

Is the Department of Atomic Energy shifting the goal posts for its three-stage nuclear power programme?

P. Rodriguez[†] and S. M. Lee*

In the context of India's three-stage nuclear power programme, there have been a number of recent submissions emphasizing the disadvantages of using thorium in fast breeder reactors (FBRs), and implying that thorium utilization should be through thermal reactors in the third stage. In this article, it is pointed out that the advantages of using thorium in fast reactors far outweigh the perceived disadvantages, which are anyway common for the thermal reactors also. Therefore, we advocate a strategy that ensures both growth and sustainability in nuclear electricity generation through a symbiotic combination of Pu/²³⁸U FBRs and Pu/²³⁸U FBRs with thorium radial blankets early enough in the second stage, and using the ²³³U so produced to set up ²³³U/Th FBRs along with thermal reactors (breeders or advanced converters), which will then become the mainstay of the third stage. The key concept is to avoid a sequential mind-set and have proper blend and gradual merging of the stages.

Keywords: Fast breeder reactors, nuclear electricity generation, nuclear power programme, thorium utilization.

The three-stage nuclear power programme

THE strategy for the three-stage nuclear programme, originally enunciated by Homi Bhabha^{1,2} and spelt out in detail by his successor Vikram Sarabhai³, is as follows. The first stage is the building of pressurized heavy water reactors (PHWRs) based on natural uranium (U) to the maximum possible (based on indigenous uranium resources) capacity of about 10–15 GWe. The second stage will have two parts: the first part will be a symbiosis of PHWRs and fast breeder reactors (FBRs) employing the Pu/²³⁸U cycle to increase the base of nuclear power. The second part of the second stage involves starting utilization of thorium (Th) in FBRs to generate ²³³U. The emphasis in the third stage will be on continued use of the thorium reserves through a symbiosis of ²³³U/Th FBRs and thermal reactors with ²³³U as the fuel.

Are there disadvantages in early launching of thorium utilization?

In the last two years, a number of papers, presentations and lectures have appeared^{4–8} emphasizing that due to the nuclear properties of thorium there are many disadvantages in the early launching of thorium utilization in India.

[†]P. Rodriguez died on 31 August 2008.

S. M. Lee is in the Safety Research Institute of the Atomic Energy Regulatory Board, Kalpakkam 603 102, India.

*For correspondence. (e-mail: sureshlee@rocketmail.com)

A corollary to this argument is the suggestion that the second and third stages should be sequential. The Commentary by Venkateswarlu⁸ (both the paper and the author will be referred to as KSV in subsequent sections) belongs to this genre.

KSV seems to be unaware of the studies done at Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam, showing the feasibility of using advanced FBRs for simultaneous introduction of Th cycle along with electric capacity growth^{9–11}, and also of other IGCAR studies on fuel cycles for FBRs^{12–18}. Many of the disadvantages of the Th cycle, mentioned in the paper, are in fact applicable to thermal reactors like advanced heavy water reactor (AHWR)¹⁹ or a thorium 'breeder' reactor (ATBR)²⁰ and not to FBRs²¹.

It is well known that the breeding ratio (BR) for the ²³³U/Th cycle in FBR is low compared to that for the Pu/²³⁸U cycle. However, it seems to be less well known that the BR for an FBR with Pu/²³⁸U in the core and Th in the blankets is not much reduced compared to that with Pu/²³⁸U in the core and ²³⁸U in the blankets. The calculations of Lee *et al.*¹¹ give the results shown in Table 1 for the BR of reference and advanced FBRs with carbide fuel.

For similarly optimized advanced designs, the results for breeding ratios reported by the International Nuclear Fuel Cycle Evaluation Working Group 5 (INFCE WG5)²² for different fuel materials and fuel cycles are given in Table 2.

From the above it is clear that the non-negligible reductions in BR and system growth rates occur only when

Table 1. Breeding ratios for reference and advanced FBRs with carbide fuel¹¹

FBR configuration	Breeding ratio	
	Reference design	Advanced design*
Pu/ ²³⁸ U core and ²³⁸ U blankets	1.284	1.406
Pu/ ²³⁸ U core, ²³⁸ U axial blanket and Th radial blanket	1.282	1.388
²³³ U/Th core and Th blankets	1.028	1.098

*The advanced design is optimized for high breeding with thin clad, thick blankets, high fuel volume fraction, high fuel smeared density, high peak burn-up, low cycle losses, etc.¹¹.

