film Laboratory (TFL). I had mentioned in my recently published book that growing polymer films epitaxially and doping them appropriately would be a fruitful area for R&D in developing new materials. We devised a very simple solution growth technique with very little equipment to deposit thin-films of well-known polymers such as PVC, PVB, etc. By doping and incorporating different metals in the polymer films, we created what came to be known as semiconducting "Metallopolymers". We received our very first grant of Rs 30,000 as a DST sponsored project to synthesize conducting polymer films which boosted our spirits and our credibility. We were well ahead of time in creating semiconducting polymers but were not good chemists. The discovery of conjugated polymers some 8 years later led to the Nobel Prize discovery of conducting polymers by a Japanese and two American chemists. No, we were not disappointed. Our simple Solution Growth Technique became a popular technique for synthesizing and studying polymer thin-films by numerous workers globally and our original papers were cited widely.

The number of students keen to join TFL for PhD and MTech projects started increasing rapidly. We needed to build all-purpose vacuum systems for thin-film research. A workshop was created in TFL out of whatever old tools were available within the institute All students, male or female, had to learn to use the workshop for building equipment with whatever was available anywhere in junk, waste or scrap form. The students built several vacuum systems for evaporation, and for sputtering. Since large metal vacuum chambers were not available anywhere in the market, our students bent stainless sheet into a cylindrical chamber by sheer muscle power and welded it. Improved diffusion pumps, crude pressure gauges, electron beam gun, sputtering modules, quartz crystal and optical monitor, ellipsometer, DLTS, EBIC, spray pyrolysis system rapid quenching set-up, among others, for thin film deposition by different techniques were created by *jugaad* (an Indian version of innovation).

After his visit to TFL during 1976, Dr Arcot Ramachndran, the then Secretary of the DST, asked me what DST can do for TFL. I asked for a Nanoanalytical Facility. Dr Ramachanndran lost no time in sanctioning Rs15 lakhs. I persuaded a US company which, at that time, was developing a Scanning Auger Microprobe -cum- Electron Spectroscopic Chemical Analysis, to give us the instrument for experimentation and evaluation at a nominal coast of Rs. 15 lakhs. The SAM-ESCA was the first such instrument anywhere in India We maintained and used this instrument extensively for almost two decades. We received some more analytical equipment such as an electron microscope and spectrophotometers under the Indo-UK aid agreement With further development of facilities, TFL became a foundry to develop a large number of home-made physical, chemical, and electrochemical thin-film deposition techniques and a range of micro and nano-analytical tools. At one time, TFL was considered globally as one of the few best Thin-Film R&D facilities under one roof.

Our research contributions were appreciated globally. TFL attracted lots of visitors – foreign dignitaries, academics from all over the world, and several Nobel Laureates. The TFL was open and functioned 24X7. The Nobel Laureate Dr Abdul Salam visited TFL in the late evening. A theoretical physicist, himself, he was so impressed to see our work that he asked me if we could set up a similar facility in the International Centre for Theoretical Physics, Trieste, Italy of which he was the Director at that time. Two prominent Japanese scientists came all the way only to verify our claim of having created transparent conducting ZnO films for the first time. German scientists visited at night to look at our work on thin-film CdS/Cu_2S solar cells. The vice President of IBM Research Centre at Yorktown Heights, USA spent six months of his Sabbatical leave in TFL. The list of prominent visitors is endless.

Invitations to me for lectures came from all over the world. Requests for engaging my students for postdoctoral fellowships came on telephone from many scientists abroad. The CEO of ULVAC- a leading Japanese Vacuum and Thin Film Company - requested me to send three of my students as PDFs on a 5-year contract. During my visits

abroad, I spent some time to consult at the Research Centres of IBM, Westinghouse, and ARCO in USA. The pinnacle of our global recognition came when TFL was asked to hold the 7th International conference on Thin Films in 1987. With 700 participants, including three recent Nobelists, from all over the world, the Conference held in Vigyan Bhavan is still remembered by the world community for the high quality of presentations, superb arrangements and hospitality- all taken care of by the TFLians.

