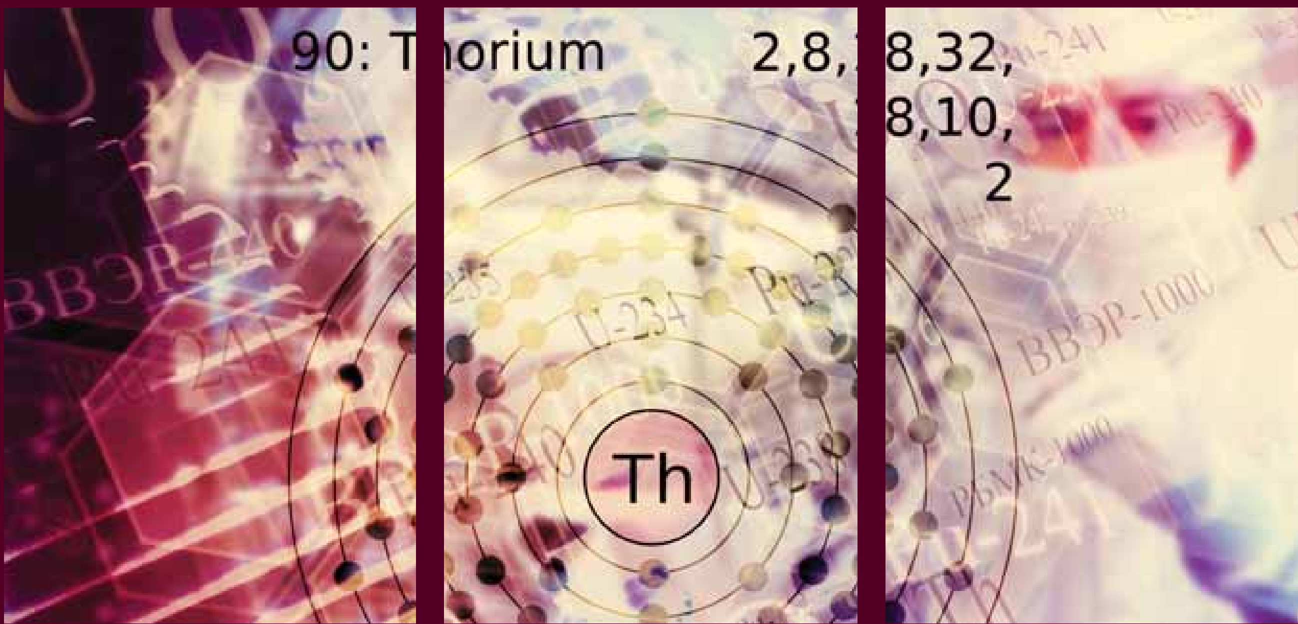
Bellona report 2013

Certain issues of economic prospects of thorium-based nuclear energy systems



BELLONA

Bellona report 2013

Certain issues of economic prospects of thorium-based nuclear energy systems

Leonid Andreev

BELLONA

Contents

INTRODUCTION 4

THORIUM FUEL IN EXISTING REACTOR DESIGNS 5

ELEMENTS OF THE THORIUM FUEL CYCLE 6

COST ASSESSMENT OF THORIUM FUEL UTILIZATION
IN CONVENTIONAL NUCLEAR ENERGY SYSTEMS 8

PROSPECTIVE REACTORS 14

CONCLUSION 18

References: 19

List of abbreviations and reactor type designations used in this overview 21

INTRODUCTION

Thorium-based nuclear fuel is thought to play a variety of roles depending on a particular nuclear energy system, which makes it challenging to form judgments regarding the economic prospects of thorium. Assessments of the costs and merits of individual elements of a thorium technological cycle are directly contingent on the choice of the fuel cycle and the various technological solutions involved – solutions that as yet do not exist. Furthermore, there is a scarcity of reliable data on the costs of thorium-based nuclear energy systems, and conclusions often have to be drawn based on expert evaluations or data obtained indirectly.

In principle, thorium fuel can be used in a rather broad range of nuclear reactor types – practically in all the existing designs and a number of those under development. Economic assessments of a thorium fuel cycle vary considerably depending on whether thorium is suggested for use in reactor types that are already in operation in the nuclear energy industry or whether prospective designs are meant (these would imply, first and foremost, molten salt reactors and accelerator-driven subcritical reactors).

In the case of the former, we are dealing with developed technologies, which, under certain conditions, would allow the substitution of thorium fuel for traditional fuel. These may be both light water and heavy water reactors. The latter will be nuclear energy systems developed specifically for a thorium fuel cycle. In this case, it is only possible to make rather basic assumptions regarding such development trends that promise lower costs compared to traditional nuclear energy technologies. The potential economic advantages of thorium-based fuel cycles stem directly from the peculiarity of thorium as a nuclear fuel.

Firstly, there exists – though so far, it is yet to be technologically implemented – the principal possibility of creating a thorium fuel that will generate more uranium-233 in thermal reactors than will be consumed. The fissile breeding potential is a unique characteristic of thorium fuel, something that cannot be achieved using fuel based on uranium.

Secondly, to initiate reaction, thorium-based fuel can use as driver fuels slightly enriched uranium or highly enriched uranium, recycled uranium from light water reactors, or reactor-grade or weapons-grade plutonium. Application of thorium-based fuels would mean both plutonium and transuranium elements could be burned, which has immense significance from the point of view of management of radioactive waste.

THORIUM FUEL IN EXISTING REACTOR DESIGNS

Thorium fuel as an alternative to traditional MOX fuel for light water reactors. One development trend that is deemed to be promising is the use of thorium fuel as an alternative to MOX fuel. This type of fuel would be based on thorium and weapons-grade plutonium, a mixture that would be delivered as fuel assemblies to conventional nuclear reactors and burned there, generating electricity in the process. In this case, the reactors would be running on plutonium and breeding the fissile uranium-233, which, following separation, would be used in the uranium-thorium fuel cycle. It is suggested that such fuel will not only facilitate plutonium disposition, but will also prove twice as cost-effective as MOX fuel, since, in contrast to MOX fuel, fabrication of the thorium-plutonium mix will not require costly modifications or structural adjustments in the reactors where it is intended to be used. This was exactly the challenge that proved to be one of the biggest impediments to the implementation of the MOX program [Thorium as a Nuclear Fuel (2013)].

Developers also say that the properties of the spent fuel generated when the thorium-plutonium mixture is burned in a reactor rule out any possible weapons use the plutonium had before its disposition in the reactor. By contrast, MOX spent fuel can still be separated for bomb-grade plutonium [Digges (2003)].

A number of experiments have been conducted that proved, in principle, successful for prospective use of thorium-plutonium fuel. For instance, thorium-based fuel for light water reactors of the PWR type was tested in the U.S. at the Shippingport reactor, where uranium-233 and plutonium were used as the initial fissile material for the fuel [Olson et al. (2002)]. It was concluded that thorium would not significantly affect operating strategies or core margins [Encyclopedia of Earth, Thorium (2013)].

Germany, too, has attempted to use thorium-plutonium fuel in light water reactors. For instance, Germany's 60 MW BWR Lingen reactor ran for a period of time on test thorium-plutonium fuel [IAEA (2005)].

Norway has developed and is currently planning to test mixed thorium-plutonium oxide fuel at a research reactor in Halden [Thorium as an Energy Source (2008)].

Russia has conducted a series of experiments with thorium-plutonium oxide fuel for its VVER-1000 reactors. It turned out, however [Bekman (2010)], that thorium's neutron emission rate during irradiation in a VVER-1000 reactor was 10% higher than in the case of uranium, which jeopardized the ability to control the reaction.

Thorium use in heavy water reactors. Tests of thorium-based fuels in heavy water reactors of the CANDU PHWR type in Canada, India, and other countries in the past 50 years have shown that heavy water reactors are relatively easily amenable to conversion from uranium to thorium fuel without extensive modifications [WNA, Thorium (2013)].

Heavy water reactors have proven very well suited for thorium fuels due to their flexible on-line refueling capability as well as excellent neutron economy and slightly faster average neutron energy, which facilitate neutron absorption by thorium and thorium conversion to uranium-233 [WNA, Thorium (2013)].

