Fusion power, who needs it?!

P. K. Kaw

It is pointed out that the fusion community world wide has not aggressively pursued a faster pace of development, which can indeed be justified on the basis of its technical accomplishments, because of certain faulty assumptions. Taking some relevant data of energy consumption (based on fossil fuels) and its environmental impact in the projections for developing countries like India and China, it is demonstrated that there is extreme urgency (time-scale of less than 20–25 years) to develop technologies like fusion if one has to prevent stagnation of per capita energy production (and quality of life) in these countries. We conclude by calling for a new agressive goal for the world wide fusion programme, namely development of a demonstration power plant producing electricity in an environmentally acceptable manner by the year 2015.

The title of this article is 'Fusion Power: Who Needs it?!' My chief concern here is that we in the fusion community, have come to accept a pace of fusion funding which could be better described, by a title 'Fusion power? But who needs it, right away?'. At a time when our technical accomplishments world-wide are excellent, and our experiments are producing beautiful results, we are less than ambitious in our request for funding. When we should be running, we are barely crawling! Thus no new tokamaks have been constructed or are under construction for so many years now, in spite of several excellent proposals. Our next generation experiments (INTOR, NET, SSTR, ITER) continue to be caught up in the loop of design and redesign and re-redesign and.... we have no major fusion technology facilities. We glibly talk of 50 years time-scales for commercial systems and so on. I believe that the reason for this state of affairs is that we, as a community, have formulated a set of questionable premises (never explicitly stated but more or less tacitly accepted by everybody). These are,

1. Energy situation in the world is comfortable and there is *no urgency* to develop fusion technology.
2. Even if fusion technology is developed faster, nobody will buy it, because it will be *too expensive*.
3. We can develop and *perfect* the technology over the *next 50 years or more* and then it may be put to commercial use.

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Are we really comfortable on the energy front?

Here I present a perspective that I know best, viz. that of developing nations like India and China (similar trends are visible in other parts of Asia, Latin America and Africa). Table 1 presents the data on per capita consumption of electricity in several countries. It may be noted that whereas the average consumption in most of the developed world is more than 6000 units/year, the figure for India is a meagre 250 units/year, i.e. 4% of the average in the developed world. Many will argue that the actual consumption in the developed world today is too high and is likely to come down because of efforts in energy conservation and improved efficiency of energy systems. Even if the numbers come down, it is instructive to note that India today is at 1/6th of world average (1500 units/year). When the energy planners in India and China think of the immediate future (up to 2020), they at least think of coming up to the world average. What are the energy requirements then? Table 2 summarizes the data. It may be noted that even at this modest requirement, India and China need ~1 terrawatt of power by 2020. Let us next ask how this

Table 1. Per capita consumption of electricity in different countries (1990)*

	1 unit = 1 kWh	
Canada	19000	May reduce because of energy conservation and improved efficiency drives.
USA	12000	
UK	6000	
Japan	7000	
Brazil	1850	
China	500	
India	250	= 1/6 world average

* Bhasin *et al.* (ref. 4).

Table 2. Power position and projections in India* and China**

	Year			
	1950	1990	2000	2020
India	1.5 GW	65 GW	100 GW	450 GW
China	?	120 GW	250 GW	500 GW

*Chand (ref. 5).
**Zhou, D., *et al.*, (ref. 1).

Table 3. Distribution of power generation methods in India and China

	India*		China**	
Supply option	1990 (GW)	2020 (GW)	1990 (GW)	2020 (GW)
Thermal (coal + oil + gas)	44.5	220	115	400
Nuclear	1.5	30	0.5	45
Hydro	19.0	180	5	55 (Hydro + Nonconventional sources)
Nonconventional sources	–	20	–	
Total	65	450	120	500

* Chand (ref. 5).
** Zhou, *et. al.* (ref. 1).

