Face to Face

This section features conversations with personalities related to science, highlighting the factors and circumstances that guided them in making the career choice to be a scientist.

The Challenge Of Thor

Anil Kakodkar talks to Sujata Varadarajan

…These are the gauntlets
Wherewith I wield it
And hurl it afar off;
This is my girdle
Whenever I brace it,
Strength is redoubled!

…Force rules the world still,
Has ruled it, shall rule it;
Meekness is weakness,
Strength is triumphant,
Over the whole earth
Still is it Thor's Day!

(The Challenge of Thor, H W Longfellow)

These words, written in the nineteenth century, describing a challenge issued by the Norse God of Thunder, Thor, appear curiously apt in describing the challenge of unleashing the power of thorium (named after the God himself) in current times.

Thorium (Th), a silvery white, naturally occurring, slightly radioactive metal has leapt into the headlines after recent political debates on India's nuclear strategy. India, which has very little natural uranium, has an estimated quarter to a third of the world's thorium reserves. Much of this is in the form of Monazite deposits along the southern and eastern coasts.

Box 1. Thorium: An Option for Nuclear Fuel

Thorium is 3-5 times more abundant than uranium in the Earth's crust.

Thorium (Th-232) is not fissile and needs an additional step to convert it to the fissile element U-233. So this involves higher fabrication cost than a uranium based reactor.

The physical and nuclear characteristics of thorium make it a more efficient fuel than uranium. [A]

Thorium based fuel produces 10 to 10^4 times less radioactive wastes than uranium or plutonium based fuel. [A, B]

Th-232 can also form protoactinium (Pr-233), an intermediate with a long half-life (27 days). Most of this eventually forms U-233 but some of it is diverted to other pathways, thus reducing efficiency. The uranium fuel cycle does not generate such long-lived intermediates.

[A] http://en.wikipedia.org/wiki/Thorium_fuel_cycle;
[B] http://ie.lbl.gov/education/isotopes.htm

The skyrocketing price and limited availability of uranium (U) has led to India's choosing thorium as a nuclear fuel for the coming years. In addition, the thorium fuel cycle is more efficient and cleaner than that of uranium (*Box* 1). Though uranium has been traditionally used in nuclear reactors world wide (*Boxes* 2, 3), several scientists acknowledge the potential of thorium as a fuel source for the future. Notable amongst these is the Nobel laureate Carlo Rubbia[1], who has also proposed a safe, controllable fission reaction (fission explained in *Box* 4), called Energy Amplifier, which is similar to the Accelerator Driven System (ADS) (see *Box* 5) on which much research is currently being carried out.

www.barc.ernet.in/press/2007/images/2007014.jpg

India has evolved a 3-stage nuclear power programme (terms explained in *Box* 6), which will use:

1) Pressurized heavy water reactors (PHWR) and light water reactors, fuelled by natural and low enriched uranium respectively, to produce plutonium (Pu-239).

[1] Carlo Rubbia, along with Simon van der Meer won the Nobel Prize in Physics, in 1984, for the discovery of two high energy particles called the W and the Z.

Box 2. Nuclear Reactors

Nuclear reactors are devices in which nuclear chain reactions are initiated, controlled and sustained at a steady state. The heat generated by nuclear fission reactions in a reactor is of the order of 10^6 times that produced by an equal amount of coal, and this heat can be converted into usable energy.

Commonly used isotopes in nuclear reactors are:

- Natural uranium: a mix of U-235 (fissile) and U-238 (fertile, converted to the fissile Pu-239).
- Enriched uranium: uranium containing a higher amount of U-235 than natural uranium.
- Plutonium (Pu-239 is fissile, used as a nuclear fuel and for making nuclear weapons).
- Thorium (fertile), converted to the fissile U-233.

The critical mass of nuclear materials is arranged in specific geometric shapes, in an optimal configuration, within a nuclear reactor. This is the *reactor core.* Once the reaction is initiated, neutrons are released by the fuel within the nuclear core. These are often too fast to propagate further fission and need to be slowed down by moderators (eg., light water (H_2O), heavy water (D_2O), etc.). Thermal reactors use slowed or thermal *neutrons to initiate fission* and fast neutron reactors directly use fast neutrons (the fission reaction depends on the concentration of fuel used). The number of fissions occurring is *modulated by control rods* made of a neutron absorbing material (eg., boron, cadmium, etc.). Inserting the control rod deeper into a reactor reduces the rate of fission and extracting the control rod increases the rate of fission. A *cooling source* (light water, heavy water or a liquid metal) circulates around the nuclear core. This absorbs the heat generated and transfers it to another source which *generates steam to run turbines* for electricity production.