The only reactor currently running on thorium fuel is a heavy water CANDU reactor in operation in India. Heavy water reactors with a capability to use thorium-based fuel should play a key role in the Indian nuclear program because of these systems' fueling flexibility: Thoria-based HWR fuels can incorporate recycled uranium-233, residual plutonium and uranium from spent LWR fuel, and also minor actinide components in radioactive waste reduction strategies. [WNA, Thorium (2013)]

It is assumed that specially designed advanced heavy water reactors (AHWR) will run on a mix of thorium and plutonium, which will help dispose of plutonium produced in breeder reactors – reactors that, in their turn, use conventional uranium-based light water reactor SNF. In the closed fuel cycle, the driver fuel required for starting off is progressively replaced with recycled U-233, so that on reaching equilibrium, 80% of the energy comes from thorium. Fleets of PHWR-type reactors with near-self-sufficient equilibrium thorium fuel cycles could be supported by a few fast breeder reactors to provide plutonium. [WNA, Thorium (2013)]

Calculations performed in a 2012 IAEA report [IAEA (2012)] show that the advantages of thorium fuels when applied in heavy water reactors may be quite sufficient for the introduction of these types of fuel into the nuclear cycle. India's nuclear program should confirm the viability of the thorium-based nuclear fuel cycle.

Thorium fuels in breeder reactors. Thorium can be used in fast neutron reactors, but its utilization is demonstrably economically inexpedient. According to [IAEA (2012)], an FR operating with a uranium-plutonium fuel cycle and a conversion ratio equal or more than one (breeding) is a self-sufficient system that consumes only depleted uranium, which is a practically unlimited resource with material cost close to zero.

Further, the introduction of thorium blankets in an FR leads to the necessity of:

– Installation and maintenance of corresponding reprocessing and fabrication facilities of thorium fuel;

– ntroduction of coupled reactors in the nuclear energy system, i.e. reactors that will consume uranium-233 produced in an FR blanket;

– Reactors that will produce plutonium necessary for FR fresh fuel;

Such nuclear energy systems will consume not only depleted uranium, but also thorium, with costs in the same order as natural uranium. The size of a thorium blanket in some reactor types can be several times the size of a uranium blanket, which leads to an increase of reprocessing demands and cost of produced fissile material. [IAEA (2012)]

ELEMENTS OF THE THORIUM FUEL CYCLE

The 2008 OECD/NEA, IAEA publication "Uranium 2007: Resources, Production and Demand" (the "Red Book") [OECD/NEA, IAEA (2008)] estimates reasonably assured and inferred world thorium resources (recoverable at a cost of <$80/kg Th) and prognosticated resources at a total of 4.4 million tons.

Currently, the thorium market is an extremely small niche, and demand for thorium is accounted for by non-energy-related companies, which use this material for such applications as high-temperature ceramics, melting tanks, catalysts, welding electrodes, and some alloys. Thorium use is gradually decreasing due to the radioactivity of thorium. Additionally, because thorium is a byproduct of recovering other materials – first and foremost, rare earth metals – and is used in the manufacture of special glass products and metals, its supply is significantly in excess of demand. In 1988, global thorium production was estimated at 37,500 tons. Many countries have accumulated considerable thorium stockpiles as a production byproduct. Thorium prices were quoted in the 1960s and 1970s, and hovered within the range of $30 to $35 per kilogram, but price publications have ceased owing to the decline in demand [U.S. Geological Survey (2012); U.S. Geological Survey (1999)].

Thorium is much more abundant in the Earth's crust than uranium, which prevents any particular players from asserting their dominance on the market and ensures predictability of prices at which the source material is sold, keeping the gap between production costs and selling prices within an acceptable range. On the other hand, the lack – with certain exceptions, such as the major Norwegian deposit in Telemark [Berg et al. (2012)] – of rich thorium deposits currently makes thorium production a more complicated and expensive process than that of uranium.

Thorium production costs are also influenced by the following factors:

Firstly, because thorium so far remains a byproduct resulting from production of other mineral resources, it is currently largely viewed rather as a kind of useless production waste. Should thorium become a product with a positive value, this could alter significantly the economics of many industrial processes.

Secondly, thorium prices will depend significantly on how large a share of the nuclear power industry will switch over to thorium fuel, since this will be the only source of demand for thorium ore. A radical switchover to thorium may lead both to a drop in the price per unit due to the economy of scale and a rise in the price on account of the limited availability of cheap sources of thorium ore.

The following competing factors may affect the costs of the thorium fuel cycle:

At the fresh fuel fabrication stage:

– Generating the same amount of power requires approximately twice as little thorium as it does uranium;

– Thorium does not require re-enrichment, but it does have to be purified, which is a rather costly process because of the high level of radioactivity accumulated in uranium-233 that is chemically separated from irradiated thorium fuel. Separated uranium-233 is always contaminated with trace amounts of uranium-232, which has a half-life period of 69 years and decays into high-energy gamma-emitting daughter nuclides – such as thallium-208. This complicates the fabrication, transportation, and operation of thorium-based fuel rods.

– The cost of thorium per se does not account for all the costs incurred in fresh fuel fabrication. The uranium isotopes uranium-233 or uranium-235, or plutonium-239 are also required in order to initiate nuclear reaction.

– A combination of thorium and a driver fuel is used to fabricate fuel assemblies suitable for use in reactors. Because of the more sophisticated fuel composition, the cost of manufacturing such fuel assemblies is somewhat higher than in the case of conventional uranium fuel.

At the waste management stage:

– Spent thorium fuel is highly radioactive on account of the high radioactivity of thorium-228, which is an alpha emitter with a half-life period of two years. Reprocessing irradiated thorium fuel rods is more expensive and complicated than reprocessing uranium fuel.

There are a variety of cost assessments for the front end of the thorium-based nuclear fuel cycle, but on balance, experts mostly agree that fresh thorium fuel currently continues to be more expensive than uranium fuel [Thorium as an Energy Source (2008)].

Fuel costs account for a small part of the total costs and their fluctuations within a rather large range do not have a critical impact on the economics of the nuclear power industry. In that sense, the argument made about the inexpensiveness of thorium fuel has limited appeal. The moderate effect that the fuel cycle cost has on the cost of electricity makes it possible to ignore the continuous and insurmountable lack of reliable input data, a problem that would otherwise become a formidable hurdle for the analysis of nuclear fuel cycle options [IAEA (2012)]. The authors of a comprehensive study published in [INL (2008)] compiling data on the cost of various fuel cycle options claim that the only documents found that presented a uniform costing methodology for all fuel types were prepared nearly 30 years ago by the Oak Ridge National Laboratory for the International Nuclear Fuel Cycle Evaluation (INFCE) effort. However, the efforts to define the origin of all of the cost data used in INFCE were also not fully successful.

The parameters of uranium-plutonium fuel cycle front end are based on the existing technologies and materials and are relatively more transparent, and deviations are not so crucial for the end result. The values of mining and milling cost, conversion cost, enrichment and uranium oxide fuel fabrication cost either have very little influence or converge to certain values with acceptable discrepancies caused by differences in conditions (e.g. vendors, time). However, back end fuel cycle cost, i.e. SNF reprocessing, MOX, waste management, and related cost data, are far less reliable. [IAEA (2012)]

Front end and back end cost of the fuel cycle are included in the cost of electricity via fuel cost, which aggregates cost of material and services at every stage of nuclear fuel production, storage, reprocessing, and waste disposal. [IAEA (2012)]

Detailed cost data for process steps of thorium fuel cycles are not yet available, and particularly in the back end and in reprocessed fuel utilization, the data sources [IAEA (2005); OECD/NEA (2002); OECD/NEA (2001); US DoE (2001); GIF (2007); Kazimi (2003)] still have a large degree of uncertainty. According to [IAEA (2005)], in the area of non-irradiated fuel, the costs of front end parts of ThO2-UO2 and conventional uranium cycles are similar, e.g. the cost of UO2 fabrication ($250/kg HM) and ThO2-UO2 fabrication ($300/kg HM) differ by about 20%. The estimation published in [Kazimi (2003)] also shows that the cost of thorium-based fuel can deviate by up to 10% (up or down) from the cost of conventional uranium nuclear fuel. [IAEA (2012)]

The results of economic analysis documented in [OECD/NEA (2001)] show that fuel costs for a ThO2-UO2 LWR core, which is designed to be operated up to an average burnup of 72 MW·d/kg HM, are about 10% higher than for an all-uranium core operated up to the conventional burnup of 45 MW·d/kg HM. [IAEA (2012)]

The Kurchatov Institute and the corporation Thorium Power [INL (2008)] claim that their once-through thorium fuel cycles (fuel component of the cost of electricity) are at least 20% cheaper than the conventional UO2 fuel cycle. Although fuel fabrication costs in a thorium cycle are not cheaper than in a uranium fuel cycle, the thorium cycle is shown to have favorable economics based on high burnup and long core residence time (up to nine years) of the fuel assemblies. Economics of UO2 fuel cycle could, however, also be improved by increasing residence time and burnup. Moreover, since economic effects of the thorium fuel introduction and the improved fuel claddings (for high burnup and long residence time), still to be developed, are not taken into account, the cost advantage of the thorium cycle over UO2 may be lower. [IAEA (2012)]

Historically, the currently existing uranium-plutonium fuel cycle has come together as part of the military nuclear program and the infrastructure in use often has a dual purpose. The investment made in the past for military applications created a certain economic barrier against the introduction of other fuel types.