electrical energy is likely to be generated. In the absence of any new technologies, our planners base the projections on the existing methods of energy generation. Table 3 illustrates the distribution of power generation methods in India and China for the year 1990 and projections for 2020. It will be noted that about 1/2 terrawatt of additional power production will be by burning fossil fuels. What conclusions can we draw from the above tables? It is clear that in the next 20–25 years massive increase in the use of fossil fuels for power generation is going to take place in the developing world (the typical factor will be about 5). This will seriously degrade the local environment in these countries. We already see warning signs in China, which has to use a lot of coal for power generation. It *has been noted that China already has the highest atmospheric sulphur dioxide in a city anywhere in the* world; acid rain has been observed[1] *in* Chongquing, Nanchang, Changsha, etc. Let us assume that the developing world can live with a somewhat degraded environment. However, what is likely to happen after 2020 *is really frightening*. As described above at 1500 units/year per capita consumption (which is only 1/4th of that of the average in the developed world), India and China alone will be generating about 1 terrawatt of electricity, half of it from fossil fuels. This is 10% of the total world production today. Beyond 2020, if they *bring up the consumption to that of the developed* world and if we add the requirements for the rest of the countries in the developing world, the *impact on the global environment is simply staggering*. This means that if we continue to rely on fossil fuels for our energy needs, we will literally choke up on this planet. Very severe comparable warnings have come from scientists who have examined the impact of continued use of fossil fuels on accumulation of CO_2 in the atmosphere and the associated greenhouse effect.

There are other points of concern also for the developing world. The massive dependence on fossil fuels makes them vulnerable to oil price shocks. This became very clear during the seventies when the oil crisis took place. Oil prices have and can be put at a level which is out of reach for developing countries. It is also important to note that one cannot assume major contributions to power production *from fission power* as there are important questions related to safety, *public acceptability and international safeguards*.

So, where does this state of affairs lead one to? It *seems that the world will have to make one of three* choices:

(i) Every nation in the world must *reduce* its energy *consumption significantly.*
(ii) We allow *stagnation* of per capita energy *consumption in developing world.*
(iii) We have increasing *impact* of new technologies like *fusion*, renewable energy sources, etc.

Choice (i) would be made in an ideal world. It is *unrealistic to expect that it will be made in the real one!* Choice (ii) seems to be the most *likely* one. In fact it is *interesting that energy planners in the developed world* are already talking about such scenarios in their futuristic documents[2]. What the developing world would really like is that choice (iii) be available.

My conclusion is that the energy scene in the developing world is far from comfortable. The worst scenario is one where these countries are forbidden to burn coal because of environmental constraints, cannot buy oil/gas because it is too expensive and cannot use nuclear power because of safety issues and international safeguards. So, what do they do then? It is obvious that *there is urgency to develop a new technology like fusion.*

With what certainty can we say that fusion energy will be more expensive than other energies?

Table 4 is extracted from a recent report published in *Nuclear Fusion* and compares the projected costs of electrical power generation among thermal, fission and fusion power systems. It is to be noted that fusion power costs are only marginally higher than those of fission and thermal power. In fact if one makes agressive assumptions in physics and technology (as in the Aries II design), fusion power costs are quite comparable to those of other systems.

Importantly, Table 4 also shows that in the thermal power costs, a significant element is the cost associated with fuel. We must therefore ask, what determines the

Table 4. Costs of electrical power options*

	Thermal (coal)	Fusion		Magnetic fusion	
		PWR-ME**	PWR-BE†	Aries-I (Tokamak)	Aries-II (Tokamak)
Net electric power (MWe)	2 × 550	1100	1100	1000	1000
Cost of electricity mills/kw-e-h					
– Capital	22	57	30	53	35
– Operation & maintenance	6	13	9	7	7
– Fuel etc.	22	8	7	6	6
– Decommissioning	0.1	0.6	0.6	0.5	0.5
– Total	50	78	46	66	48

*Conn *et al.* (ref. 6).
** ME, Median experience.
† BE, Better experience.