Box 3. Uranium Nuclear Reactors

Natural uranium comprises of predominantly U-238 (currently approximately 99.3% by weight), U-235 (approximately 0.7% by weight) and traces of U-234, a long-lived decay product of U-238. Enriched uranium, often used in reactors, is uranium containing a higher proportion of U-235 than natural uranium. This is done by a process called isotope separation.

In a light water reactor, nuclear fuel rods typically consisting of enriched uranium in the form of an oxide are stacked in bundles in the reactor core. Control rods containing hafnium or cadmium are used to modulate the reaction. All this is enclosed in a water-filled pressure vessel called reactor vessel. Light water (H_2O) functions as a coolant as well as a neutron moderator (it slows down fast moving neutrons). In the boiling water reactor, the heat generated during fission turns the coolant water into steam which can be used to drive turbines. In the pressurized water reactor, the coolant water is kept under pressure to increase its boiling point. In this case, the coolant does not boil directly, but the heat is transferred to another loop, which then produces steam.

Heavy water reactors are based on the same basic principle as light water reactors. However, they typically use natural (unenriched) uranium as fuel, heavy water (D_2O) as a neutron moderator and coolant. Heavy water absorbs fewer neutrons than light water, making it a more efficient moderator and enrichment of the uranium fuel is therefore not required.

Box 4. Nuclear Fission

When neutrons of particular speeds hit the nuclei of some heavy elements, the nuclei absorb these neutrons and then fragment. This results in the formation of lighter elements with the release of energy, radiation and neutrons. This process is called fission. Elements which undergo fission are termed fissile. During fission, some of these released neutrons may be absorbed by other fissile atoms and a chain reaction could be set up in this way. This is the principle used in most of the nuclear reactors.

Examples of fissile materials commonly used as fuel in nuclear reactors are U-235 (an isotope of uranium) and Pu-239 (an isotope of plutonium). U-233, though not a naturally occurring isotope of U, is also fissile and is produced by the transmutation (nuclear conversion) of thorium (Th-232) when it is irradiated with neutrons. In this case, Th-232 captures a neutron, is converted to Th-233 and then decays to form U-233, which is the nuclear fuel in thorium based reactors.

Certain elements are not fissile, but can be converted into fissile elements after irradiation with neutrons– these are called fertile isotopes. Examples of fertile elements are Th-232 (an isotope of thorium) which can be converted to the fissile isotope U-233 and U-238 (a naturally occurring isotope of uranium) which can be converted to the fissile isotop.

Box 5. Accelerator-Driven System

In the accelerator-driven system (ADS), high energy protons are made to collide with nuclei of high molecular weight atoms (such as lead) resulting in a reaction called spallation, where high energy neutrons are produced. These can be directed to a reactor containing subcritical thorium (the thorium fuel cycle normally doesn't pump out enough neutrons by itself to sustain the reaction with a comfortable margin). This results in the conversion of Th-232 to U-233 and its subsequent fission. Thus a fission reaction can be sustained and easily regulated by controlling the generation of neutrons. The ADS can also be used to destroy heavy isotopes, especially actinides and long-lived fission products which are the non-useable components generated through fission, in nuclear reactors. It does this by transmuting (converting one isotope or element into another through a nuclear reaction) these into shorter lived radioactive isotopes which decay rapidly.

2) Fast breeder reactors (FBR) using plutonium based fuel to enlarge nuclear power generation capacity and to produce U-233 from Th-232. The core and the blanket around the core will have U as well as Th so that more Pu-239 will also be produced.

3) Advanced heavy water reactors (AHWR) to burn the U-233, Pu-239 and Th-232, getting about 70% of their power from the Th. The used fuel will be reprocessed, fissile materials from it separated and recycled.

Dr. Anil Kakodkar has been an active proponent of the use of thorium as a nuclear fuel for many years. A highly skilled and experienced engineer and nuclear technologist, his words are not to

Box 6. India's 3-Stage Nuclear Programme

- PHWR is a nuclear power reactor that uses heavy water as a coolant and moderator. Heavy water absorbs fewer neutrons than light water, making efficient use of the neutrons emitted and allowing the reactor to function without fuel enrichment. The heavy water coolant is kept under high pressure to raise its boiling point so that it can absorb more heat without boiling.