Table 2. Breeding ratios reported by INFCE WG5 for different fuel materials and fuel cycles in FBRs²²

FBR configuration	Breeding ratio				
	Oxide	Fuel material		System doubling time for metal fuel* (years)	System growth rate for metal fuel** (% per year)
		Carbide	Metal		
Pu/ ²³⁸ U core and ²³⁸ U blankets	1.325	1.479	1.582	8.5	8.1
Pu/ ²³⁸ U core, ²³⁸ U axial blanket and Th radial blanket	1.314	1.450	1.519	10.0	6.9***
Pu/ ²³⁸ U core and Th blankets	1.305	1.426	1.459	11.8	5.9***
Pu/Th core and Th blankets	1.184	1.223	1.301	23.8	2.9***
²³³ U/Th core and Th blankets	1.099	1.114	1.115	75.1	0.9

*For 2 years external cycle time with 1% fuel cycle residue loss for Pu/U fuels and 2% fuel cycle residue loss for Th-based fuels.

**System growth rates calculated by the authors from the system doubling times.

***The reactors breed both Pu and ²³³U or only ²³³U for the Pu/Th core case. ²³³U has to be used as a fuel in another appropriate reactor, such as FBR with ²³³U/Th core and Th blankets or thermal reactors with ²³³U as fuel. The system doubling time and system growth rate indicated therefore essentially refer to growth in fissile material inventory.

²³³U/Th is introduced in the core. Lee *et al.*¹¹ have exploited this fact to show that even with the early introduction of thorium in FBR blankets, the installed electric capacity can reach a desired level nearly as fast as that without introducing thorium. The concomitant benefits of this approach are diversification of the nuclear resource base, flexibility in the choice of breeder concepts and fuel cycle and extending the use and availability of the country's uranium resources. These advantages of the simultaneous use of thorium with electric capacity expansion based on FBRs and of avoiding the sequential mind-set have recently been reiterated by Rodriguez²³, and have also received the attention of commentators in the popular print media (for example, Ramchandran²⁴).

There is a subtle difference between the strategy proposed by Rodriguez²³ and that earlier proposed by Lee *et al.*¹¹. To make the difference clear, we quote from Lee *et al.*¹¹.

'An alternate strategy is to first use the plutonium and depleted uranium stock to set up Pu/²³⁸U breeders. *Either, immediately or after a certain period of growth these LMFBRs are equipped with thorium radial blankets* (emphasis added) such that they are self-sustaining on the bred plutonium while excess ²³³U is produced for setting up of ²³³U/Th breeders (either fast or thermal). The growth rate of the nuclear capacity will depend on the relative proportion of Pu/²³⁸U LMFBRs and the ²³³U/Th reactors. By adjusting the initial period of growth it is possible to adjust the proportion of Pu/²³⁸U LMFBRs to the total reactor population and to adjust the growth rate.'

On the other hand, instead of using a time lag to adjust the overall growth rate, Rodriguez²³ suggested that the growth rate of the mix of reactors could be adjusted as desired by introducing thorium in the radial blankets of a variable fraction (say up to about 50%) of the number of Pu/²³⁸U FBRs to be built with metal fuel and using the ²³³U so produced for setting up ²³³U/Th breeders (either fast or thermal). This incidentally also serves the purpose of early introduction of thorium into the nuclear power programme.

Is reprocessing more difficult in FBR Th cycle?

KSV makes the statement: 'Chemical reprocessing losses in a closed Pu/Th cycle might bring the final yield of ²³³U to less than unity, thus losing the meaning of breeder'. The meaning of this statement is not clear, as a Pu/Th cycle cannot be closed in the same reactor, since the fertile material Th does not produce Pu. The crucial point is that INFCE studies show adequately high BR for the Pu/Th core and Th blanket cases with enough margins for the reprocessing losses such that there would be net gain of fissile material. The fear of reprocessing losses leading to net loss of fissile material may occur only for an FBR with ²³³U/Th core and Th blanket and which has not been optimized for high breeding (i.e. having thick clad, thin blankets, low fuel volume fraction, low fuel smeared density, etc.).