cost of fossil fuel? For example, it is clear that there is nothing like the 'real' cost of oil and that the cost is totally determined by the oil cartels and political conditions in the world. Figure 1 is an illustration of how the cost of oil has varied in the past 20 years or so. One can see that in the late seventies, the cost of oil jumped almost by a factor of 3 within one year. This is because the oil cartels had decided to increase the price of oil. Another important factor in the cost of fuel is the tax structure in each country. As an example, in Table 5 we have shown the prices of several gasoline products in different countries in 1986. It may be noted that at the same given time, the prices of gasoline and kerosene varied by as much as a factor of five between Mexico and Italy. This again clearly shows that there is nothing like a real price for a given fuel. There are other important factors involved. At the present moment, a strong environmental lobby is asking the question, who

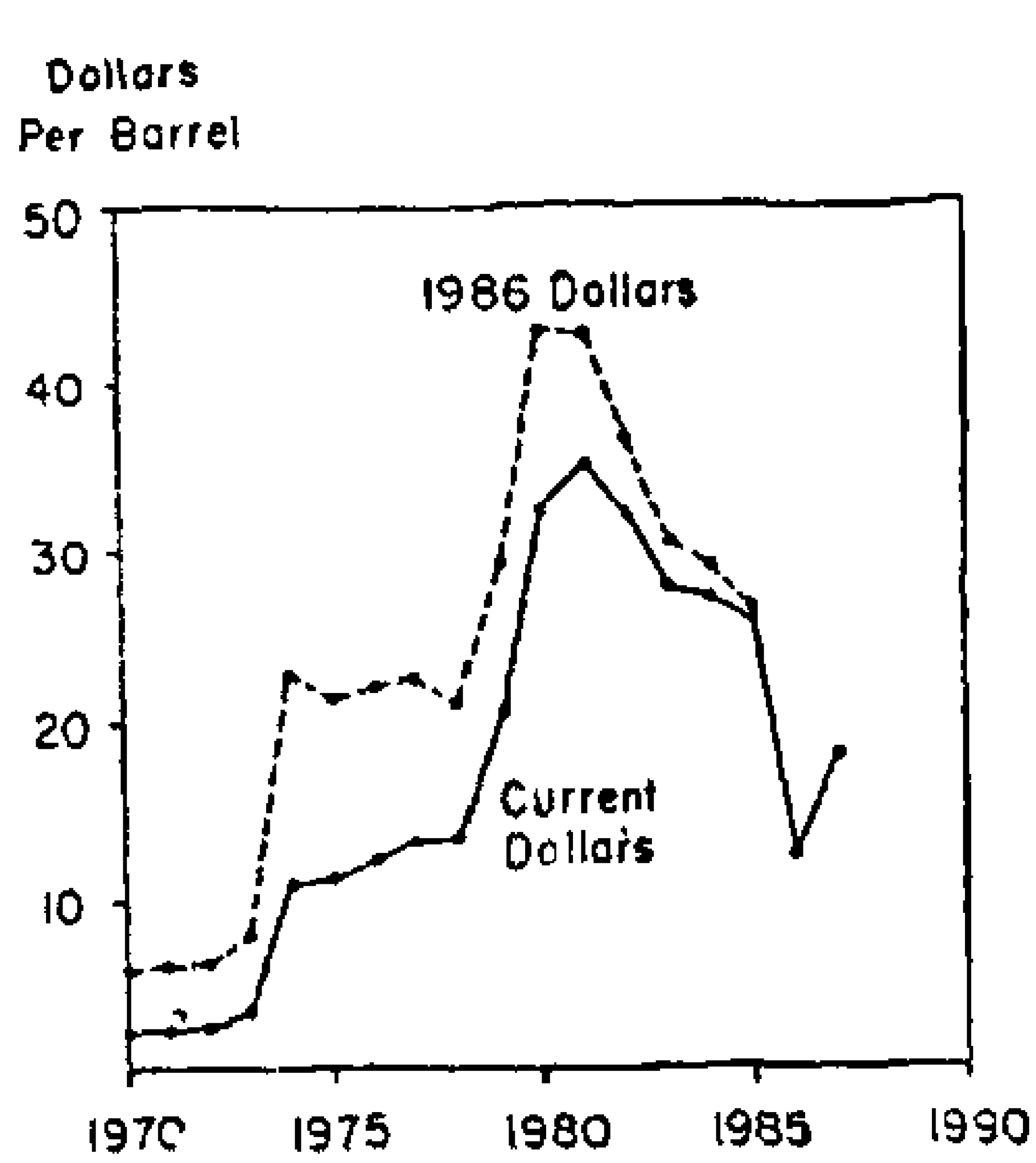

Figure 1. World price of oil, 1970–87. (Sources: US Department of Energy and the American Petroleum Institute)