In order to succeed, a thorium-based fuel cycle has to supplant the uranium fuel cycle to a considerable extent and almost simultaneously where all fuel cycle stages are concerned – from ore production and fabrication of fuel rods to redesigning reactors, safety systems, waste management, etc. This is only possible if a large-scale and dedicated effort is undertaken to this end, such as the Indian nuclear program. A nuclear fuel cycle of a fundamentally different kind requires a costly infrastructure that will be specialized to a considerable degree for the production of uranium-233 and its further recycling from spent fuel. Even though there are no significant technological obstacles to using thorium fuel right now, the economic and other advantages of the thorium fuel cycle have to be substantial enough to enable such a transition.

India, which owns the world's largest thorium deposits, on the one hand, but very limited uranium resources, on the other, and which, because of its military nuclear program, suffered for a period of time from restricted access to uranium owing to the constraints of the non-proliferation regime, has special reasons to be the first to introduce thorium-based nuclear energy on a broad scale. Implementation of such a program could yield a lot of useful technological and economic information for other countries.

COST ASSESSMENT OF THORIUM FUEL UTILIZATION IN CONVENTIONAL NUCLEAR ENERGY SYSTEMS

The suitability of a nuclear material of one kind or another for the purpose of generating electricity determines its economic value. Data on the cost of electricity produced and the real costs of existing nuclear fuel cycles serve as the initial points of reference used to assess any alternative technologies or nuclear materials.

There are a number of studies dedicated to the economics of the nuclear fuel cycle, including those examining thorium-based fuel cycles. This overview is partly based on a 2012 International Atomic Energy Agency report entitled "Role of Thorium to Supplement Fuel Cycles of Future Nuclear Energy Systems" [IAEA (2012)], which assessed, among other things, the economics of using thorium in conventional LWR, HWR, and fast reactors. These reactors can consume U233/thorium fuel and have similar analogues among reactors using uranium-plutonium fuel. Other thorium-fueled reactor concepts do not have well established analogues in the uranium-plutonium fuel cycle. Some of the reactor types in this group – such as MSRs and ADSs – as well as certain economic characteristics suggested for these reactors, are described further, under Prospective reactors.

The IAEA report used an INPRO (International Project on Innovative Nuclear Reactors and Fuel Cycles) methodology to compare the levelized unit energy cost (LUEC) of different reactors with different fuel cycles. This methodology requires calculation of a scope of economic parameters for a nuclear energy system: the LUEC, which is the ratio of total lifetime expenses to total expected power output, expressed in terms of present value equivalent; total investments; and economic figures of merit such as internal rate of return and return of investment. These economic parameters are compared against every other possible energy supply option. [IAEA (2012)]

Similar methodologies have been used in analogous studies such as [MIT (2009)] or [Bunn et al. (2003)]. Differences in results are usually due to differences in the values chosen for specific parameters.

A common problem for such studies is the availability and quality of input data and the reasonable choice of parameter values. For instance, capital costs of nuclear installations – a key factor for the nuclear energy industry – are not only technology-dependent, but also country-specific [OECD/NEA, IEA (2010)], e.g. the overnight cost of pressurized reactors may vary from $1,556/kW(e) published in South Korea to $5,863/kW(e) in Switzerland at the same time. [IAEA (2012)]

This is why studies are often based on rough estimates providing comparisons of the costs of reactors of different types [MIT (2009)]. The IAEA report [IAEA (2012)], for instance, assumes the capital cost of HWRs to be 10% higher than that of LWRs, and the capital cost of FRs 25% higher than of LWRs. For each of these three reactor types, the difference between uranium-plutonium and U233/thorium fueled reactors of the same type in capital cost and in cost of operation and maintenance is assumed to be low enough to be negligible. The cost of operation and maintenance depends on many factors, including reactor type and national infrastructure development, but its modest contribution to the final cost of electricity allows it to be assessed at a similar level for all three types of reactors. Reactor decommissioning cost is included in the fixed operation and maintenance cost.

There is a great uncertainty in the values of published parameters, but also sometimes different authors assume very different values for the same parameters. For example, contingency cost and owner's cost may be included in overnight cost or may be treated separately; spent fuel reprocessing cost and MOX fabrication cost depend on the assumptions made in their definition (some assumptions are analyzed in [MIT (2009)]). In addition, however, some of the published economic values lack the appropriate justification [OECD/NEA (2002); INL (2008)] that would allow estimating the reliability of these data, for instance, the cost of MOX fuel fabrication. [IAEA (2012)]

Data on the cost of MOX fuel fabrication is an illustrative example of the common lack of reliability of data used in economic analyses of nuclear fuel cycles. For instance, according to the published data, the cost of MOX fabrication is $1,100/kg [OECD/NEA (2002)], and the same parameter for uranium oxide fuel is $275/kg (in both cases, the cost of nuclear material is not included), i.e. a ratio of 4 to 1. The cost of MOX fuel fabrication published in the last years, e.g. presented in [IAEA (2005); OECD/NEA (2002); OECD/NEA (2001); US DoE (2001); GIF (2007); Kazimi (2003)], usually refers to the same source of input taken from a chain of OECD/NEA reports [OECD/NEA (2002); OECD/NEA (1994); OECD/NEA (1989)], each referring to a previous one. The final explanation of the MOX/uranium oxide fuel cost ratio as 4 to 1 is given in an 1989 OECD/NEA report documented in [OECD/NEA (1989)], whose authors provided a justification of this ratio substantiating that glove boxes should be obligatory for MOX fabrication. At that time, uranium oxide fuel was often fabricated without glove boxes but today they are also commonly used for uranium oxide fuel fabrication [OECD/NEA (2002)]. Since today, glove boxes are usually used for both MOX and uranium oxide fuel fabrication, the ratio 4 to 1 may be obsolete, although possible distinctions in ventilation requirements, container designs, radiation shielding, etc., may still affect (increase) the cost of MOX fabrication. [IAEA (2012)]

The main economic parameters and data on fuel cycle costs are presented in Tables 1 and 2. Two sets of input data – main and alternative – are given for parameter values. The main difference of the alternative set of input data is the more realistic cost assumptions expressed in an approximate doubling of the capital cost of all reactor types and tripling of the reprocessing cost of thorium-containing spent fuel.

Table 1. *Reactor capital and operation and maintenance costs.*

Item	Unit	Reactor type	Range*	Reference value (main input data set)	Cost (alternative data set)
Capital cost	$/kW(e)	LWR	1200–4000	2000	3800
		LWR /MOX	1200–2300	2000	3800
		HWR	1200–2800	2200	4180
		FR /MOX	—	2500	4750
Fixed O/M cost	$/kW/a	LWR, LWR /MOX	49–63	55	70
		HWR	55–63	60	75
		FR /MOX	80**	60**	75
Variable O/M cost	¢/kWh	LWR, LWR /MOX	0.047–0.09	0.05	0.07
		HWR	0.047–0.09	0.05	0.07
		FR /MOX	—	0.05	0.07

* See data sources here: [MIT (2009); Bunn et al. (2003); INL (2008); OECD/NEA, IEA (2005); OECD/NEA (2001); US DoE, (2001); WNA, Economics of Nuclear Power (2010)].
** The fixed O/M cost value of FR is estimated in [Bunn et al. (2003)] as equal to that of LWR and HWR, and the variable O/M cost is assumed to be zero.