The ²³²U contamination of ²³³U in the Th cycle is well known and is considered by some an advantage from non-

proliferation considerations. Clean-up methods are being developed in BARC²⁵. It may be noted that the choice of initially putting Th in the FBR blankets leads to a substantial reduction of ²³²U contamination of the ²³³U produced. In a report²⁶ to IAEA on the status of thorium fuel options, the Russian Federation has mentioned that an essential feature of fast reactors, caused by the possibility of providing an optimal neutron spectrum for production of ²³³U, is the capability of producing nearly pure ²³³U with ²³²U content of only 10⁻⁶–10⁻⁷. This effect has been substantiated by both calculations and by irradiating thorium samples in the BN-350 reactor. This possibility of near pure ²³³U production at the initial stage of the thorium fuel cycle is important, since it allows easier research and development efforts (without heavy shielding for gamma activity) for establishing the technologies of fuel reprocessing and fuel refabrication, which are the most difficult aspects in the realization of the thorium fuel cycle. Yet another advantage of ²³³U produced in the blanket of a fast reactor is that it simplifies ²³³U and thorium fuel manufacture for thermal reactors (at least for the first stage of fuel utilization, i.e. without multiple recycling).

At this stage, it is pertinent to refer to another paper that KSV has co-authored with Iyer²⁷ (to be referred to as KSV–MRI) in which the following statement appears: ‘Pyrometallurgical reprocessing of metallic fuels is more of a research activity at present. To translate it into plant scale would take a long time. Refabrication would be another big hurdle because of ²³²U’.

Since the DAE plan⁶ is to change over to metal fuel for the advanced 1000 MWe FBRs to be built after the first four 500 MWe FBRs with oxide fuel, pyrometallurgical reprocessing becomes necessary very early for the Pu/²³⁸U cycle itself. As the reprocessing method for metal alloy fuel has incomplete removal of the fission products, remote handling techniques also become necessary for the Pu/²³⁸U cycle. As pointed out by Rodriguez²³, once developed for the Pu/²³⁸U cycle, extending these to ²³³U/Th cycle will not be difficult. The big hurdle is in developing the reprocessing and refabrication technology for metal fuel for the Pu/²³⁸U cycle; without these technologies and metal fuel, all the talk about fast growth is meaningless.

KSV has mentioned, as a disadvantage, the need to have a cooling period of 140 days to avoid ²³³Pa complications in the reprocessing. In fact, such cooling periods are normal in the FBR fuel cycle. Also, the issue of ²³³Pa absorption of neutrons is not important in the FBR neutron spectrum.

Factual errors

There are some factual errors in both KSV and KSV–MRI. In a brief summary of the progress on Th utilization in India, in the numbered item 5 in KSV, there is an erroneous statement on the use of nickel in FBTR. Actually a

nickel reflector (and not ‘filters’) is used in FBTR. It was introduced to reduce the core fissile inventory and increase the irradiation testing flux to power ratio and not for the purpose of softening the spectrum in the blanket.

KSV–MRI makes the following statement: ‘At that time, the fast reactor programmes around the world were confined to France, Russia and UK’. In fact, in the late sixties, the countries with fast reactor programmes were Russia, France, Japan, USA, UK, Germany, Italy and India. It was only subsequently that the programmes were reduced or terminated in USA, the UK, Germany and Italy.

Both KSV and KSV–MRI quote from Raja Ramanna’s 20th Sri Ram Memorial lecture on 20 November 1985 and claim that he reformulated the second and third stages of our nuclear power programme as follows:

‘Phase II. Construction of FBRs, which utilize plutonium and depleted uranium, the by-products of phase I reactors.’

‘Phase III. Use of thorium by converting it to uranium-233.’

KSV–MRI even emphasizes that by using the word ‘conversion’ to ²³³U, Ramanna has ruled out the breeding of ²³³U in FBRs. It is also implied that the redefined three stages have been followed by leaders who succeeded Ramanna.