Table 5. Prices of some petroleum products

Country	Gasoline	Diesel	Kerosene
	(Price in dollars/gallon)		
Italy	3.71	1.55	1.56
Brazil	2.94	1.92	1.07
Japan	2.89	1.80	1.08
UK	2.24	1.77	NA
India	2.17	1.01	0.65
USA	0.82	0.87	0.83
Mexico	0.71	0.61	0.30

(Source: *USDOE: International Energy Annual* 1986).

should bear the cost of clean up of the mess created by fossil fuels? There are serious suggestions of a Carbon Tax to be imposed on all fossil fuels, which could readily increase the electricity costs by 10–20%. I understand from a colleague in Europe that in certain quarters, a taxation level as high as 50% has been proposed. Other relevant questions which are being asked are who should bear the cost of security of oil-rich regions, cost of strategic petroleum reserves, etc.? Should all these costs continue to come from general taxation of the public or should they be internalized in the cost of fossil fuel? We may conclude that it is by no means certain that the cost of energy from fossil fuels is likely to stay at the levels where it is today. It could significantly increase. Much will depend upon how long the various vested interests (oil lobbies, utilities, etc.) are able to protect themselves, through political connections.

The fission power cost column of Table 4 illustrates another interesting point. There is a factor 2 difference in the *capital* cost between the median experience (ME) and the best experience (BE) (in fact the capital costs of fission reactors have ranged over a factor 5 from $ 1300 to $ 6000 per kilowatt electric[3]. The basic reason for these substantial variations is that if effort is put into standardization of equipment, licensing reforms, improved project management, etc., the actual costs can be considerably reduced[3]. Yet another aspect can play a role in reducing the cost of a new technology when it comes into the market and starts competing with the existing ones. This is illustrated in Figure 2, taken from the data for a renewable energy technology based on photovoltaic cells. It may be noted that in the early eighties, as the number of worldwide photovoltaic shipments significantly increased, there was a steep decline in the average price per peak watt.

So, what may one conclude from the above arguments? Given the substantial uncertainties described above, can one really say that fusion power is going to be definitely more expensive than thermal or fission power? The question that I would like to ask my fusion colleagues here is that if fossil energy prices go up by a significant factor in a few years, are we ready with an alternative technology? Can we take over what cannot be done by fossil fuels at that time? When the fusion community says that we will not develop fusion *today* but will, do it slowly over a period of 50 years because the power it produces *may* be more expensive (based on uncertain arguments of the type critically examined above), the lay public thinks 'Here is another swindle for fifty years!'. I believe that the time has come that we actually demonstrate to the tax payers who support us, in as short a time as possible, that fusion can indeed produce electricity. Even if our power costs are higher than those of existing power systems, we would be far more credible as a group. To give this technology a chance, we must get it out into the market. Similar things have happened in renewable energy source systems. Many of these technologies are costlier than present energy systems but they are out in the market and people can see that they really work and generate electricity.