The cost of reprocessing spent thorium fuel is much higher than that of reprocessing uranium SNF (see Table 2).

Table 2. Uranium-plutonium and thorium fuel cycle costs (with main and alternative values).

Fuel cycle step	Units	Uranium-plutonium fuel cycle				Thorium fuel cycle			
		Type	Range*	Reference value	Alternative value	Type	Range*	Reference value	Alternative value
Conversion	$/kg uranium	LWR, HWR	3–12	8	10				
Enrichment	$/kg SWU	LWR UOX	80–164	110	150				
Fuel fabrication	$/kg HM	LWR UOX	200–300	275	275	LWR 0	200–300	275	275
		HWR UOX	65–135	85	100	LWR 1	—	325	325
		LWR MOX	1000–1500	325	325	LWR 2	1000–1500	1500	1500
		FR-MOX	650–2500	350	350	HWR 1	—	100	125
		Uranium blanket in FR	350–700	350	350	HWR-2	—	500	625
						FR-MOX	650–2500	350	350
						Thorium blanket in FR	350–700	350	350
Reprocessing	$/kg HM	UOX	700–900	800	800	UOX	700–900	800	800
		MOX	700–1000	800	800	MOX	700–1000	800	800
		FR-MOX	1000–2500	1000	1000	FR-MOX	1000–2500	1000	1000
		Uranium blanket in FR	900–2500	800	800	Thorium blanket in FR	1000–2500	1200	3000
						Th/HEU	**	2000	6000
						Th/Pu	**	2000	6000
						Th/Pu/ U233	**	2000	6000
SNF direct disposal	$/kg HM	LWR	600	600	600	LWR (Th)	—	600	600
		HWR	73	Variable***	Variable***	HWR (Th)	—	Variable***	Variable***

* See data sources here: [IAEA (2005); OECD/NEA (2002); MIT (2009); Bunn et al. (2003); INL (2008); OECD/NEA, IEA (2005); OECD/NEA (2001); US DoE (2001); WNA, Economics of Nuclear Power (2010); GIF (2007); Kazimi (2003); Posiva Oy (2010)].
** A range of $6,000/kg HM to $20,000/kg HM was presented in [OECD/NEA (2002)], where it is used for the cost of reprocessing of the fuel from ADS and FR systems designed for burning minor actinides. In the [IAEA (2012)] study, a more optimistic value of $2,000/kg HM was chosen for the main input data set, and $6,000/kg was given in the alternative data set.
*** The cost of direct disposal of HWR spent fuel may depend on the fuel composition and is roughly proportional to burnup by a factor of 10.

In a Generation IV International Forum publication [US DoE (2001)], the time lags and some cost data (e.g. reactor construction time, licensing time, overnight cost) for the reactor operating in an open thorium fuel cycle are assumed to be approximately the same as those for a conventional LWR. In addition, some of the fuel cost parameters such as the fresh fuel fabrication cost, the spent fuel cooling and storage time, and the disposal cost (including the shipping cost) are assumed to be the same as the corresponding LWR cost. [IAEA (2012)]

The IAEA report [IAEA (2012)] also believes it necessary to assess possible trends of cost constituents of innovative reactors. For example, the electricity that could be produced by fast reactors of current design would be several times (from 40% to three times according to the estimation in [IAEA (2010)]) more expensive than that from thermal reactors or from coal-fired power plants. However, the necessary improvements in the FR design are integrated into current R&D programs to make their cost of electricity competitive. Fast reactor developers optimistically assume that cost of energy supplied from fast reactors will equal cost of energy from advanced LWRs. [IAEA (2012)]

In the IAEA's calculations, the construction period was assumed to be five years for every reactor type and investments during construction of every reactor were distributed evenly. The real discount rate was assumed to be 0.04, which is a rather low value that increases the importance of fuel cost compared to capital cost and probably disguises some deficiencies of reactors with high capital costs but relatively low fuel expenses, such as FRs.

Compared to the current status of nuclear fuel cycle systems, the main input data values in the IAEA report are consciously biased in favor of innovative reactors. This is done both by selecting parameter values favorable to the capital-intensive alternatives (discount rate, construction period) and by settling on assumptions based on declared but as-yet-to-be-achieved targets for reducing various costs. This corresponds, the authors say, to the aim of their report to assess the impact of economic parameters on the reactor type fractions (structure) in the system. For comparison purposes, and to estimate the level of influence of specific parameters, the report also considers the alternative, more realistic, set of economic input data.

The report states, in fact, that the objective of its economic analysis of thorium utilization is only to compare different fuel cycles rather than to give a quantitative assessment of the cost of nuclear power. This comparison is furthermore based on some optimistic expectations of the reactor and fuel cycle data for the 21st century. Some of these data are in fact quite hypothetical since, as the report says, they fall out of the range published in the economic studies referred to, which usually demonstrate that the capital costs of nuclear power plants have significantly increased in recent times. Therefore, using data assuming a significant and soon-to-be-expected decline in costs as a result of innovative activities appears overly optimistic.

Additionally, the IAEA report does not take into account costs associated with long-term storage of depleted uranium, storage of recycled uranium, and storage of fissile materials separated during reprocessing. Potential losses of nuclear material in the fuel cycle (e.g., during conversion, reprocessing) are assumed to be zero.

The cost of disposal of spent nuclear fuel and high-level radioactive waste gives a modest influence on the total energy cost [OECD/NEA (2006),] and is estimated via linear extrapolation. The cost of direct disposal of spent fuel for LWRs was taken from [Posiva Oy (2010)] and the same parameters for other reactor types, including HWR, were estimated as:

$$C_{SNFDD}[\$/\mathrm{kg\ HM}] = 10 \times B[\mathrm{MW \cdot d/kgHM}]$$

where C_{SNFDD} is the cost of direct disposal, and B is the average burnup of spent fuel.

This estimation is based on published data on the cost of direct disposal of 7 MW·d/kg HM burned HWR fuel at $73/kg HM and the LWR data mentioned above. The cost of disposal of the fissile products after reprocessing of spent fuel is assumed to be equal to the cost of direct disposal of spent nuclear fuel [Bunn et al. (2003)].

The cost of plutonium retrieved from spent fuel of a reactor operated in once-through mode and consumed in different reactor types was estimated as a difference:

$$c(^{total}Pu) = c_{repr} + c_{FPdisp} - c_{SFdisp}$$

where $c(^{total}Pu)$ is the cost of plutonium unit, crepr is the cost of reprocessing of spent fuel necessary to produce plutonium unit, c_{SFdisp} is the cost of direct disposal of the same amount of spent fuel, and c_{FPdisp} is the cost of disposal of fissile products separated at reprocessing.

It was conservatively assumed in the IAEA's analysis that the cost of uranium-233 was related to the cost of plutonium as follows:

$$c(U^{232}) = \frac{m(^{total}Pu)}{m(Pu^{239}+Pu^{241})} \times c(^{total}Pu)$$

The main equation for the levelized unit energy cost (LUEC) is as follows:

$$LUEC = \frac{ONC + IDC + \dfrac{FE_{firstcore}}{\eta \cdot \delta_{th}}}{8760 \cdot L_f} \cdot \left(\frac{1 - \left(\dfrac{1}{1+r}\right)}{1 - \left(\dfrac{1}{1+r}\right)^{t_{LIFE}}} \right) + \frac{\left(1 - \dfrac{1}{t_{LIFE}}\right) \cdot FE_{reload} + BE}{Q \cdot \eta} + LBF + LD + LOM$$

where:

ONC is the total overnight cost (per unit of installed capacity), including contingency and owner cost;
IDC is the interest paid during construction per unit of installed electrical capacity;
FE is the levelized fuel front end cost per kg of heavy metal. To define this parameter one has to know corresponding data on heavy metal mass flow;
BE is the fuel back end cost of considered type of reactor represented in US $ per kilogram of heavy metal of spent fuel;
Lf is the average load factor;
Q is the average burnup of unloaded fuel;
r is the real discount rate;
tLIFE is the lifetime of the plant;
η is the net thermal efficiency of the plant;
δth is the average power density in the reactor core at full power (during the first reactor cycle);
LBF is the levelized back fitting cost (exists only if the plant design envisages lifetime extension);
LD is the levelized decommissioning cost per unit of produced energy;
LOM is the levelized unit lifecycle operation and maintenance cost including refurbishment cost.
LUEC is equivalent to the average real price that would have to be paid by consumers to exactly repay the capital, operation and maintenance, and fuel cost with a proper discount rate (and without profit) throughout the entire life of the system (plant).