- FBR is a nuclear reactor that generates new fissile material at a rate greater than that which it consumes. Production of fissile material in a reactor of this kind takes place by irradiating fertile isotopes along with some fissile isotope. The fertile material may be present in the core (along with the fissile isotope) or in a breeder blanket surrounding the core, or in both. In the FBR being developed in India, the centre of the fuel rod contains plutonium, which is the seed for the reaction. Wrapped around this is a blanket made of a mix of uranium and thorium-based fuel. The plutonium provides the necessary neutrons to the blanket to kick-start the thorium and uranium fuel cycles, resulting in the generation (breeding) of U-233 and Pu-239.

- AHWR is an innovative advanced nuclear reactor using thorium as its main nuclear fuel. It is light water cooled, heavy water moderated and uses (Th-U-233) O_2 and (Th-Pu) O_2 as fuel.

be dismissed lightly. He was appointed Director of the Bhabha Atomic Research Centre (BARC) in 1996. He has been Secretary of the Department of Atomic Energy (DAE) since 2000 and has recently retired. He is a member of numerous national and international academies. He was a member of the International Safety Advisory Group in 1999–2000.

Dr. Kakodkar's enthusiasm, clarity and precision are evident through his words, which remain unpretentious and down-to-earth while describing futuristic and challenging goals. Through his conversations, he comes across as being a pragmatic and very gracious person. His aptitude for troubleshooting and his single-minded drive to achieve targets have contributed to his tremendously successful career path.

At a relatively young age, he played a key role in the design and construction of the 100 MW reactor Dhruva (one of the most powerful and useful reactors of its kind), which required the development of innovative processes of engineering and technology. Subsequently, he found new ways to enhance the safety mechanisms of nuclear reactors and pushed to the forefront the development of PHWRs and FBRs. He has also succeeded in rehabilitating the nuclear reactors Kalpakkam-1 and 2 and Rajasthan-1, which were on the verge of being written off. He was involved in the Pokhran experiments, both in 1974 and 1998. His endeavour to make India self sufficient in energy generation has spurred on research in thorium based nuclear reactors, the design of the AHWR and experiments on the ADS in the country.

He has received several accolades for his contributions to the field of nuclear energy technology and his service to the nation, including the Padma Shri in 1998, the Padma Bhushan in 1999 and the Padma Vibhushan in 2009.

After studying mechanical engineering, Anil Kakodkar chose to apply to the Atomic Energy Establishment (now BARC) rather than take up a corporate job. The decision (as he explains) was driven by his interest and personal goals. Selection of a viable career track remains as difficult and relevant a question today as it was in the sixties, if not more so. When one has the option of an attractive corporate job, why consider working in a government institution, especially one oft criticized for its lack of transparency and accountability? Some of the answers are provided by Dr. Kakodkar in this interview. But there are others, which are sometimes overlooked. India is apparently paving the way to becoming a key player in alternative nuclear energy research and development (some of the other countries being the US, Japan, Russia France, China and Korea). Its achievements in the areas of fast breeder technology and thorium based reactors are unique.

SV: Could you talk about your early education and how the path led you from mechanical engineering to atomic energy?

AK: I was born in a small town in Madhya Pradesh, a town called Barawani. I did my entire schooling in a nearby place, a relatively bigger place called Khargaone. It's a modest sized town, maybe 50,000 population. However I had the good fortune of having some very good teachers. I developed a liking for Mathematics because we had a very good Mathematics teacher whose name was Buddhivant. I think as a teacher, as a mentor, he was just superb. He had a sense of doing things with an elegant mathematical logic – solving an arithmetic problem the arithmetic way and not the algebraic way.

Then I came to Mumbai for college education – this was in 1958. It was an urban setting so there was all this problem of adjustment; there was also a problem of language in the sense that I did my primary school in Marathi (although it was a small place in Madhya Pradesh). After that my secondary school education was all in Hindi and in college it was English.

In Ruparel college, I did Intermediate Science. In those days you did first year and Intermediate and then you would go on to do engineering or BSc. When I passed out of Intermediate Science, I again went to the Vice Principal just to thank him because he had given me admission without knowing my marks, and to say that I had cleared with good marks and all.

He asked me, "What are you going to do?"

So I said, "I'll do BSc. I'm continuing in our own college" and he said, "No, no, no, you have got good marks, you'll get admission in an engineering college."