To start with, this talk about reformulation or redefining by Ramanna is a case of *Suppressio veri, Suggestio falsi*. In a paper published just a few months after his Sri Ram Memorial lecture, Ramanna²⁸ emphasized the importance for India of breeding ²³³U in FBRs as follows:

‘Though the large-scale utilization of thorium is expected only in the third stage of the Indian nuclear power programme, there is considerable incentive for R&D in the technology of thorium reactors and the associated fuel cycles in order to have a balanced developmental strategy, which will enable optimised retrofitting of the thorium cycle schemes into PHWR and LMFBR systems at the appropriate time. An advantage of the early introduction of the thorium cycle and the production of ²³³U is that it leads to a diversification of energy resource base and allows greater flexibility in the choice of breeder reactor concepts and fuel cycles. It must be noted that any fuel cycle development takes a long time, and it is necessary to generate essential data and establish semi-industrial experience well in advance of the actual large-scale utilization in the long term. It may be necessary to have a symbiotic association of LMFBRs and PHWRs or even introduce a new reactor type for efficient utilization.’

The conclusion is that by the use of the phrase ‘Use of thorium by converting it to uranium-233’ in his lecture, Ramanna has not intended a redefining of the DAE strategy. The term ‘conversion’ also often denotes the use of thorium in blankets of FBRs operating on Pu/²³⁸U cycle, as the ²³³U produced is not recycled in the same reactor even though the breeding ratio is greater than unity.

KSV implies and KSV–MRI openly make the misleading statements: ‘Dr. Ramanna visualized the use of thermal reactors for producing ^{233}U from thorium. This is the path that BARC has been pursuing for the last 25 years under the leadership of Dr Kakodkar. . . . Thus the general understanding among scientists and engineers of the Department of Atomic Energy was that to begin with, thorium would be deployed in thermal reactors rather than in FBR.’ We have already seen that Ramanna himself visualized thorium utilization in the FBRs. Nor has there been any shift in this approach by any of his successors.

Among his successors, it is well known that P. K. Iyengar has always been an ardent supporter of ^{233}U production in FBRs and we quote from a message²⁹ he sent in 2007 to IGCAR: ‘Thorium utilization through fast reactors has always been the dream for energy security in India. Homi Bhabha made Pandit Jawaharlal Nehru talk about it in the inauguration function of IREs Alwaye plant in 1952. We have come a long way. We do proudly claim that we can talk of tons of plutonium and uranium-233 from Kalpakkam. To me this is the greatest achievement of DAE considering we were sidelined by advanced countries after 1974. At this point in the history of Atomic Energy we need to emphasize the need for self-reliance and objectivity for the future without succumbing to external pressure. A large part of the responsibility lies with the staff of Kalpakkam.’

R. Chidambaram, who succeeded Iyengar, was no less emphatic about the role of FBRs in thorium utilization. In a detailed paper³⁰, Chidambaram has highlighted the importance of combined cycles of FBRs with $\text{Pu}/^{238}\text{U}$ in the core and Th in the blankets, with the ^{233}U produced being used to fuel thermal reactors. To quote him: ‘The combined cycle is most attractive for countries like India and Brazil, which have large reserves of thorium’. He has reiterated this position in his Founder’s Day Address³¹ at BARC in 1999: ‘An Advanced Heavy Water Reactor (AHWR) using Plutonium and Uranium-233 as fuel is being designed at the Bhabha Atomic Research Centre (BARC). AHWRs constitute a part of the third stage of our nuclear power programme, which will mark a transition to the thorium– ^{233}U cycle as it will use as fuel the ^{233}U obtained by the irradiation of thorium in PHWRs and FBRs’.

KSV is wrong in implying and KSV–MRI seriously misleading in stating that there has been a shift in the DAE policy under Kakodkar’s leadership and that ‘the general understanding among scientists and engineers of the Department of Atomic Energy was that to begin with, thorium would be deployed in thermal reactors rather than in FBRs’. We are not aware of any debate or discussion that ever took place when such a consensus was reached. As late as on 4 July 2008, in his public lecture⁵ delivered at the meeting of the Indian Academy of Sciences in Bangalore, Kakodkar envisages the introduction

of thorium-based fuel in FBRs to initiate the third stage, where ^{233}U bred in these reactors is to be used in the thorium-based thermal reactors. This is the scenario advocated by Rodriguez²³ also. The only difference with the strategy advocated by Rodriguez, and that in Kakodkar’s Academy lecture is, when exactly to introduce thorium in the blankets of FBRs? At one place in his lecture Kakodkar mentions that this could be when the FBR capacity has reached 200 GWe; at another place, he mentions that the right time would be in the third decade after the introduction of metal fuel in FBRs. What Rodriguez has argued, based on the earlier studies of Lee *et al.*^{9–11} on advanced FBRs with carbide fuel, is that with advanced FBRs on metal fuel and with appropriate strategies this lag could be much less than three decades. In view of the recent debate, we are planning updated studies on combinations of different FBR configurations with metal fuel and with different lags in introducing Th.