Calculation results are presented in Table 3 for eleven reactor types and different values for natural uranium cost, with the main and alternative sets of input data used.

Table 3. *LUEC depending on the natural uranium cost (Unat $/kg U).*

Unat $/kg U	HWR		LWR		ALWR		LWR0		LWR1[1]		LWR2[2]		LWR2[3]	
50	30.1	47.6	29.7	46.3	27.3	42.4	31.2	47.4	40.2	69.9	37.2	54.4	35.6	56.4
150	32.1	49.7	32.7	49.3	29.7	44.8	37.2	53.4						
300	35.3	52.8	37.2	53.8	33.2	48.3	46.2	62.5						
1000	49.8	67.4	58.3	75.0	49.9	65.0	88.4	104.6						

Unat $/kg U	HWR1[1]		HWR2[4]		HWR2[5]		AHWR[6]		FRTh[9]		FR[7]		FR[8]	
50	36.4	64.4	40.9	78.9	38.9	81.4	27.6	42.1	32.0	54.0	29.8	46.9	34.2	52.3
150							32.6	47.0						
300							40.0	54.4						
1000							74.7	89.1						

Notes:
[1] Plutonium from ALWR spent fuel.
[2] U233 from LWR1, plutonium from ALWR.
[3] U233 from LWR1, plutonium from LWR1.
[4] U233 from HWR2, plutonium from ALWR.
[5] U233 from HWR2, plutonium from LWR1.
[6] Once-through mode.
[7] Plutonium from FR.
[8] For the first six years of operation plutonium is taken from ALWR.
[9] Plutonium from FRTh plus a small amount from ALWR.

The results of calculations performed in the IAEA report based on the main input data show rather low electricity cost values, especially for fast reactors, which was quite to be expected, taking into account the choice of the low discount rate (only 4%) and the very optimistic economic assumptions with regard to the FR capital cost (only 25% higher than LWR).

The significant increase in construction costs resulting from the alternative input data set causes an overall increase in electricity generation cost and slightly changes its dependence on uranium cost for several reactors. The increase in the reprocessing cost of thorium-based spent fuel significantly influences the cost of energy produced by reactors operating in a closed thorium fuel cycle with relatively low burnup (HWR2 – heavy water CANDU type reactor utilizing thorium fuel and recycled uranium-233 (in a self-sustainable mode) and plutonium). Other thorium-based reactors are less vulnerable to the cost of reprocessing. [IAEA (2012)]

An FR with a blanket consisting of depleted or reprocessed uranium has the lowest electricity generation cost (¢2.88/kWh) of all fast reactors considered. Using a thorium blanket in a fast reactor slightly increases its cost of electricity generation (to ¢3.2/kWh) as part of its needed plutonium has to be reprocessed from ALWR spent fuel. Cost of electricity (¢3.42/kWh) generated by an FR consuming plutonium recycled from ALWR spent fuel during its first six years in operation is 15% higher than in the case of consumption of its own plutonium (¢3.2/kWh). This is caused by the much higher reprocessing effort needed to produce fuel for FR from ALWR spent fuel instead of from FR spent fuel with a much higher plutonium content. Therefore, at the initial stage of a fast reactor program, all new FRs will pass through a stage of rather expensive fuel. The same effect of higher plutonium cost causing higher electricity cost occurs at the initial stage of commercial deployment of fast reactors with a thorium blanket (FRTh). [IAEA (2012)]

The variable parameter in economic assessment models for nuclear systems is usually represented by the exogenous variable – the market price of natural uranium. The influence of the price of uranium may differ with different alternatives, therefore, a price may be calculated that will average them out. However, energy costs of all reactors using reprocessed fuel (LWR1, LWR2, HWR1, HWR2, FR, and FRTh) are not dependent on natural uranium cost [IAEA (2012)]; thus, when comparing the economics of various alternative reactor types by the cost of uranium, the costs of these reactors – as a function of the price of uranium – represent constant values and can only be compared with all other alternatives, but not between themselves.

Thermal reactors with a closed fuel cycle show similar effects as with fast reactors: The use of plutonium from spent fuel of a different reactor increases its generation cost for electricity. Among thermal reactors with a once-through fuel cycle, the AHWR using thorium generates some of the cheapest electricity at low uranium cost. It is competitive against the ALWR below a uranium price of ~$50/kg and against conventional water cooled reactors (LWR, HWR) up to a cost of $150 per kilogram of natural uranium. This is stipulated by the AHWR's high capacity factor and also by the combination of its long service life (100 years) and low discount rate assumed (0.04), and not directly due to the fuel type used, although high capacity factor and reactor lifetime are achieved in the design of thorium-uranium fueled reactor. However, in the once-through fuel cycle, the AHWR has one of the steepest growths of energy cost by an increase of uranium cost due to the high enrichment of the uranium fraction in fresh fuel and the relatively high share of uranium-235 in spent fuel. At a higher cost of uranium, AHWR reactors – originally designed to work in an open fuel cycle – might be compelled to introduce reprocessing. Such reactors using thorium and envisaging reprocessing may become competitive with the traditional thermal reactors operated in once-through fuel cycle at a cost of natural uranium at a level of $400/kg. [IAEA (2012)]

The once-through application of thorium in AHWRs remains competitive against conventional water cooled reactors up to the cost of $250 per kg of natural uranium. The cost of uranium required to make the introduction of a closed thorium fuel cycle (LWR2 – light water reactor with plutonium, uranium-233, depleted uranium fuel) competitive against traditional thermal reactors (LWRs, HWRs) operated in a once-through fuel cycle depends on the type of reactor using thorium and starts at a value of ~$400/kg. [IAEA (2012)]

PROSPECTIVE REACTORS

Subcritical accelerator-driven systems (ADS). The concept of a thorium and uranium-233 based system with a proton accelerator[1] was proposed by the noted physicist Carlo Rubbia, who remains its major advocate. A lobbying organization in the UK called the Weinberg Foundation is working to promote this concept and secure allocation of funding for further research.

In an ADS system, high-energy neutrons are produced through the spallation reaction of high-energy protons from an accelerator (usually > 500 MeV) striking heavy target nuclei of lead, lead-bismuth or other material, and neutron spallation occurs. Up to one neutron can be produced per 25 MeV of the incident proton beam. These neutrons can be directed to a subcritical reactor containing thorium, where the neutrons breed U-233 and promote the fission of it. If the spallation target is surrounded by a blanket assembly of nuclear fuel, such as fissile isotopes of uranium or plutonium (or thorium-232, which can breed to uranium-233), there is a possibility of sustaining a fission reaction. This self-sustaining fission reaction can be used either for power generation or transmutation of actinides resulting from the uranium/plutonium fuel cycle. The use of thorium instead of uranium means that less actinides are produced in the ADS itself. [Encyclopedia of Earth, Thorium (2013); WNA, Accelerator-Driven Nuclear Energy (2013)]

Earlier ADS proposals required the use in such reactors of a proton accelerator with an 800 MW to 1 GW beam hitting a thorium-based fuel element. But creating such an accelerator is a challenge, and its operation would be extremely energy-intensive. It is likewise difficult to ensure operational reliability of such a system. Contemporary concepts envision a reactor operating at a level very close to criticality and, therefore, requiring a relatively small proton beam to ensure neutron spallation. A 10 MW proton beam might thus produce 1,500 MW of heat (and thus 600 MW of electricity, some 30 MWe of which drives the accelerator). Today's accelerators, however, are capable of only 1 MW beams. [WNA, Accelerator-Driven Nuclear Energy (2013)]

ADS research is carried out in a number of countries. The most notable is the UK-Swiss accelerator-driven thorium reactor (ADTR) proposal, which has gone to feasibility study stage, for a 600 MWe lead-cooled fast reactor. This envisages a ten-year self-sustained thorium fuel cycle, using plutonium as a fission starter. Molten lead is both the spallation target and the coolant. In contrast to other designs with neutron multiplication coefficients of 0.95-0.98 and requiring more powerful accelerators, this ADTR has a coefficient of 0.995 and requires only a 3-4 MW accelerator, with fast-acting shutdown rods, control rods, and precise measurement of neutron flux. [WNA, Accelerator-Driven Nuclear Energy (2013)]

A 2008 report commissioned by the Norwegian Ministry of Petroleum and Energy [Thorium as an Energy Source (2008)] described the following advantages of thorium-based ADS reactors as compared to conventional nuclear reactors:

– Minimal probability of runaway reaction. In other words, an ADS is expected to be much safer than traditional reactors. An ADS can only run when neutrons are supplied to it because it burns material which does not have a high enough fission-to-capture ratio for neutrons to maintain a fission chain reaction. One then has a nuclear reactor which could be turned off simply by stopping the proton beam – i.e., turning off power supply – rather than needing to insert control rods to absorb neutrons;

– Low-pressure system;

– Much smaller production of long-lived actinides and efficient burning of minor actinides;

– Incineration of nuclear waste. The main advantage of this type of reactors is their ability to burn long-lived actinides (uranium, americium, curium, etc.) – in other words, not so much their ability to generate cheap electricity per se as their ability to facilitate simpler and cheaper nuclear waste disposal.