In those days the application forms for admission to engineering colleges were routed through science colleges. So he said, "Nothing doing, tomorrow you come to my office and I'll give you the form for the engineering college. You fill it up and give it to me."

I said, "No, but I want to do BSc."

In those days one could not argue too much with teachers. They knew what was best for children. So he said, "No, all that we'll see later, but you fill in that form, you come tomorrow."

I was in no position to contradict him or counter him. So I said, "Okay, I'll come to your office tomorrow."

As I was leaving, he said, "By the way, I'm sure you'll get admission in the engineering college but supposing there is a necessity for you to continue in BSc, what subject do you want to do?"

By that time I was getting more interested in Physics. For BSc, you have to specify two subjects (a main subject and a subsidiary subject), so I said, "I want to do physics, mathematics."

He asked "Why do you want to do physics, mathematics?"

I said, "Because that's what I like, so that in MSc I can do Physics."

He said, "If the need arises, I'll give you admission in BSc but in mathematics, physics, not in physics, mathematics."

I said, "Why?"

He said, "You don't know, you're a young fellow. This world is not so straightforward as you may think. I don't want you to do MSc in a subject where there are practical examinations," because – according to him, the marks you got in practical examinations had nothing to do with your caliber. "A lot of manipulation goes on and if you don't score well in MSc then you have no career, no future. On the other hand if you do mathematics, then you are your own master, nobody can interfere with your performance."

I got admission in engineering and it seemed to me that I had better take his advice and go to engineering, and so I landed up in VJTI (Veermata Jijabai Technological Institute). I did mechanical engineering from VJTI. To get into such activities which allow you to explore things, which allow and to do new things everyday, was very attractive to me and after completing the engineering degree, I went and met several people. Some of them said, "If you join the Atomic Energy Establishment in Trombay – BARC's name in those days was Atomic Energy Establishment – you may get a job of the kind that you are looking for."

In those days the job market was such that we were all eagerly sought after, so I had – not only I – all of my friends had a full file of appointment letters, in many cases even without going for interviews. Industries used to send appointment letters if they came to know you were passing out from VJTI. They would tell you, "We are doing the following things, you may be interested in joining us and if you are interested, fill in this form and send it and then come to us." My colleagues in VJTI were not in favour of my joining Atomic Energy Establishment. When they came to know I was thinking of something like this, they put huge pressure on me not to do it, not to get into a government job. They said, "You must get into an industry job," because government jobs were not high paying.

So when they knew that I had got this call letter for the interview, some of my friends took away that call letter. They said, "You are not appearing for that interview." And I actually missed the interview. I was already recruited by a company the day I finished my examination. Even before the results were announced, I already had a job and I had started working.

But this thought that, "No, I must work in Atomic Energy," was still in my mind. My friends gave me back the call letter after the interview date was over thinking that it's now useless. So I took that letter and went to the Atomic Energy Establishment. The interviews there go on for 10–15 days and they were still going on. So I told the person there, "I was supposed to come on such and such date, but for some reason I couldn't come. I would be happy if I could be interviewed now."

He was angry but I persisted saying that I have come because I'm interested in the job. Finally I was interviewed by one of the committees and was selected.

I entered the training school and we were the 7th batch. It was a good experience. I was the top ranker in my batch. At that time we had a system (even now we continue that system) in terms of the final placement of the trainees. Normally your placement goes in accordance with your rank and available choice. But for top rankers, they would even go out of their way to create a specific position of your choice.

I opted for Reactor Engineering because I found that's one place where I can use my engineering knowledge and background. I thought I'll join the group called Power Reactor Design Section – which has gone through several transformations and today it is Nuclear Power Corporation.

However, the people in the Reactor Engineering Division advised me to work on the development aspect.

So I thought, "Maybe that's the right advice," and I got into the engineering laboratory. This allowed me to get involved with the reactor development (aspect) right from scratch. We had to conduct heat transfer experiments on a large facility, looking at the containment both from the point of view of the stress analysis as well as energy management. So I did lots of experiments and it was really a satisfying experience. I learnt the relative importance of different parameters, how to balance the different competing demands when you're working on a complex system involving several areas.

SV: What did you work on subsequently?

AK: After the work on Madras Atomic Power Station containment system, we took up the development of reactor components of a standardized 220 MW PHWR which required a lot of work at several levels – this was in the sixties. Later they asked me to work on the 100 MW Dhruva reactor.

