THORIUM ENERGY

S. Peggs, BNL, USA and ESS, Sweden
R. Seviour, ESS, Sweden and Huddersfield U., UK and Lund U., Sweden
R. Cywinski, Huddersfield U., UK

SAFETY, PROLIFERATION, AND WASTE

Uranium-based nuclear fission technologies are an important energy source for many industrialised nations, although use has been limited by: high cost; perceived adverse safety; the potential for proliferation; and the management of nuclear waste. A thorium fuel cycle, combined with alternative technologies, presents numerous potential advantages [1]. Thorium fuel cycles are intrinsically more proliferation-resistant, reduce plutonium production, and can consume legacy plutonium and waste actinides. The different characteristics of the thorium cycle options arise not only from the different system designs, but also from the physical properties of the fuels themselves [2, 3].

Safety: Molten salt reactor (MSR) and high-temperature gas-cooled reactor (HTGR) thorium reactors have safety advantages over conventional light water reactors (LWR) [2, 3, 4]. The liquid fuel in an MSR may provide improved reactivity feedback and can be removed from the reactor core [4]. HTGRs can withstand very high temperatures in excess of 2000 K without fuel failure [5]. As demonstrated at the German AVR, these designs may survive a complete loss of power event [2]. The use of thorium in LWR fuel can have advantages over solely U-Pu systems because of its better thermal, physical, and irradiation performance [5].

Proliferation: Thorium occurs in nature as a single fertile isotope. In itself, it cannot be enriched to produce weapons grade material. Consequently it has been argued that thorium is "proliferation resistant" [6, 7]. Additionally, production of Pu-239 is extremely small in most proposed thorium cycles, due to the different actinide distribution, thereby posing a significantly lower proliferation risk. However, thorium cycles do generate U-233 as the fissile isotope, rather than the Pu-239 bred from U-238 in the U-Pu cycle. U-233 is in principle useable in nuclear weapons, but the inherent co-generation of U-232 provides significant protection due to the steady growth of hard-gamma emitting Tl-208 in its decay chain. This makes non-state weapons manufacture difficult, and easily detectable.

Waste: Thorium systems have the ability to burn actinides, and provide several routes to plutonium stockpile disposal [6]. Waste forms for thorium-bearing fuels have been studied and shown to have advantages based on their physical and chemical properties [3, 5, 8, 9].

SOLID FUEL REACTORS

Thorium can in principle be used as a solid fuel component in all the main reactor types that have operated to date: boiling and pressurised light water reactors (BWRs and PWRs), heavy water reactors (HWRs), HTGRs, and sodium-cooled fast reactors. Thoria based fuels offer higher operational safety margins and accident tolerance due to various favourable, robust, properties: a very high melting point; non-oxidizability; general chemical inertness; reasonable thermal conductivity; and a strong ability to retain fission products within its crystal lattice.

Reactors without accelerators: Thorium cycles have been investigated in a variety of reactors, including Gas-Cooled Reactors (GCRs), BWRs, and PWRs [10, 11, 12]. These studies demonstrated good performance of thorium in oxide form in LWRs and in carbide form in GCRs [13]. The Light Water Breeder Reactor programme in a PWR [14] demonstrated the feasibility of a closed Th-U-233 fuel cycle, confirming that U-233 breeding is achievable using a heterogeneous epi-thermal spectrum U-Th core. Near-complete transuranic waste incineration has been suggested in a thorium-fuelled PWR [15]. India has operated thorium-fuelled research reactors for many years: first the Purnima-II reactor (1984-6) and, since 1997, in the 30 kW Kamini research reactor [16], which uses U-233 bred from thorium in another reactor.

Accelerator-driven subcritical cores: The accelerator provides a controlled external source of fast neutrons in the reactor core, to breed fissile material at the same rate or faster than it is consumed. Some neutrons maintain a chain reaction while others breed Th-232 to U-233. Eventually the U-233 becomes the fissile fuel, with fertile thorium being added to the mix as necessary.