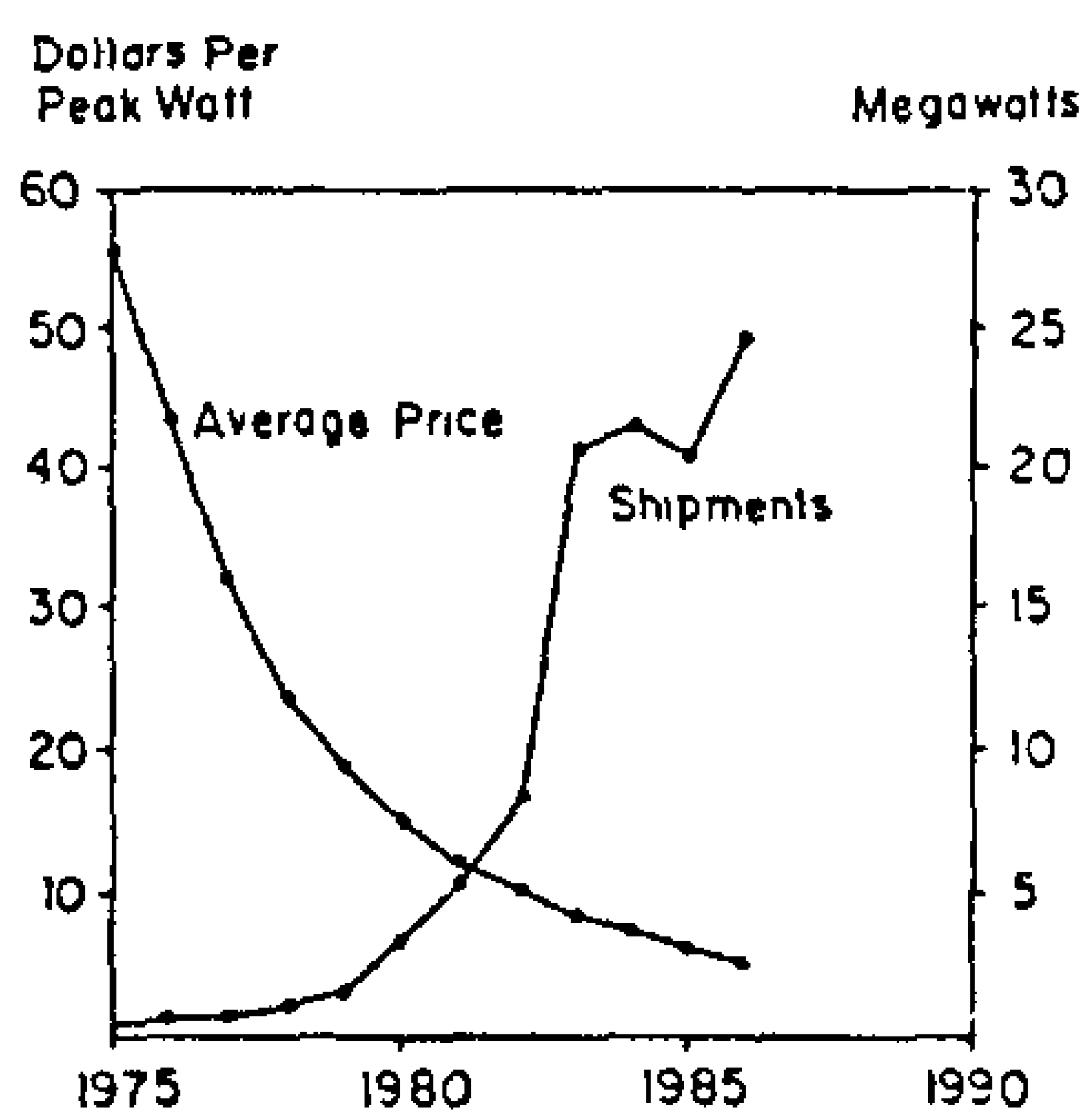

Figure 2. World photovoltaic shipments and average market prices, 1975–86. (Sources: Battelle Institute and Paul Maycode Strategies Unlimited.)

Can we perfect this technology slowly over a period of 50 years and then put it to commercial use?