Significant R & D Contributions of TFL

Some of the original and most prominent scientific contributions from TFL during my time are listed as follows:

- Developed Semiconducting Metallo-Polymers
- Developed graded refractive index multilayerd coating– the first "photonic crystal" (as it would be called today) of its kind-for nearly perfect reflection mirrors
- Established rigorously electron transport processes in thin metal and amorphous semiconducting films.
- Developed ZnO based bulk and thin-film varistors. The technology was transferred to WS Insulators, Chennai.
- Developed scientifically a Chemical Bath Deposition process for CdS Films – which some call it a Chopra process- used globally by all Thin Film Solar Cell industries today.
- Developed, for the first time, Transparent and Conducting Thin Films of ZnO which in its bulk form is a well-known insulator. Such ZO –TCO films are now used extensively by thin film solar cells and other optoelectronic industries- without, unfortunately, giving credit to us
- Discovered structural and optoelectronic changes in various Ge-chalcognide films which has led to the manufacturing of CDs
- Discovered Giant Photocontraction Effect in Ge-chalcogenide films and demonstrated its lithographic and reprograhic applications
- Detailed study of the Physics of Thin Film CdS/Cu_2S solar cells
- Developed nanostructured aluminum oxide template for synthesizing nanostructured optically selective coatings for solar–thermal applications. Creation of templates of various materials is now an established industry
- Developed hard metal carbide and nitride coatings for surface engineering and machine tools

Since patenting of innovations was not encouraged in educational institutions at that time, we missed an opportunity to patent several significant innovations which were adopted in due course by global industries. However, TFL attracted industrial consultancy assignments and thus interacted strongly with the industry in India. Various consultancy jobs, and technology development and transfer assignments were executed by our students under the supervision of the faculty. The first consultancy assignment in IITD was offered to TFL by the then well-known razor blade company manufacturing 7-O'Clock shaving blades. We were required to improve the smoothness, sharpness and life of blades by coating nanometric Cr films by a sputter-deposition process. The project was successfully executed to the satisfaction of the razor blade company by our students who also tested the performance of the blades by regular shaves in the morning inside TFL.

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Some of the interesting consultancy and translational research projects undertaken by us were:

- Sputter deposition of Cr on 7 O'Clock razor blades (Malhotra Razor Blade Co)
- Study of nanostructure of imported silica powder for rubber tyres (Good Year, Delhi)
- Thin Film CdS Photo- cells (manufactured by Patel Enterprises, Bangalore)
- Thin Film Colour Coatings on Opthalmic Glasses (Laxmi Opticians, New Delhi)
- Manufacturing of Electron Microscope grids (Montek Industries, Chandigarh)
- ZnO Varistors (manufactured by W S Insulators, Chennai)
- Moire Gratings for Lathe Machines (HMT, Bangalore)
- Thin Film Strain Gauge for Roorkee University

- Thin Film IR Detector for DRDO
- High power Electron Gun (manufactured by VICO, Delhi)
- Magnetron Sputtering module (manufactured by VICO, Delhi) ;
- Optical Monitor for Thin Film deposition (Hind High Vacuum, Bengaluru)
- Optically Selective Copper Black Coatings for solar- thermal applications (Jyoti Ltd and BHEL)

A Unique TFL Ecosystem for Engineering Physics:

The conduct of original and high quality research by PhD students, training and mentoring MTech students, mentoring by postdoctorals, and translational role of all for providing consultancy service and for technology transfer required a new model under Indian academic conditions. It called for a seamless and effortless environment for moving from physics to engineering physics. A unique ecosystem was evolved which made it possible for TFL to grow into an Engineering Physics Institution for learning, mentoring, working collaboratively, hand holding, family-like group activities, innovations and entrepreneurship. Some of the salient features of this system are as follows:

- Keeping TFL neat and clean was the responsibility of all- students, staff, and faculty- under my personal supervision. The cleaning activity was carried out every month on Saturdays and was followed by snacks and tea for all in a convivial get-together.
- TFL was open all days, including national holidays, on a 24X7 basis
- Total responsibility for running and maintaining major instruments in good working conditions rested with the faculty and students assigned for each facility.
- Before starting any research work, every student was expected to spend a few months to learn to handle workshop tools, learn to know who was who and who was doing what and why in the TFL. The success of this homogenization process of the student was evaluated by me before being allowed to proceed to start his/her work independently.
- Irrespective of who the official supervisor(s) of the student was, he/she had access to all the TFL facilities. At the same time, every student was expected to help any other student who needed help.
- Coming punctually to TFL in the morning was mandatory for students. Random discussions regarding their work were held with individual students during the day. Though working in TFL in the evenings after dinner was discretionary, most students worked at nights.. I visited TFL frequently after dinner largely to chat with the students working at night.
- Publication of any research paper by a student or PDF was allowed only after rigorous discussions. Students were expected to write drafts of the paper. The paper was submitted for publication only after approval following thorough discussions and appropriate changes.
- On completion of PhD, every postdoctoral fellow (PDF) was obliged to spend at least 1-2 years in TFL to mentor our MTech, and PhD students. Whereas PhD students concentrated on research for a PhD thesis, MTech students were expected to demonstrate a working device or instrument, or a proof-of -concept of a new device. The PDFs learned how to mentor and work with others and also they were exposed to the process of translating research ideas to a useful product or process. Our research projects provided Fellowships to PDFs and they were assured of another PDF assignment abroad. Exceptional achievements by anyone were rewarded with a special prize.
- The TFL group, which became as large as 40 persons, including several faculty members, had a weekly packed - lunch meeting for 2-3 hours. Everybody brought a packed sandwich lunch and we sat together to eat it. By rotation, a group of students had the responsibility of preparing and serving hot- I mean piping hot- cups of coffee to all of us. Using the consultancy money earned by TFL, excellent facilities for making tea/coffee were set up. At the weekly lunch meeting, students and faculty had an equal opportunity and freedom to talk about any problem or subject related to his/her project, availability of any instrument, any new global developments in the area, any controversial views on academic matters, etc. This meeting was invariably full of heated debates and excitement.

- Seminars in TFL by the students and faculty were held regularly and ritually on Saturday afternoons. These seminars often led to intensive and spirited discussions. Students were encouraged to participate in such discussions
- Very frequently, a visiting distinguished academic/ researcher visitor from India or abroad joined our group lunch. His/her sandwich lunch was sent by my wife along with mine from my house. Discussions by students with such visitors were encouraged and were often quite animated. These face to face discussions with prominent scientists in the field generated a lot of confidence among our students
- TFL was the first destination of visit by distinguished political and academic guests of IITD. While taking the visitor around, I expected the students to explain as to what they were doing and why. This nurtured student's confidence and sharpened their communication skills.
- Any event calling for shared joy and happiness provided an opportunity for a group dinner party. Such events included the publication of a first research paper, award of a degree, offer of a PDF from abroad, any form of professional recognition, marriage etc. The party was held at my residence with cooked food brought from outside by the students. With students, faculty and their wives sitting on the floor of my large drawing room, the dinner was followed by a long jam session wherein individuals recited poetry, sang, told jokes and stories, etc. I contributed a few Urdu couplets that I was fond of writing in my younger days. My wife contributed jokes. The group experienced a very warm and intimate family togetherness
- The students, faculty and their families looked forward to periodic picnics arranged and managed by the students. The larger TFL family enjoyed picnic food as well as sports.
- The TFL Code of Conduct included punctuality in all activities, equality among all researchers, transparency, duly earned credit for authorship, strict discipline and disciplinary action against any form of scientific misconduct, plagiarism or conflict of interest. Toughened by this kind of discipline, TFLians cite this attribute as one the most important contributing factor to what they are today

Mentoring of Entrepreneurship :

During my 17 years at TFL, I supervised/co-supervised 55 PhDs and some 60 MTech projects .All my students have done well in a variety of technical professions as teachers, researchers, entrepreneurs and Chief Executives. Officers. We published over 300 research papers and a large number of review articles in international journals of repute. Several of our papers became classics by virtue of citations. One of our reviews on Transparent Conducting Oxide Films had the distinction of being the most cited paper in the international journal for over two decades in a row. Our two monographs, namely Thin Film Solar Cells and Thin Film Device Applications, first in the field, were co-authored with my two students, Suhit Ranjan Das and InderJeet Kaur, respectively.

There was a global demand from reputed academic institutions to employ my students as postdoctoral fellows (PDF).The feedback from those who invited my students for PDF was that my students were enterprising and indeed were up to any challenge, even in new areas of research Over a dozen of my PhD students have chosen to become entrepreneurs and they have set up their own successful industries in related areas, both in India and abroad. Milman Thin Film Systems created by Milind Acharya in India, FLISOM (Flexible Solar Modules) established by Ayodhya Tiwari in Switzerland, Coatings Mantra established by Sunil Kumar in Australia, InSTech (information, science and technologies) Consultants by Jagriti Singh in Australia, RF Array Systems Inc. by Chandra Deshpandey in India and USA, etc. are some notable examples of such companies. Several global Thin Film Solar Cell companies are being steered by my former students.