Another area of current interest in the use of ADSs is in their potential to dispose of weapons-grade plutonium, as an alternative to burning it as mixed oxide fuel in conventional reactors. Two alternative strategies are envisaged: the plutonium and minor actinides being managed separately, with the latter burned in ADSs while plutonium is burned in fast reactors; and the plutonium and minor

[1] See, for instance, Michael Anissimov's blog "A Nuclear Reactor in Every Home" [Anissimov (2006)], which summarizes various arguments made for this reactor type by its advocates.

actinides being burned together in ADSs, providing better proliferation resistance but posing some technical challenges. Both can achieve major reduction in waste radiotoxicity, and the first would add only 10-20% to electricity costs (compared with the once-through fuel cycle). [WNA, Accelerator-Driven Nuclear Energy (2013)]

The problem with this reactor type is that it has yet to complete the stage of feasibility studies. More needs to be done in order to understand its potential and technical limitations.

These are the main challenges associated with developing this type of reactor [Thorium as an Energy Source (2008)]:

– More complex design because of the use of the accelerator. Creating an accelerator with required parameters (continuous, not pulsed operating mode) is an extremely complex task as the two systems (a powerful accelerator and the reactor), each in itself being very technologically complex, must work perfectly well together;

– Use of the accelerator makes the system less reliable;

– Electricity generation discontinues with accelerator shutdown;

– The reactor produces almost no long-lived waste, but spent fuel is highly radioactive;

– Large production of volatile radioactive isotopes;

– The beam tube may break containment barriers;

– Cooling is required for the spallation target as it becomes heated due to exposure to the proton beam.

Commercial application of partitioning and transmutation, which is attractive particularly for actinides, is still a long way off, since reliable separation is needed to ensure that stable isotopes are not transmuted into radioactive ones. New reprocessing methods would be required, including electrometallurgical ones (pyroprocessing). [WNA, Accelerator-Driven Nuclear Energy (2013)]

ADS advocates cite very low costs for the technology. For instance, Carlo Rubbia expects that serial production of this reactor type would reduce power production cost by about 30% [Thorium as an Energy Source (2008)][2], but the complexity of ADS technology and the inescapable problems of technological development and definition of the safety features cast doubt on the particularly low future costs estimated by its promoters.

The 2008 Norwegian report cites a comparative study of the fuel cycles of ADSs and fast reactors, issued in 2002 by OECD/NEA [OECD/NEA (2002)]. This study was primarily focused on reducing the long-term radiotoxic inventory of waste. The expert group considered that a possible cost reduction of a subcritical reactor compared to a conventional reactor (for instance, with the possible elimination of control rods) may be offset by cost increases related to complications in containment and other systems. In estimates done in that study, the cost of an ADS was higher than that of an FR roughly by virtue of the added cost of accelerator and target. The study also concluded that "Fuel cycle schemes that involve the use of the more expensive ADS technology show an overall economic benefit by burning as much of the plutonium as possible in less expensive more conventional systems, i.e. MOX-LWRs and MOX-FRs." [Thorium as an Energy Source (2008)]

In 1997, the Euratom Scientific and Technical Committee (STC) was requested by the European Commission to evaluate the proposals for a nuclear accelerator-driven system for electricity generation. The STC not only questioned the complexity of an ADS as it did not consider it "[…] realistic to pursue development of the whole system at once" and saw "[…] significant technological and commercial risks in almost every aspect of the proposals," but was also convinced that for electricity production an ADS "would not be economically competitive with the improved light water reactor systems […]." The STC concluded that further work on ADS should be primarily aimed at waste management. [Thorium as an Energy Source (2008)]

The expensiveness of the spallation technology, coupled with the need to develop the necessary high-intensity accelerators, means that it will not be possible to employ this method soon.

According to the Norwegian report, OECD/NEA experts have regularly concluded that energy production with an ADS cannot compete economically with critical reactor technology. As Kjell Bendiksen writes [Bendiksen (2006)], it is impossible to even

[2] [Thorium as an Energy Source (2008)] refers to a 1996 European Organization for Nuclear Research (CERN) report – "A Preliminary Estimate of the Economic Impact of the Energy Amplifier" by R. Fernández, P. Mandrillon, C. Rubbia, and J.A. Rubio (CERN/LHC/96-01 (EET)) – for the estimated approximate 30% cost advantage of a unit in the series planned by the CERN group over the costs, in ¢/kWh, for a serial PWR in France announced in 1996 by the report's authors.

imagine the cost of energy produced by such a reactor.

Molten salt reactor. A molten salt reactor – a breeder concept in which thorium fuel is circulated in molten salt, without needing external cooling – is one of the prospective reactor types among the so-called Generation IV reactors. The thorium-fuelled MSR variant is sometimes referred to as the Liquid Fluoride Thorium Reactor (LFTR). The primary circuit runs through a heat exchanger, which transfers the heat of the fission reaction to a secondary salt circuit for steam generation. The fluid fuel incorporates thorium and uranium (U-233 and/or U-235) fluorides and serves as both heat transfer fluid and the matrix for the fissioning fuel. Certain MSR designs will be designed specifically for thorium fuels to produce useful amounts of U-233 – eventually leading to the self-sustaining use of thorium as an energy source. [WNA, Thorium (2013)]

In the last decade, says a 2011 MIT report, "The Future of the Nuclear Fuel Cycle," a new reactor concept has been proposed: the Advanced High-Temperature Reactor (AHTR) that uses liquid fluoride salts as coolants and the coated-particle fuel developed for gas-cooled high-temperature reactors. It is also called the fluoride-salt high-temperature reactor (FHR). It has potentially promising economics, the MIT report says, because of the compact primary systems that operate at low pressures with large thermal margins and sufficiently high coolant temperatures to enable use of higher efficiency power cycles. Unlike other reactors, it naturally uses a combined uranium-thorium fuel cycle in a once-through mode and may have a conversion ratio near unity if operated with a closed fuel cycle. In the context of fuel cycles it is a radical departure because one variant can use flowing pebble-bed fuel to enable three dimensional optimization of the reactor core with time that creates new fuel cycle options that are today only partly understood. [MIT (2011)]

For the molten salt reactor type, the following technological and economic advantages are described [Anissimov (2006)]:

– Reduced capital costs. The lower pressure in the reactor means that one can rule out accidents associated with reactor vessel breach or core meltdown, which could help cut some of the existing safety requirements to reactor design and significantly decrease capital costs as well as reduce construction time frames. For instance, it is pointed out that with molten salt reactors, containment becomes unnecessary. The expensive high-pressure coolant injection system could be dispensed with as well. This could have significant effects on the nuclear energy economics because the bulk of electricity generation costs is accounted for by capital costs (over 60%), and out of those, up to 80% is measures installed against various core meltdown scenarios. In estimates proposed by advocates of these reactor systems, reducing costs by eliminating unnecessary and expensive safety measures will mean that a 1 GW plant could be built for at most $780 million, rather than today's $1.1 billion, or for even as low as $220 million or below, given the corresponding paring down of safety requirements, where the higher level of inherent safety of these reactors would be taken into account.