Proton-driven spallation is the usual choice (especially for GW-scale reactors), although other particles including electrons have also been proposed. Heavier nuclei bring little advantage at considerable cost. The required beam current I is given by

$$I = e\,\frac{(1-k)P}{nfE_f} \tag{1}$$

where $k < 1$ is the "criticality" factor of the reactor, P is the thermal power, n is the number of neutrons produced per incident proton, of which a fraction f induce fission, and E_f is the mean energy release per fission. A typical 1 GWe reactor requires average currents of about 10 mA and a beam power of about 10 MW, beyond today's most powerful accelerators.

In 1996 the Indian Atomic Energy Commission initiated design studies for a 200 MWe PHWR ADS system fuelled by uranium and thorium [17]. Jacobs Engineering Group Inc. (Jacobs) have produced a conceptual design of an Accelerator-Driven Thorium Reactor (ADTR$^{\mathrm{TM}}$) 600 MWe power station, based on the lead-cooled fast reactor illustrated in Figure 1 [18, 19]. The ADTR$^{\mathrm{TM}}$ challenges previously established criticality margins, with a proposed k value of 0.995 [20].

ISBN 978-3-95450-122-9

MOLTEN SALT REACTORS

The Molten-Salt Reactor Experiment (MSRE) operated from 1965 until 1969 using a fuel/moderator mixture of lithium, beryllium, thorium and uranium fluorides [21]. It built on the success of the 1954 Aircraft Reactor Experiment [22], and on other early liquid-fuel schemes; the basic feasibility of such designs is well demonstrated. The graphite moderator ensures the correct neutron spectrum while the fuel salt circulates in a closed loop. Increased power (in a fluctuation) expands the liquid fuel, in turn reducing the power output. This safety feature was tested during MSRE operation, performing as expected. MSRs have further safety advantages and some disadvantages in comparison to solid-fuel reactors [23]. More modern Lithium Fluoride Thorium Reactor designs are being proposed as an alternative fuel cycle solution by several advocacy groups [24, 25].

Most MSR advantages are maintained in an ADS implementation. The target in the salt bath produces additional neutrons, making it easier to optimise performance. One promising target design, from BARC, uses an inert gas injected into a long vertical column to create a mass imbalance that circulates the lead-bismuth eutectic (LBE) and also removes gaseous poisons [26].

It is sometimes said that the accelerator trip requirements for an ADS MSR are considerably relaxed compared with a solid-fuel ADS reactor, because the timescales for stresses are longer since there is no Hastelloy cladding on the fuel rods. The comparison depends on the power rating of the fuel pins in the solid-fuel reactor. Recent studies have shown that in some cases the fuel cladding is the limiting factor [27] while in others it is the inner barrel [28]; an ADS MSR has no need for fuel cladding but does require an inner barrel.

ACCELERATOR IMPLICATIONS

Optimising spallation output in terms of proton energy cost per neutron gives a broad plateau beginning at about 1 GeV, a value chosen by the Spallation Neutron Source (SNS) [29]. A lower value of 600 MeV reduces the capital costs of the MYRRHA proposal, but provides enough neutrons for a power of 57 MWth [30]. The European Spallation Source [31] energy of 2.5 GeV is rather higher.

At least 20 neutrons are produced for each incident 1 GeV proton in a typical spallation target – 1 neutron per 50 MeV of beam energy. About 150 MeV of wall-plug energy is therefore required for each neutron, assuming a typical accelerator efficiency of 30%. Maximising this efficiency is an important accelerator design goal.

Beam losses must be kept to a low level to allow hands-on maintenance: a proton loss rate of 1 W/m is considered a maximum. This is also a major design challenge.

Reliability and availability: Extremely high accelerator reliability is required in a full-scale ADS power station. Repeated short trips lead to thermal stresses in reactor components, and long trips lead to economically very damaging losses of generating power [32]. Recent analyses of maximum allowable beam trip durations considering thermal stress and damage to reactor components suggest that the required accelerator reliability is much less severe than originally thought (but is still very challenging) [28]. Several uncertainties remain, especially concerning irradiated materials properties, erosion and corrosion related aspects in an LBE environment, and reactor restart sequences.