I believe that the answer to this question is a definite NO. In 1955, at the first Geneva Conference, Homi Bhabha had declared that fusion systems producing energy would be developed within two decades. When in the nineties, after working on the problem for 35 years, the community goes around saying that we still need 50 years to exploit fusion as a commercial technology, it has two negative effects: (a) One gives a very poor impression about the actual accomplishments of the programme. Nobody outside the community really gets to know what it is that has been achieved in the last 35 years. The fact that we are really manipulating large, reactor grade plasmas that have nearly reached break-even conditions gets lost. (b) It leads to a rapid loss of our credibility. When we say that fusion systems still need 50 years for development, the lay public thinks that perhaps such systems will work in the twenty-second century. The planners do not take us seriously at all; they probably believe that these systems will never work. In the past few weeks, I have been scanning the energy planning documents of several developed and developing nations to see if fusion energy is included in any documents as a major source of energy production at any time in the twenty-first century. I did not find even a single mention anywhere. This shows the degree of credibility we carry in the minds of planners. We simply have not reached them or they do not believe us. Some of my colleagues will argue that we have to be cautious and that in the past we have suffered because we promised too much too quickly. But when caution begins to hurt programmes, it is time to question the basic premises. We are already on the back burner and let me assure you that there is a very short distance between the back burner and the garbage can. If we keep talking of 50 years time-scales of development, it is not clear where we will end up.

There are several other reasons why we should not talk of very long time-scales of development. The fusion programme has made very significant progress in the past decade. This has given our technical programmes considerable momentum which is likely to die if we talk of very long time-scales. Secondly, it is important to emphasize that the world has created a major human resource in the fusion scientists and engineers, some of whom we see here today. This is an asset which we should not squander away. There is every likelihood that this group will disband if we talk of very long time-scales. It is also certain that no fresh blood in the form of bright young people is going to enter a programme which is seen as very long term. If we ask a bright young man today whether he would like to join an effort which *may* lead to something useful fifty to hundred years down the road, there is every likelihood that he will shun away.

Finally, we must realize that the perfection of a technology only occurs by competition in the market place. There is no way that fusion systems can be perfected in the quiet of the laboratories. We thus need to build real life systems as soon as possible and then let them improve by competition.

A new goal

I hope that the above discussion has convinced you that we, in the fusion community, have made a set of faulty premises and allowed them to dominate our thinking on the pace of fusion funding and fusion research in the world. I think that it is time to reorient ourselves and define a new goal which I would like to put down as follows: We must bring fusion systems to a level such that *fusion power is considered as a credible energy alternative on the fastest, technically realistic, time-scale.* We must demonstrate generation of fusion electricity as early as possible and show that it is environmentally better than the other competing energy sources.

What are our major uncertainties in realizing this goal? The technological issues involved are well-known and we will hear a lot more about them during the Conference. Briefly, we must demonstrate ignition without significant degradation of critical plasma parameters, impurity control, fuelling and ash removal, long pulse or steady state operation; we must find acceptable new materials for plasma facing components and first wall, develop hot blankets for breeding tritium, demonstrate reliability, high duty cycle and safety and so on. Many experts believe that the above problems can be addressed and solved in 2–4 tokamak systems, built partly in parallel, over the coming 15 to 25 years. That is, in principle, we could have a *demonstration power plant as early as the year 2015.* We must *make this a goal of the world fusion programme.*

Let us ask what this really requires. The most important thing is that we have to raise resources for such a programme. At a very rough estimate, this overall development should cost around US $ 50 billion in twenty years. This is by no means a large sum to develop a technology which will satisfy the energy hunger of this planet for all time to come and considerably improve the quality of life. Let us put this number in some perspective. We are nearly five billion people on this planet today. Thus one is asking for US $ 10 per person in the next twenty years (50 cents a year!). Is this too much of a capital to invest for a future energy source? Let us give another perspective. If one charges 1 cent per gallon 'fusion tax' on gasoline one can generate this much revenue in less than 5 years and the consumers won't even notice. Yet another perspective. This total cost of development is likely to be less than the cost of a Space Station which is very much under consideration in several places. Another perspective can be given in the form of cost of high-tech defence systems such as SDI which may indeed be redundant in the present post-cold war era. The total cost of fusion development is likely to be less than the cost of a few such pieces of equipment. Thus the total cost of fusion development is not so large that the world cannot comfortably bear it. It is simply a question of convincing the right people. But if we have to convince others, we must first convince ourselves and then speak with conviction. We must spend some time in educating the general public about what fusion can do, what the stakes are if it is not developed early enough, what our actual accomplishments in the last 30 to 35 years are and so on. We can learn from the example of NASA which has done an excellent job of keeping the public informed through excellent educational material in the form of publications, video films, advertisements, films, etc. We must also develop a strong lobby which will work for us with various governments and international bodies. We must establish linkages with other like-minded groups who are interested in improving the environment and quality of life all over the world.