– A small core leads to lower capital costs overall and makes it possible to build reactors of any size or power capacity, which could have a serious impact on the development of the nuclear energy industry. Smaller plants (100 MW), such as the Department of Energy's small, sealed, transportable, autonomous reactor (SSTAR), will be 15 m tall, 3 m wide, and weigh 500 tons, using only a few centimeters of shielding.

– Fewer personnel. With fewer safety requirements and a greater level of automation, staffing requirements could be reduced (from 500 to 30 employees, according to the concept's proponents). Therefore, staffing costs for a 1 GW plant could decrease from $50 million to $5 million per year.

– Because the molten salt continuously recirculates the fuel, the replacement of fuel rods is not necessary, which translates into direct savings – since there are no refueling costs – as well as saving on eliminating downtime caused by refueling.

– LFTRs generate less waste than uranium reactors both in terms of the amount of waste and the half-life periods of the components that it comprises. On the whole, this reduces waste management costs both for this reactor type and the existing uranium reactors, whose waste can be reprocessed in the LFTRs. Of each ton of the LFTR waste, 17% remains radioactive for around 300 years, and those waste products that present the biggest challenge in terms of management or disposal (americium, curium, plutonium) could be re-used and disposed of in the LFTR reactors. [Liquid Fluoride Thorium Reactors (2010)]

[Anissimov (2006)] cites as one of the drawbacks the need, if molten salt is used as a coolant, to recirculate and purify molten salt external to the reactor vessel. This requires a chemical reprocessing facility, of a type that has only yet been demonstrated in a lab. The scale-up to industrial levels has currently been labeled as uneconomic, but improvements in salt purification technology over the next decade will bring the costs down greatly, and eventually the entire process will be automated. Thorium reactor proponents argue that if thorium reactors become popular, the technology could improve to the point where the cost of maintaining a 1 GW nuclear reactor will eventually drop as low as $1 million a year, or less.

Disadvantages of thorium fuel:

1. All fuel-involving operations will require the use of remotely operated equipment due to the fuel's radioactivity and high temperature;

2. With spent fuel management, a highly complex instantaneous evaporation system will be needed to remove water content and condense plutonium nitrate into crystals in order to rule out a criticality event.

All molten salt reactors so far exist as concepts only, but work is under way to create a technologically viable prototype (the largest effort is being undertaken in China). Until solutions are found to some of the technological challenges, it is impossible to assess to what extent the advantages cited can really reduce a thorium-based power plant's capital or O/M costs. For instance, experience gained with operating experimental models of this reactor type demonstrates that the reactor vessel is vulnerable to severe corrosion.

R&D costs. All the described technological and economic advantages have so far been insufficient to spark a considerable interest in the world in preparing the groundwork needed for the application of thorium-based fuels. A lot of costly and extended research will be necessary to overcome the existing engineering barriers.

In that regard, assessing R&D costs has a special significance. Investments required to solve the various technological problems, create prototypes, and conduct tests have to be weighed against the potential gain and adjusted for the risks, and there are as yet no indications that such investments will pay off. A number of projects have been undertaken in the world to develop a thorium fuel cycle, and the costs have proven enormous. In the 1970s, Germany spent around EUR 500 million (in 2008 money) to develop a thorium fuel cycle and EUR 2.5 billion on the high temperature reactor itself. More recently, the Generation IV International Forum (GIF) in its technology roadmap to develop Generation IV advanced nuclear energy systems estimated at around $1 billion the funds needed to assess the viability and the performance of one system before any decision to develop and build a demonstrator. [Thorium as an Energy Source (2008)]

Nuclear energy has in the past demonstrated quite a number of examples where technological problems and the associated rise in costs have been less than duly appreciated. Thus, until a successful reactor design of any of the types under discussion in this overview is developed and is shown to meet all safety standards, an assessment of the capital costs of these reactors will remain impossible.

CONCLUSION

The economics of thorium-based nuclear energy are as yet quite speculative. So far, one can offer but “guesstimates” as to the likely cost of thorium-produced energy as compared to that of energy derived from uranium. The value of this or that nuclear material depends on the process flow that it forms part of. If it is a material with potential use in an actually existing nuclear fuel cycle, it is assessed based on the cost of materials it is capable of replacing, adjusted for the larger or smaller cost at which it is procured. If, on the other hand, a fundamentally different fuel cycle is under consideration, then the comparison must be made with the existing fuel cycles on the whole, with waste management, safety, insurance, and other costs taken into account.

The choice of one or another nuclear energy development strategy affects all economic indicators at once, therefore, comparing specific cost items is generally not very practical. At each stage, and for the entire system on the whole, the cost minimization tasks are approached depending on the multidirectional impacts that a variety of factors have on the costs.

The main economic advantages of thorium reactors do not apparently lie in the cheaper energy that they produce, but rather in the lesser cost of management of spent fuel generated by conventional, uranium-based nuclear reactors.

For instance, in its 2010 report [NNL (2010)], the UK National Nuclear Laboratory said it believes that the thorium fuel cycle does not currently have a role to play in the UK context, other than its potential application for plutonium management in the medium to long term. The technology is innovative, although technically immature and currently not of interest to the utilities, representing significant financial investment and risk without notable benefits. In many cases, the benefits of the thorium fuel cycle have been overstated.

References:

1. Anissimov (2006): Anissimov, M., A Nuclear Reactor in Every Home, 2006, www.acceleratingfuture.com/michael/blog/2006/10/a-nuclear-reactor-in-every-home/.
2. Bekman (2010): Бекман И.Н. Торий. Учеб. пособие. М.: Московский государственный университет им. М.В. Ломоносова, 2010. / Bekman I.N. Torii. Uchebnoye posobiye. M.: Moskovsky gosudarstvenny universitet im. M.V. Lomonosova, 2010. (Bekman I.N. Thorium, a study guide. Moscow: Lomonosov Moscow State University, 2010).
3. Bendiksen (2006): Bendiksen, K., Thorium - et nytt norsk energieventyr? Institutt for Energiteknikk (IFE), 14.12.06, www.ife.no/no/ife/filer/Nyhets-fil/thorium-artikkel.
4. Berg et al. (2012): Berg, Ø., Bjørnstad, T., Dahlgren, S., Nøvik, S., Rondeel, W. og Totland, A., Thorium - En framtidsressurs i Oslofjordregionen? Thorium Think Tank rapport til Oslofjordfondet. Rapport nr 2-2012, Regiongeologen, Buskerud Telemark Vestfold fylkeskommuner, 2012, www.ife.no/no/ife/filer/Nyhets-fil/thorium-en-framtidsressurs-i-oslofjordregionen.
5. Bunn et al. (2003): Bunn, M., S.Fetter, J.Holdren, and B.van der Zwaan, The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel, Managing the Atom Project, Belfer Centre for Science /International Affairs, Harvard University, USA, 2003, belfercenter.ksg.harvard.edu/files/repro-report.pdf.
6. Digges (2003): Digges, C., Thorium-Based Fuel May Play Role in Plutonium Disposition, Bellona Foundation, 08/05-2003, www.bellona.org/english_import_area/international/russia/nuke-weapons/nonproliferation/29510.
7. Encyclopedia of Earth, Thorium (2013): The Encyclopedia of Earth, Thorium, retrieved in February 2013, http://www.eoearth.org/article/Thorium.
8. GIF (2007): GIF, Cost Estimating Guidelines for Generation IV Nuclear Energy Systems, Prepared by The Economic Modeling Working Group Of the Generation IV International Forum, GIF/EMWG/2007/004, printed by the OECD/NEA, 2007, http://www.gen-4.org/Technology/horizontal/EMWG_Guidelines.pdf.
9. INL (2008): Idaho National Laboratory, Advanced Fuel Cycle Cost Basis, INL-2008, Idaho Falls, USA, 2008, http://www.inl.gov/technicalpublications/documents/3915965.pdf.
10. IAEA (2010): International Atomic Energy Agency, Assessment of Nuclear Energy Systems Based on a Closed Fuel Cycle with Fast Reactors, IAEA-TECDOC-1639, 2010, http://www-pub.iaea.org/MTCD/Publications/PDF/TE_1639_Rev1_web.pdf.
11. IAEA (2000): International Atomic Energy Agency, Thorium based fuel options for the generation of electricity: Developments in the 1990s, IAEA-TECDOC-1155, 2000, www-pub.iaea.org/MTCD/publications/PDF/te_1155_prn.pdf.
12. IAEA (2005): International Atomic Energy Agency, Thorium fuel cycle – Potential benefits and challenges, IAEA-TECDOC-1450, 2005, www-pub.iaea.org/mtcd/publications/pdf/te_1450_web.pdf.
13. IAEA (2012): International Atomic Energy Agency, Role of Thorium to Supplement Fuel Cycles of Future Nuclear Energy Systems, IAEA Nuclear Energy Series NF-T-2.4, 2012, www-pub.iaea.org/MTCD/Publications/PDF/Pub1540_web.pdf.
14. Kazimi (2003): Kazimi, M. Thorium fuel for nuclear energy, American Scientist, Vol. 91, No. 5, 408, 2003.
15. Liquid Fluoride Thorium Reactors (2010). Hargraves, R. and R. Moir. Liquid Fluoride Thorium Reactors: An old idea in nuclear power gets re-examined, a reprint from American Scientist, the magazine of Sigma Xi, The Scientific Research Society, July-August 2010, http://www.energyfromthorium.com/pdf/AmSci_LFTR.pdf.
16. MIT (2003): Massachusetts Institute of Technology, The Future of Nuclear Power, MIT, Boston, 2003, web.mit.edu/nuclearpower/pdf/nuclearpower-summary.pdf.
17. MIT (2009): Massachusetts Institute of Technology, Update of the MIT 2003 Future of Nuclear Power, MIT, Boston, 2009, http://web.mit.edu/nuclearpower/pdf/nuclearpower-update2009.pdf.
18. MIT (2011): Massachusetts Institute of Technology, The Future of the Nuclear Fuel Cycle, MIT, Boston, 2011, http://mitei.mit.edu/system/files/The_Nuclear_Fuel_Cycle-all.pdf.
19. OECD/NEA (2002): Organisation for Economic Co-Operation and Development, Nuclear Energy Agency, Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles, A Comparative Study, 2002, https://www.oecd-nea.org/ndd/reports/2002/nea3109-ads.pdf.
20. OECD/NEA (2006): Organisation for Economic Co-Operation and Development, Nuclear Energy Agency, Advanced Nuclear Fuel Cycles and Radioactive Waste Management, 2006, http://www.oecd-ilibrary.org/nuclear-energy/advanced-nuclear-fuel-cycles-and-radioactive-waste-management_9789264024861-en.
21. OECD/NEA (1994): Organisation for Economic Co-Operation and Development, Nuclear Energy Agency, The Economics of the Nuclear Fuel Cycle, 1994, http://www.oecd-nea.org/ndd/reports/efc/EFC-complete.pdf.
22. OECD/NEA (2001): Organisation for Economic Co-Operation and Development, Nuclear Energy Agency, Trends in the Nuclear Fuel Cycle: Economic, Environmental and Social Aspects, 2001, http://books.google.no/books?id=tH3ziRgq-ycC&printsec=frontcover#v=onepage&q&f=false.
23. OECD/NEA (1989): Organisation for Economic Co-Operation and Development, Nuclear Energy Agency, Plutonium Fuel, An Assessment, 1989, https://www.oecd-nea.org/ndd/reports/1989/nea6519-plutonium-fuel.pdf