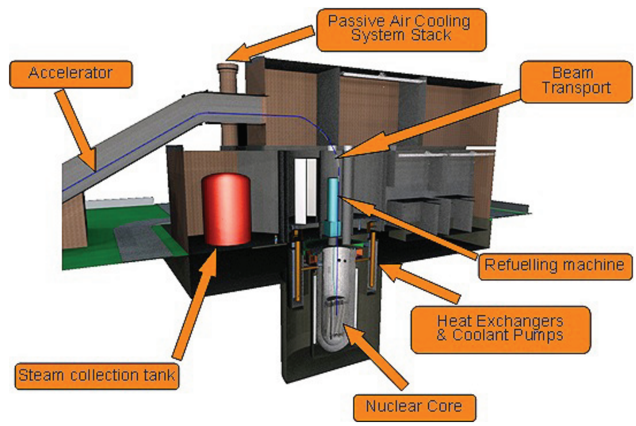

Figure 1: The ADTR™ power station reactor building.

Erroneous initial optimistic predictions of the number of allowed emergency reactor stops due to beam trips could lead to premature replacements of components, reduction of reactor lifetime, and to a dramatic decrease of availability. Thus, the MYRRHA project requirements conservatively allow fewer than 5 beam trips (longer than 3 seconds) per 3-month operating period, following PHENIX reactor experience [33, 34]. In any case, major improvements in accelerator reliability are most certainly required for the ADS mission.

Industrial experience shows that reliability is achievable – at a cost – through redundancy, under-rating, graceful failure, and planned maintenance, using a holistic analysis of the complete system. It may be advantageous to use several independent accelerators, so that when one is off-line the current in the others can be increased.

Accelerator technologies

Linear accelerators (linacs) can provide the necessary energy and current, and appear to offer sufficient reliability, availability, and rapid fault recovery. However, they are expensive relative to cyclotrons or synchrotrons. A 1.4 MW linac like the SNS would be ∼300 m long, at a cost of ∼0.7 B$, so that it would nonetheless not dominate the total project cost, assuming that a thorium reactor costs about the same as a uranium reactor, ∼5 B$.

Cyclotrons are restricted to non-relativistic energies, and are limited by space-charge effects and by the need for orbit separation, but achieve MW-class beam powers at PSI and TRIUMF. A recent proposal for a 5 MW, 800 MeV, strong-focusing cyclotron would overcome both of these limitations [35]. There are also other proposals for ADS cyclotrons [36].

Rapid Cycling Synchrotrons (RCS) like ISIS operate at frequencies as fast as 50 Hz with beam powers well above 100 kW. Much faster repetition rates are attractive, but face the need to develop rapid frequency swing Radio Frequency (RF) systems, and also face technical issues with magnet and vacuum chamber eddy currents.

Fixed-Field Alternating Gradient (FFAG) accelerators currently exist only as low power prototypes, both proton [37] and electron [38]. An isochronous FFAG could be run with continuous beam like a cyclotron to achieve large currents. Non-isochronous designs face the same frequency swing challenges as RCS RF systems.

NECESSARY RESEARCH

A recent study assessed the technological readiness of accelerator and target technology for ADS systems, and outlined the necessary R&D activities [39]: it concluded that accelerator and target technology had advanced significantly in the last two decades, and was now ready for a full scale demonstration of the coupling of a MW-class accelerator to a subcritical core. Recent experimental accelerator/reactor coupling demonstrations have been made at low power at GUINEVERE [40] and KURRI [37]. The key performance requirements are very high proton beam power ($\simeq$ 10 MW), very low beam loss ($<$ 1 W/m) and very high reliability. Key research areas include:

1. development of highly reliable and fault tolerant accelerator systems and accelerator components;
2. advancing the state-of-the-art in accelerator systems, including linacs, FFAGs and RF systems;
3. improved understanding of beam loss mechanisms, emittance and halo growth.

Required spallation target R&D includes: 1) LBE handling, oxygen control and cleanup; 2) development of windowless target technologies; 3) materials irradiation studies; 4) full scale mock-up of cooling systems; 5) engineering the accelerator-to-target sub-critical blanket interfaces.

ACKNOWLEDGEMENTS

Active and profound contributions were made by V. Ashley, R. Ashworth, R. Barlow, J.-L. Biarrotte, S. Henderson, W. Horak, A. Hutton, J. Kelly, M. Lindroos, P. McIntyre, A. Norlin, H. Owen, G. Parks, and T. Roser.