The IIT Kharagpur Challenge:
I served IITD as Head, Physics Department, Head, Centre for Energy Studies, Dean, Post Graduate Studies and founder Dean, Industrial Research and Development (IRD). As a Dean, I was keen to translate my enthusiasm for nurturing innovations on a larger platform of the institute. The Department of Science & Technology offered all financial support and land to IITD to set up a Science Technology Entrepreneur Park (STEP). Although I was very enthusiastic about the project, the then Director of IITD was not so keen on this venture which he considered as

being beyond the purview of the Institute. And, then in 1987, a totally unexpected event took place. I, a Physicist, was persuaded by the Ministry of Human Resources & Development to take up the challenge of heading and reviving the run down IIT, Kharagpur- the mother of other five IITs, as I call it.. Apprehensive though I was, I accepted the challenge and started head-on with academic, management and governance reforms and innovations The blueprint for these changes was essentially the same as that for creating TFL which included : leading from the front by action and by example, total transparency in all activities of the institute, treating faculty, students and staff as partners in progress and in reinventing of the institute, and strict enforcement of ethical values and codes of conduct for all stake holders.

Despite being busy with the IITKGP affairs, I continued my research albeit at a slow pace. Several research students and some faculty members helped in setting up a state of the art Microscience Laboratory. During my tenure of 10 years at IIT, I co-supervised 4 PhDs, and co-authored a book on "Vacuum Science and Technology" with Professors V V Rao and T B Ghosh. We explored new and emerging areas of science and technology of thin-films. We developed a chemical technique for synthesizing nanopowder of multicomponent oxides on a large scale. The technology was transferred to ACC. The alumni of Microscience Laboratory have done well professionally.

The creation of a STEP in IIT Kharagpur was topmost in my mind and, indeed, was one of my priorities. The WB government gifted 100 acre land area near the IIT campus for the proposed STEP. Mr Jyoti Basu, the Chief Minister of West Bengal and I laid the foundation stone of STEP which was sponsored by DST. This STEP, the only one among the IITs even today, and one of the 12 STEPS in the country, is presently doing well and is self-sustaining. Several IITs have subsequently followed the example of IITKGP by setting up different versions of tech - parks such as an incubator, technology business incubator, technology park, etc.

Some of the novel and innovative ideas adopted by us in IITKGP for translational work through academia-industry interaction are:

- Members of the faculty, alumni, and students were encouraged to become entrepreneurs in STEP so as to explore the commercial viability of their research outcome in IITKGP. This was an extraordinary step that was taken for the first time in the country. I am happy to state that similar concepts have now been adopted by most IITs
- Faculty members were allowed to earn any amount from their successful ventures in the STEP as long as accounting, transparency and IIT's share of turnover were assured through the STEP management.
- Joint ventures with selected industries in the area of expertise of IIT faculty were initiated
- The industry was persuaded to sponsor Chairs with the proviso that the Chair Professor would conduct research work in areas of mutual interest Both Joint Ventures and Industry Sponsored Chairs were unique concepts in Indian academia at that particular time. Both concepts have now been emulated by other IITs.

After retirement from IITKGP, I have continued to persuade many technical and academic institutions in the country to take a step towards any form of STEP as an integral part of training and nurturing technical manpower. I have helped establish Incubators in St Xavier's College and West Bengal University of Technology in Kolkata. Several other institutions have sought my advice to initiate steps in the direction.

Concluding Remarks :

Today, the economic power of a country is determined in no small measure by its knowledge power. A transparent, liberal, flexible, seamless, multidisciplinary and ethical ecosystem must be created in the academia to produce, disseminate, and nurture translational and transformative knowledge. Such a system has indeed enabled my numerous students and faculty colleagues to contribute to the success of our journey towards translational research in physics and engineering physics. Any success in a multidimensional research results only from a group effort. I had the privilege of working with many gifted co-workers during my long academic career. Indeed, I stand on the shoulders of my colleagues. I have received numerous awards and honours from the government of India, professional bodies and academic Institutions. The Life Time Contribution Award in Engineering to a physicist by

education and engineering physicist by practice is a very special one which recognises what a research group "thinking individually and working collectively" in a seamless academic environment can achieve.by the fusion of science and engineering. I am immensely grateful to the Indian National Academy of Engineering for the recognition and honour conferred on me.