Conclusions

1. There is urgency to develop new technologies like fusion since otherwise per capita energy production (and the quality of life) in the developing world is likely to stagnate in 20–25 years.
2. The fusion DEMO generating electricity in an environmentally acceptable manner, should be built as rapidly as technically feasible, say by the year 2015. This calls for an aggressive development of a number of parallel systems which solve the various problems of physics, technology, safety, environmental acceptability, etc. Some pruned version of ITER could be one of the required parallel systems needed for overall development.
3. To raise resources for an accelerated programme, we must spend effort in educating the general public, the energy planners, the environmental groups, the politicians, etc. about the merits of fusion and about how close we have come to the final goal. Resources should become available because the developing nations can be convinced that this is the surest means of ensuring a decent standard of living for their citizens and the developed nations can be convinced that there is a huge energy market out there which can be tapped and that they cannot continue to pollute the environment at the rate at which it is being done at the moment.
4. A few words about international cooperation. We

know about developments in ITER and the international cooperation among the four major blocks. But this collaboration, totally leaves out programmes in the rest of the world. I would like to briefly discuss about them. Programmes in many countries, especially some of the developing ones, have now started to mature and must establish linkages with each other and with mainstream activities like ITER etc. Considering the importance of fusion for developing nations, it should be possible to raise resources for a joint mature experiment which can then address an important set of questions for the mainstream fusion programme. This can also be treated as an insurance so that at some point of time in the future, if the developed nations feel that they would prefer to wait, the developing nations can take off on their own and solve their energy problems themselves.

Finally, I cannot resist the temptation of quoting Academecian L. A. Artsimovich. In response to a query he is reported to have said, 'The first fusion system will be built when there is a great need for it'. I believe that if Lev Artsimovich were alive today, he would have been a rather unhappy man. Not because we have not taken his technical work seriously. We have indeed adopted his baby and taken it to new and brilliant heights. He would be unhappy because we do not share his vision. He would see a world in which there is great need for fusion, a world where there is technical ability to develop it but he would ask, 'Where is the will?!'.

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Tokamak experiments at Institute for Plasma Research

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Introduction

THE quest for attaining controlled fusion power in the laboratory has been described as the most challenging scientific endeavour of the present century and the ultimate solution to the growing energy needs of the world. The notion that one is attempting to recreate the conditions of the interior of stars on earth has also led to such fanciful description of fusion energy as 'a bid to trap a star'. The imagery is quite apt, for one of the necessary first steps in the quest for achieving controlled thermonuclear fusion in the laboratory is the creation of an efficient trap to hold the reacting elements long enough for them to fuse. At the temperatures necessary for fusion (around 80 to 100 million degrees centigrade) the nuclear fuel is completely ionized and is in the form of a hot plasma. A convenient way to confine plasma is through the use of magnetic fields. Since charged particles execute tight helical trajectories around magnetic field lines, their transverse excursion is naturally restricted and they tend to stick to magnetic surfaces. Thus the basic idea is to create suitable configurations of magnetic surfaces that will confine the plasma most effectively. The tokamak is one of many such magnetic confinement devices designed to hold a plasma in physical and thermal isolation from the container walls. It is a toroidal magnetic trap and its name is a Russian acronym constructed from the words *toroid*, *kamera* (chamber), *magnit* (magnet) and *katushka* (coil). The concept was first proposed by Sakharov and Tamm and the first experiments on this concept were carried out at the Kurchatov Institute in Moscow by Artsimovich and his colleagues[1]. The basic configuration, illustrated in Figure 1, consists of a strong toroidal magnetic field created by a set of external coils wound around a toroidal vacuum vessel and a poloidal magnetic field created by inducing a toroidal current in the plasma itself with the help of another set of external coils. The combination of the two fields creates a set of