The reactor was new, even conceptually. There was no reactor identical to this anywhere. All reactors work on the same principles, but in terms of design concept it was quite new. The project consisted of several systems, but the main reactor system was given to me. The people responsible for the other systems were older than me by at least ten years. I was the youngest not just in years but in experience. It was useful. You learn to deal with people much older than yourself.

SV: You designed the core?

AK: Yes. Well, the physics was being done by someone else but then I had to engineer that. The core geometry that was worked out was not the best geometry for engineering (it). Based on the background I had acquired, keeping the important physics parameters the same, I had to transform the core map to make it more convenient from the engineering point of view. So that involved a lot of work. The reactor was a multipurpose facility. It provided experimental facilities for a lot of people – those engaged in neutron scattering, or in irradiation for a multitude of science studies. To develop a system which provides the required neutron flux output at thermal energy as well as fast energy for different users was a lot of challenge. A configuration of that kind could not have been evolved unless we resorted to electron beam welding for example, and this on a very large scale did not exist. So we had to build an electron beam welding facility and this was done by some of my friends who were on the technical physics side. We had to put it through a lot of qualification checks. Manufacturing people –

they would not accept a new technique of this kind because they felt that this would not be robust and reliable, but it was clear that unless we adopt such new technologies we cannot realize our goal.

Then there was the question of making openings – for neutrons to come out of the reactor you require openings which are transparent to neutrons, but still be a barrier for heavy water. We thought of creating windows of zirconium alloy connected with the stainless steel construction. The windows were required to be quite big – almost 30 cm diameter. So – how to connect this? You can't weld zirconium alloy and stainless steel. We had to develop mechanical rolled joints. It required its own tooling to be worked out, so we got a tool made. Reentrant cans of zirconium alloy had to be fabricated by welding. That's a reactive material, so welding had to be done again using an electron beam, but of a different technology. The stainless steel calandria (part of the reactor core, containing heavy water) was welded by a machine where the electron beam welding machine sits on the job in the open – it's called partial vacuum technique – that's one kind of welding technique. The reentrant cans were welded in a full vacuum – you put the item to be welded in a vacuum chamber and then carry out the welding – a more standard way of electron beam welding. That was done and so it was, I think, a major effort, first of its kind. Then, we also thought that we should try out some new ideas in this reactor – ideas emerging for power reactors. So, it was a lot of fun in terms of experimenting and developing.

During commissioning, we had a lot of problems with vibration and everybody said this reactor will never work. Then, slowly we diagnosed that using noise analysis techniques and then we fixed that problem.

A little before I started work on the Dhruva reactor, I was also roped in for the first Pokhran experiment. I also did design another reactor called Pulsed Fast Reactor – which never saw the light of day. It was a reactor where you take a reflector block very close to the reactor core at very high speed and in so doing, pulse the reactor – take it to a little beyond critical as a matter of fact, and then quickly move it away to cut off the chain reaction. The reflector sitting at the tip of the large rotor spinning at high speed sweeps past the reactor core and thus you periodically pulse the reactor core – that was the concept. And the question was – can we have a block of beryllium spinning at a very high speed and can that be brought at that high speed very close (within mm distance) to the reactor core and be flipped away. We carried out the design of the rotor but finally this reactor was never built.

SV: Why did you want a pulsed reactor?

AK: For experiments you require a very high flux. Now, in a steady-state mode, if you produce the same very high neutron flux, you have to also cope with very large power evacuation. Then, the engineering of the reactor becomes very complex. On the other hand, if you run the reactor in a pulsed mode then you get neutron impulses at a very high level with fairly modest power evacuation system. Its utility for experimentalists goes up many-fold, but at the same time, in terms of the thermal management complexity, it's not very big. So there are lots of advantages in that kind of reactor. It didn't get realized, but it was of course a great experience.

SV: How did you plan the process of thorium reactor development?

AK: We had done small-scale irradiation of thorium and Kamini was either being built or had just been built. It's a 30 KW system, running on U-233. The next logical step was to enhance our experience with thorium. Major technology initiatives were necessary, because transition from second stage to third stage will have to take place at fairly high capacity deployment level. So although we knew thorium utilization at pilot-scale or laboratory-scale, unless we acquired large-scale technology experience with actual power generation, we would not be able to make the transition quickly. We thus needed to develop thorium power reactors.