KSV–MRI make a reference to India’s report²⁶ in the IAEA Technical Document 1155, and claims, because there is no reference in the report to thorium utilization in FBRs, that this aspect of the three-stage programme has been abandoned by India. This is again misleading and erroneous, because the Indian presentation starts with a paragraph describing the three stages of our nuclear power programme and in the subsequent paragraphs the discussion is restricted only to the third stage of the nuclear power programme.

On the other hand, the Indian position and programme are fully described in a subsequent IAEA document³², published in May 2005, as a result of an International Working Group on ‘Thorium fuel cycle – Potential benefits and challenges’, chaired by C. Ganguly from India, meetings of which were held during 2002–03. In this report the irradiation of thorium in FBR blankets is indicated to start in the second stage itself.

Advantages and disadvantages of thorium cycles arising from the nuclear properties of thorium

The general thrust in the arguments of both KSV and KSV–MRI is that the use of thorium in the thermal neutron region suffers from none of the drawbacks associated with its use in FBR. This is not correct and again open for debate. Many of the disadvantages of the Th cycle, mentioned in the papers, are in fact applicable to thermal reactors like AHWR or ATBR and not to FBRs. To amplify this, the advantages and disadvantages in the thorium cycle arising from nuclear properties of thorium are given in Table 3.

It is clear from Table 3 that many of the advantages and disadvantages are common for the use of thorium in both thermal and fast reactors. It is true that the BR in an FBR achievable with the $^{233}\text{U}/\text{Th}$ cycle is lower than what is achieved with the $\text{Pu}/^{238}\text{U}$ cycle for all fuel forms,

Table 3. Advantages and disadvantages in the thorium cycles arising from nuclear properties of thorium

Advantages	Disadvantages
	No fissile isotope present in natural thorium.
Breeding possible in both thermal and fast reactors.	In thermal reactors, maximum breeding ratio (BR) is 1.07 in MSR. In most other thermal reactors, BR attained ≤ 1 .
Much lower quantity of Pu and long-lived minor actinides (Np, Am and Cm) are formed; this minimizes problems of toxicity of and decay heat in the waste stream.	
The gamma activity is considered an advantage for proliferation resistance of the thorium cycle.	There is significant build-up of gamma radiation dose with storage of spent Th-based fuel or separated ^{233}U , necessitating either remote and automated reprocessing and refabrication in heavily shielded hot cells or a 'clean-up process'.
If Th is used only in the blanket of an FBR, with proper adjustment of neutron spectrum, the formation of ^{232}U , whose daughter products lead to gamma activity, can be reduced.	
In the FBR, use of $^{233}\text{U}/\text{Th}$ fuel cycle has two specific advantages, viz. negative sodium void coefficient of reactivity and a more negative Doppler coefficient, both of which improve reactor safety.	The BR for the $^{233}\text{U}/\text{Th}$ fuel cycle is about 20% less than a $\text{Pu}/^{238}\text{U}$ fuel cycle for oxide fuel and the difference increases for advanced fuel materials (carbide/nitride/metal).

mainly because of the lower number of neutrons per fission from ^{233}U than from ^{239}Pu ; but when thorium is used only in the blankets, the difference in net fissile gain is small. Notwithstanding the highest value of the number of neutrons per fission for ^{233}U among all the fissile isotopes in a thermal spectrum, the maximum BR achieved in a thermal breeder is for the Molten Salt Reactor (MSR), which is only ~ 1.07 . This is less than that achieved in an advanced FBR on $^{233}\text{U}/\text{Th}$ cycle (see Tables 1 and 2). Of the several factors contributing to this, mention may be made of the loss of neutrons by absorption in the intermediate nuclide ^{233}Pa formed during the $^{232}\text{Th} \rightarrow ^{233}\text{U}$ conversion reactions. As mentioned earlier, this is not a problem in the fast spectrum. It is clear that overall, the advantages of thorium utilization in a fast reactor far outweigh the perceived disadvantages which are anyway common for the thermal reactors also. It is pertinent to note that from among the presently available technologies, FBR is the best option for building up a quick inventory of ^{233}U .