24. OECD/NEA, IEA (2005): Organisation for Economic Co-Operation and Development, Nuclear Energy Agency, International Energy Agency, Projected Costs of Generating Electricity, 2005, http://www.oecdbookshop.org/oecd/display.asp?lang=EN&sf1=identifiers&st1=92-64-00826-8.
25. OECD/NEA, IEA (2010): Organisation for Economic Co-Operation and Development, Nuclear Energy Agency, International Energy Agency, Projected Costs of Generating Electricity, 2010, http://www.debateco.fr/sites/default/files/2010%20IEA%2BOECD%20on%20Costs%20Electricity%20.pdf.
26. OECD/NEA, IAEA (2008): Organisation for Economic Co-Operation and Development, Nuclear Energy Agency, International Atomic Energy Agency, Uranium 2007: Resources, Production and Demand, 2008, www.laka.org/docu/boeken/pdf/6-01-2-20-94.pdf.
27. Olson et al. (2002): Olson, G. L., R. K. McCardell and D. B. Illum, Fuel Summary Report: Shippingport Light Water Breeder Reactor, INEEL/EXT-98-00799 Rev. 2, Idaho National Engineering and Environmental Laboratory Bechtel BWXT Idaho, LLC, 2002, www.inl.gov/technicalpublications/Documents/2664750.pdf.
28. Posiva Oy (2010): Posiva Oy, Total Costs and Funding for Final Disposal, official website, 2010, www.posiva.fi/en/final_disposal/total_costs_and_funding_for_final_disposal.
29. Principals of Economic Cost-Benefit Analysis (2013): ThorEA Wiki, Principals of Economic Cost-Benefit Analysis, retrieved in January 2013, http://thorea.wikia.com/wiki/Economics.
30. Thorium as a Nuclear Fuel (2013): Thorium Energy, Inc, Thorium as a Nuclear Fuel, retrieved in January 2013, www.thoriumenergy.com/index.php?option=com_content&task=view&id=14&Itemid=30.
31. Thorium as an Energy Source (2008): Thorium as an Energy Source – Opportunities for Norway, published by the Thorium Report Committee, 2008, http://www.regjeringen.no/upload/OED/Rapporter/ThoriumReport2008.pdf.
32. UK NNL (2010): UK National Nuclear Laboratory, The Thorium Fuel Cycle, an independent assessment, 2010, http://www.nnl.co.uk/media/27860/nnl__1314092891_thorium_cycle_position_paper.pdf.
33. US DoE (2001): U.S. Department of Energy, Generation-IV Roadmap Report of the Fuel Cycle Crosscut Group, 2001, http://energy.gov/sites/prod/files/GenIVRoadmapFCCG.pdf.
34. U.S. Geological Survey (1999): U.S. Geological Survey, Metal Prices in the United States through 1998, Thorium, 1999, http://minerals.usgs.gov/minerals/pubs/commodity/thorium/690798.pdf.
35. U.S. Geological Survey (2012): U.S. Geological Survey, Mineral Commodities Summaries, Thorium, 2012, minerals.usgs.gov/minerals/pubs/commodity/thorium/mcs-2012-thori.pdf.
36. WNA, Accelerator-Driven Nuclear Energy (2013): World Nuclear Association, Accelerator-Driven Nuclear Energy, retrieved in February 2013, http://www.world-nuclear.org/info/Current-and-Future-Generation/Accelerator-driven-Nuclear-Energy/.
37. WNA, Economics of Nuclear Power (2010): World Nuclear Association, The Economics of Nuclear Power, July 2010, http://www.world-nuclear.org/info/Economic-Aspects/Economics-of-Nuclear-Power/.
38. WNA, Thorium (2013): World Nuclear Association, Thorium, retrieved in February 2013, http://www.world-nuclear.org/info/Current-and-Future-Generation/Thorium/.

List of abbreviations and reactor type designations used in this overview

ADS	accelerator-driven system
AHWR	advanced heavy water reactor with plutonium, U233, thorium fuel
ALWR	advanced light water reactor with uranium oxide fuel
BWR	boiling water reactor
FR	fast reactor with MOX fuel, depleted uranium in blankets
FRTh	fast reactor with plutonium, depleted uranium fuel, and thorium in blankets
HEU	highly enriched uranium
HM	heavy metal
HTR	high temperature reactor with U233/thorium fuel
HWR	heavy water reactor with natural uranium fuel
HWR1	heavy water reactor with plutonium thorium fuel and breeding U233
HWR2	heavy water reactor utilizing thorium fuel and recycled U233 (in a self-sustainable mode) and plutonium
IAEA	International Atomic Energy Agency
LFTR	liquid fluoride thorium reactor
LWBR	light water breeding reactor
LWR	light water reactor with uranium oxide fuel
LWR0	light water reactor with uranium oxide, thorium fuel
LWR1	light water reactor with plutonium, thorium fuel
LWR2	light water reactor with plutonium, U233, depleted uranium fuel
MOX	mixed uranium and plutonium oxide fuel
MSR	molten salt reactor
O/M	operation and maintenance
PWR	pressurized water reactor
PHWR	pressurized heavy water reactor
SNF	spent nuclear fuel
SWU	separative work unit
UOX	uranium oxide

BELLONA

www.bellona.ru