It was about the time that there was the fall out of Chernobyl. So, the world had started moving in terms of enhancing the safety of reactor systems. There was a lot of work in terms of operational safety as to how to improve the existing reactors. There was also debate about whether we should talk about further evolution or for that matter revolution in the reactor technology. Revolution – in the sense of a completely novel way of bringing in new thoughts so that safety is taken to a significantly higher level. That debate goes on, even today. The argument is – on one side you should make only incremental changes on the basis of proven experience so that you are on a very sound footing. At the same time if you make incremental changes, your improvements will also be incremental. On the other hand, if you think of a completely new idea you can make a paradigm shift, something completely new. And so, is it possible to think of a reactor system which depends very little on the active systems – you see in the reactor systems – the pumps have to work, valves have to work and the control system as a whole has to work. There is a philosophy in nuclear reactors that you must design it with such a high degree of safety that the operator has some time to react, i.e., there should be a forgiving period. Even if the operator does not take any action following a plant upset during this time, the reactor should not get into unsafe domain. Normally this time is of the order of half an hour. So we said, "No, no, can we think of a configuration which will enhance this operator forgiving period to a very large number – say 3 days – 72 hours?"

Normally, around a nuclear reactor, we have containment. Then we have an exclusion area. We acquire something like one mile around the reactor and keep everybody away – essentially we

Box 7. Thorium Reactor

In the (thorium) reactor – thorium gets converted to protoactinium and that decays and then you get uranium-233, just as in the uranium-plutonium cycle, uranium gets converted to neptunium and then it gets converted to plutonium. The half-life of neptunium is very small, so transition from uranium to plutonium is rather fast whereas the half life of protoactinium is larger so the transition is slow, which means that whatever protoactinium will form, it remains in the reactor for a long time. Some of that protoactinium, depending on the neutron population could also see other branches – it could absorb a neutron and become a higher isotope. This problem is more severe if the neutron flux is higher. So it is clear that a good thorium reactor should have low neutron flux, so that you'll get efficiency in terms of the conversion from thorium to uranium-233. For thorium you want a reactor with low flux, or low power density. Now, on the other side, you also want a passive system for cooling. You don't want to depend on a pump, rather you want to depend on natural phenomena for cooling – thermosiphon. The two are quite consistent. If you want thermosiphon cooling, you cannot do it with very high power densities. This is a concept that has seen the best of both worlds, from the aspect of safety and efficiency.

create a barrier between the public domain and the reactor. So I said, "It may be okay today but when you want to expand then this will not be practical. You will not find so much of place. Can we think in terms of a configuration with which everybody will feel comfortable and safe even if it is located right in the heart of a big city – no exclusion distance? Can we think in terms of a system which is not dependent on complex equipment?" – because they add to cost and also you have to attend to them with much greater attention. I further thought, "Can we make a very simple, operator forgiving reactor which does not depend on complex systems and is dependent primarily on passive systems?"

Now the Advanced Heavy Water Reactor (AHWR), apart from producing electricity from thorium has addressed some of these issues. This has of course taken a lot of time and a lot of developmental work. We are actually ready to start construction of the nuclear reactor (*Box* 7). The configuration of the reactor is quite innovative.

We also said that we should talk about a reactor which has a very long life, otherwise the question is – if the reactor's life is say 30–40 years, what do you do after 30 years? Decommissioning, waste (management) – is also an issue. So we planned this reactor (to run) for at least 100 years. Initially we used to talk about 25–30 years of reactor life, nowadays we talk about 40 years. Occasionally we talk about 60 years. But with AHWR we are talking about 100 years and that is another engineering challenge and a lot of development has been done in this area.

We are also concerned about high-level waste. It was known even earlier, but in the context of

AHWR, it's even more clear now, that if you irradiate plutonium or even other minor actinides along with thorium, you can carry out the incineration of those materials in a much better way. There is a magnitude lower production of minor actinides with thorium compared to the uranium–plutonium cycle and that gives net advantage in terms of incineration of long-lived waste.

All these advantages have been realized by way of an innovative configuration of systems based on existing technology. Internationally, there is a programme called INPRO – International Project on Innovative Nuclear Reactors and Fuel Cycles. Such programmes have some of the objectives which I have mentioned. They were looking for case studies so we offered AHWR as a case study. That has made a good impact internationally. They all recognize that this configuration can work. Other countries are working on fourth generation reactors[2] but as far as AHWR is concerned, we are meeting all those requirements today. So, this will allow India to leapfrog, not only in terms of thorium but also in terms of futuristic reactor technologies. Of course, now we have to start constructing the reactor and it will take another 7– 8 years. These are all programmes which go on for a long period where a number of people work at system level, sub-system level, etc. A number of things have to be understood, a lot of hard data has to be generated, many tests have to be done to quality process steps, it's great fun…

SV: How do you feel at this crucial juncture about your efforts in developing thorium-based reactors?