REFERENCES

[1] "Towards an Alternative Nuclear Future", Thorium Energy Association, ThorEA, (2010).

[2] M. Lung & O. Gremm, V.180, 2, p.133-146, (1998).

[3] P. Rodriguez & C.V. Sundaram, J. of Nucl. Mats., V.100, p.227-249, (1981).

[4] K. Furukawa et al., Energy Conversion and Management, V.49, 7, p.1832-1848, ISSN 0196-8904, (2008).

[5] A. Talamo, Prog. in Nucl. Energy, V.51, p.274-280, ISSN 0149-1970, (2009).

[6] A. Galperin at al., Sci. & Global Sec. V.6, 3, (1997).

[7] R. Sollychin, IAEA Bulletin 51-1, p.43-44, (2009).

[8] P. Demkowicz et al., Nucl. Tech., V.147, p.157, (2004).

[9] D. Barrier et al., J. of Nucl. Matls., 352, p.357, (2006)

[10] IAEA, IAEA-TECDOC-1450, (2005).

[11] M. Todosow et al., Nucl. Tech., 151, 168-176, (2005).

[12] T.K. Kim & T. Downar, Nucl. Tech., 138, 17-29, (2002).

[13] J. Belle & R.M. Berman, Eds., US DOE/NE-0060, (1984).

[14] R. Atherton, Ed., WAPD-TM-1600, (1987).

[15] B.A. Lindley & G.T. Parks, Annals of Nucl. En., 40, 106-115 (2012).

[16] "(Indian) Nuclear Power Programme – Thorium", `http://www.dae.gov.in/publ/ar0203/chap3.pdf`

[17] S. Banerjee, "Towards a Sustainable Nuclear Energy Future", WNA Symposium (2010).

[18] C. Rubbia et al., CERN-AT-95-44(ET), (1995).

[19] V. Ashley & R. Ashworth, "The Technically Viable ADTR™ Power Station", Nuclear Future V.7 3, (2011).

[20] C. Rubbia, PCT Patent, PCT/EP2010/054132, (2010).

[21] R.C. Briant et al., Nucl. Sci. Eng., 2, 797 (1957).

[22] P. N. Haubenreich & J.R. Engel, Nucl. Appl. Tech., 8, 118 (1970).

[23] C.W. Forsberg, Trans. Am. Nucl. Soc. Ann. Meeting, (2004).

[24] Thorium Energy Alliance, `http://thoriumenergyalliance.com`

[25] The Weinberg Foundation, `http://www.the-weinberg-foundation.org`

[26] P. Satyamurthy, L. M. Gantayet & A. K. Ray, PRAMANA 68, No 2, 343 (2007).

[27] A. Ahmad, S.L. Sheehy & G.T. Parks, Annals of Nuclear Energy, 46, 97-105 (2012).

[28] H. Takei et al., Journal of Nuclear Science & Technology, 49:4, p.384-397, (2012).

[29] "Spallation Neutron Source Project Completion Report", SNS 100000000-BL0005-R00 (2006).

[30] D. De Bruyn et al., Technology & Components of ADS, Karlsruhe, OECD - NEA, p. 47-52, (2011).

[31] S. Peggs, Ed., "ESS Conceptual Design Report", ESS report ESS-2012-1, (2012).

[32] S.J. Steer et al., Elec. Pwr. Sys. Res., 81, 1662-1671 (2011).

[33] J-L. Biarrotte et al., LINAC 2010, (2010).

[34] G. Rimpault et al., submitted to ANS Nucl. Tech., (2013).

[35] P. McIntyre, IPAC 2012, (2012).

[36] L. Calabretta, Cyclotrons-10, (2010).

[37] M. Tanigaki et al., APAC 2004, (2004).

[38] S. Machida et al., Nature Physics **8**, p 243 (2011).

[39] H. Ait Abderrahim et al., `http://science.energy.gov/~media/hep/pdf/files/pdfs/ADS_White_Paper_final.pdf`, (2011).

[40] A. Degtyarev et al., Proc. of GLOBAL 2011, (2011).

ISBN 978-3-95450-122-9