Thorium utilization in thermal reactors

KSV is correct in stating that the Pu/Th combination is a poor choice as fuel for thermal reactors. Unfortunately, the AHWR and ATBR, quoted by both KSV and KSV-MRI, make extensive use of this fuel combination to generate ^{233}U (and the generated ^{233}U is less than the valuable Pu consumed!).

KSV-MRI in paragraph 8 reveal an anxiety for delaying the introduction of thorium in the blankets of FBRs fuelled with Pu as follows: 'There would not be enough Pu to start such a scheme unless AHWR route is abandoned. With several advantages of AHWR that would be uncalled for'. But Kakodkar's view⁵ is that all the Pu has

to be used in $\text{Pu}/^{238}\text{U}$ breeders to match the growth in electricity demand expected in India till 2050. He also foresees a role for thorium-based fuels in FBRs to initiate the third stage, where the ^{233}U that is bred in these reactors is to be used in thorium-based thermal reactors (see Figure 9 and statements below the figure in Kakodkar⁵). We would suggest that at any time, if there is a competition for valuable plutonium from different reactor concepts to be pursued, a decision is to be made after an open debate and discussion on all the pros and cons involved.

KSV makes much of the *in situ* burning of ^{233}U achieved in the Th bundles in thermal reactors such as AHWR and ATBR. In reality, unless the country's potential inventory of about 200 tonnes of Pu, generated from the 60,000 tonnes or so of natural uranium, is rapidly grown by a factor of ten or more, all the *in situ* burning is irrelevant.

KSV and KSV-MRI seem to advocate the use of Pu and Th in AHWRs rather than in FBRs, when the end of Phase II of the Indian Nuclear Power Programme with only $\text{Pu}/^{238}\text{U}$ breeders is reached and the ^{238}U is exhausted (i.e. tied up in the $\text{Pu}/^{238}\text{U}$ FBR base). If this path were to be followed then, at that time the country's nuclear power base would start decreasing with time as the AHWR is not a breeder and produces less ^{233}U than the Pu it consumes. A serious consequence of the negative effects of early thorium introduction in thermal reactors, without breeding ^{233}U in the blankets of FBRs, would be that we have to continue the import of uranium and reactors. For a truly self-sustaining nuclear power programme, Th should be introduced in the blankets of $\text{Pu}/^{238}\text{U}$ FBRs well before the end of Phase II, and the ^{233}U so produced should be deployed in a symbiotic combination of $^{233}\text{U}/\text{Th}$ FBRs and thermal breeders or advanced converters to seamlessly merge the second stage with the third stage.

Conclusion

Notwithstanding the small reductions in BR and system growth rate that result, when thorium is introduced into the radial blankets of Pu/²³⁸U FBRs, there are many advantages in following such a strategy:

1. An early beginning of the thorium utilization in the Indian nuclear programme leading to global leadership in this technology.
2. Sufficient lead-time for R&D, leading to industrial-scale capability in reprocessing and refabrication in the thorium cycle.
3. The possibility that ²³³U with very low ²³²U can be produced from thorium in the blankets of fast reactors offers great advantages for easier activities relating to point no. 2 above.
4. The above possibility simplifies ²³³U and thorium fuel manufacture for thermal reactors (at least for the first stage of fuel utilization in thermal reactors, i.e. without multiple recycling).
5. The concomitant benefits of this approach are diversification of the nuclear resources base, flexibility in the choice of breeder concepts and fuel cycle, and extending the use and availability of the country's uranium resources.
6. FBRs on the ²³³U/Th cycle have superior safety aspects compared to Pu/²³⁸U FBRs.
7. The strategy advocated would seamlessly lead to a symbiotic combination of ²³³U/Th FBRs with thermal breeders or advanced thermal converters in the third stage of our nuclear programme, which will ensure both long-term growth and sustainability in electricity generation capacity.

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ACKNOWLEDGEMENT. We acknowledge support from the DAE Board of Research in Nuclear Sciences through Raja Ramanna fellowships.

Received 4 November 2008; accepted 18 December 2008

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