AK: I think this experience has given me a lot of happiness. It is clear that whatever you do, if it makes an impact, you feel happy. The impact can be out of your innovative publications or innovative technology development. When your work addresses an important need it makes an impact. If your work gives you a relative time advantage the impact is higher. I am looking forward to exploring this field even further.

You see, thorium for us is very important because we have it in plenty and we don't have too much of uranium. Thorium is not going to be a matter of priority for the rest of the world. So, obviously, we can't await evolution of this technology elsewhere and then adopt it. We can't afford such loss of time.

So, the idea is – we should carry out our own research, our own translation of that research into technology, and make that technology available to society. If you do something completely

[2] Fourth generation reactors are nuclear reactor designs that are still being researched with the primary goals of improving safety, improving proliferation-resistance, minimizing natural resource usage, minimizing waste generated, decreasing capital and running costs.

new, there's a lot of national advantage and I think as far as atomic energy is concerned, it will be crucially important.

Look at our 3-stage programme. About the early years, we can say that we have developed a technology which is similar to what somebody else has developed. But we have done it indigenously, we are very proud about it. We are today in commercial mode of deployment of this technology.

Fast-breeder reactor technology has been around – initially it looked like it will take-off. However a number of countries slowed down or even stopped fast-reactor development. Today, once the 500 MW prototype fast-breeder reactor which is under construction at Kalpakkam is ready, it will be the second largest reactor in the world. The first one, a 600 MW unit, is in Russia. And in fact, worldwide it is recognized that India is globally advanced in terms of fast breeder technology.

But then, beyond thorium, there are possibilities of deriving a lot of advantage by way of accelerator systems – accelerators can be used to run the reactors in sub-critical mode and you can get a slightly better doubling time, little faster growth with thorium systems (in this way) because otherwise thorium systems don't grow so easily like plutonium–uranium. You cannot grow thorium–uranium systems (but) you can set up a fast reactor and grow the capacity. So that's how we put the thorium–uranium after the fast reactor so the growth is through fast reactors and then we can sustain the generation capacity for many, many years based on thorium.

Accelerators will also play an important role in terms of transmutation because of very high energy neutrons and also as industrial tools [2]. We are talking about accelerators which run at a very high energy, say 1 GeV or 2 GeV, and currents of the order of several mAmps. Now such accelerators don't exist. Supposing you want to do this in India, who will build it?

If you ask engineers of today that can you run a big project – let's say 5000 crore project on accelerator driven systems, they will not be able to do so. They know how to build a nuclear reactor, they know how to build a large reprocessing plant but they don't know how to build this accelerator. So you need to create a new breed of engineers who understand the accelerator physics. You also need scientists who can engineer such projects on a large scale. So, I think the boundary between 'this is science and this is engineering' has to vanish. We want to be able to build systems which are dependent on multidisciplinary knowledge. We need to strengthen our capacity in the management of activities at the interface. Atomic energy has always been good in inter-disciplinary technology work but we need to emphasize this much more.

With this basic logic, the Homi Bhabha National Institute was created. Today there are around 600 registrations for PhD. Here we want to emphasize on research on the interface between knowledge activity and practical applications as also on capability building to carry out such a translation. I think there are front-ranking research opportunities in this domain which will make a big impact on the society.

There is also a joint activity between DAE and Mumbai University on what we now call as Centre for Basic Science (CBS), at Kalina in Bombay University campus. It's actually quite small right now, there must be 40–50 students. Faculty there – while they engage with children also carry out their research and in fact, involve some of these bright chaps in that. Some very eminent people periodically come there and talk on various aspects of scientific research in physics, chemistry, biology and mathematics.

Their labs I think are quite innovative. The students – plus-two students, who have joined this year or a year before – remain engrossed in the lab work. During the vacation we thought the children will go back to their homes, but we were surprised to learn that none of them went back. They were all working in the labs. The idea is to prepare these children to learn various aspects of science and experimental skills. Otherwise they will become dependent on others to provide the experimental tools or experimental equipment. Then the limits or capability of the instrument decides what research you do, not the other way round. There will also be PhD students who carry out their research under these guides. So this whole undergraduate teaching will be in an ambience of high level research, as at NISER (National Institute of Science Education and Research) or IISER (Indian Institute of Science Education and Research). CBS is however distinctive in that it links up proximate research and education institutions with an existing university. Success with this model could lead to a large multiplier possibility to enhance experimental research culture in our universities.

SV: Do you get time for doing research?

AK: My work is basically more of developmental type. Earlier, of course I used to spend a lot of time in these activities. Nowadays I'm not able to spend as much time though I am still involved in AHWR,, but there is a structure and I am a part of that structure.

SV: Will the segregation of civil and military programmes result in the duplication of facilities?

AK: In fact it's very clear that there'll be no such segregation and no firewalls. It's the other way – what we have promised is that we will collaborate with the rest of the world in civil nuclear energy and whatever we get from outside will be under the IAEA (International Atomic Energy Agency) safeguards. But all the other programmes are outside safeguards. For example, earlier we were subject to embargo particularly for strategic activities and this embargo may well still continue. We are talking about the civil nuclear cooperation and there will be no diversion from here to strategic side. This has in fact been our policy right from the beginning.

What is civil and what is not civil is for us to decide. It is not a kind of generic dictionary definition. We will define it only on the basis that it has to be eligible for international cooperation. There has to be no bar there. For example, our nuclear power programme began in Tarapur. Tarapur has been under IAEA safeguards from day one, but we have carried on with our (other) programmes. So, same thing will be true (in the future). There will be a programme with international cooperation and we will continue our programme in an autonomous manner depending on what our country needs and in fact there is a provision that nobody will interfere with that. I'm not saying that the embargoes will vanish. But there is no question – whatever we want to do, we'll do.

Let me explain a little bit about the purpose of civil nuclear cooperation. If you look at the energy requirements of India and you provide for the full contribution of every source that you can think of within the country – coal, hydro, hydrocarbon, even the three stage domestic nuclear power as it is now – you will find that, all put together, there is a 25–30 % deficit. How do you bridge that gap? You have to import fuel for that. If you import it in the form of coal, it would be equivalent to something like 1.6 billion tones of coal annually by the year 2050. Today's deficit may look small, but these deficits are going to become much larger in years to come because economy is growing,and people will require more energy. Availability of energy resources of such large magnitude in itself would be a big issue besides the infrastructure to manage imports on such a large scale.

But, having gone through the 3-stage development through fast reactors, you can see a multiplier possibility. What I say is 10,000 MW capacity in the first stage can become a few 100 GW over a period of time without the need for any additional uranium from mines. If we use the recycle programme, the fast (breeder) reactor programme, and if we do our things well, it's possible to bridge that gap by 2050 and there will be no necessity to import energy of any kind. It's a question of expanding the base and then running the 3-stage programme logic. We can do so without sacrificing our strategic interests.

SV: Would you like to communicate anything more to the students in the country?

AK : If you ask me what is India's strength, I would say India's strength is our young people. In fact, for all the projections about India reaching the top of the world in years to come – the central driving force is our demographic advantage. Now, if you want to fully benefit from this demographic advantage, you must empower the young people through good quality education so that they become useful to the society, useful to themselves, in terms of both earning their livelihood, but more importantly (in terms of) making a contribution to national development. Now, depending on the level to which you are able to empower them, this process will be faster or slower.

I think we need to do two things: one – allow the young people to get into any vocation –not necessarily only science, I'm talking about any vocation where their aptitude would allow them to excel. They must excel. That's the key. If a larger part gets into science and technology, I think that it's a great advantage because I think the leadership positions would be driven by technological capability of the country. Also, we should create opportunities for students to be able to go through what I call the holistic experience. You learn not just the knowledge part of it but also the skill part of it, which is done through actual experience. So this learning should be a way of hands-on experience while you are learning, quite similar to what used to be in our old ashrams or for that matter if you go abroad, in some of the best educational systems, the students get that kind of learning. Some community service or community exercise may be part of that learning, working on nationally important projects could be part of that learning, learning entrepreneurship could be part of that learning and of course, excelling in the subject that you are studying should be part of that learning.

Students, I think, should seek opportunities of this kind and our system should provide these opportunities. If we do that, I think that very soon we should reach the top. The fact that we will reach the top is very clear, but how soon it happens depends on the young people. Other countries are not going to sit idle so the rate is an important factor.