Plutonium and China's Future Nuclear Fuel Cycle

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Introduction

Following the March 2011 Fukushima accident, the State Council, China's highest policy-making body, suspended approvals for new nuclear plants and initiated a range of other measures aimed at improving the country's nuclear safety provisions. The suspension of new construction approvals is expected to be lifted within the coming months,[1] after being in place for longer than initially expected. The State Council's actions demonstrated a new resolve among China's leadership to give nuclear safety considerations greater priority compared to the economic benefits of nuclear power. The Fukushima accident apparently gave policy makers a reason to fear that a similar accident in China would put the government-run nuclear programme at serious risk.

Throughout the past year, China has not moved away from its long-standing commitment to a closed, plutonium-based nuclear fuel cycle with spent fuel reprocessing and fast-neutron reactors. However, China's response to Fukushima appears to have delayed progress in that direction. The construction of conventional light water reactors (LWR) will soon gather greater pace, but further delays in China's fuel-cycle plans can be expected, as resources may need to be diverted towards improving the safety of current and future LWRs and to accelerating the shift from generation II to generation III LWR technology.

This cautious approach should be welcomed, because it provides China with further opportunity to reconsider the economic rationale and the security risks associated with reprocessing and fast-reactor technologies. The security and proliferation risks of conventional, uranium-fuelled LWRs are considered manageable, but nuclear reprocessing and fast reactors operating with plutonium-based fuel would add considerable non-proliferation challenges that China would have to manage. One concern held outside China is that these facilities may support China's strategic weapons programme. Another concern is that the subsequent spread of reprocessing and fast-reactor technologies from China through exports would run contrary to the global priority of minimising the accessibility of nuclear weapons-related technologies and materials. Additionally, a closed nuclear fuel cycle with fast reactors would have a substantial amount of weapons-usable fissile material in circulation, which increases the challenge to protect materials from being obtained by non-state actors.

[1] 'China Nuclear Reactor Programme to Resume in Q4', Reuters, 26 September 2012, http://www.reuters.com/article/2012/09/26/china-nuclear-idUSL4E8KQ0SA20120926.

Post-Fukushima measures to improve safety

Nuclear power is a logical choice for China. Years of high economic growth have boosted electricity demand and helped cover the cost of the expansion. China has a strategic interest in increasing energy security through diversifying energy sources and through decreasing dependency on fossil fuels. A report by the World Bank and China's State Environmental Protection Administration published in 2007 estimates that China loses around 5.8 percent of its GDP due to pollution,[2] much of which comes from coal combustion plants that produce the bulk of China's electricity.

The Fukushima accident led to a rethink about the importance of nuclear safety among China's leadership. Just a few days after the accident, the State Council ordered a halt to construction at 26 nuclear sites and a freeze on construction approvals for new projects. It further ordered the National Nuclear Safety Agency (NNSA), China's nuclear watchdog, to conduct safety inspections at all nuclear facilities and to draft a new nuclear safety plan. Both the inspection report and the safety plan were eventually accepted in May 2012, following initial rejection by the State Council. The safety plan envisages the redesigning of planned reactors to incorporate new safety features, yet power plants currently under construction are spared expensive alterations.

Even though China's nuclear energy programme has so far not experienced a serious safety incident, key aspects of China's nuclear safety provisions have been considered inadequate to support the rapid growth of the nuclear programme. The mere fact that 22 generation II reactors are under construction in China, more than in any other country, means that the majority of China's nuclear fleet will not fulfil the highest possible safety criteria for several decades to come. Generation II reactors generally do not have advanced inbuilt safety features compared to their generation III successors. Since the middle of this year, increased attention within China has therefore been given to developing indigenous generation III reactor designs, with all three (state-owned) operators more actively promoting their new designs.[3]

The safety deficiencies that need to be addressed relate especially to the undersized cadre of safety experts at NNSA and the inadequate regulatory system. It has been estimated that by 2020 the number of staff per installed GWe capacity will be much lower than in Western countries,[4] albeit improvements have been pledged after the Fukushima accident.[5] China can drive forward and realise ambitious construction projects at impressive speed, but it is no secret that build quality can fall behind the required standard. A shortage of experienced nuclear engineers can thus have an effect on nuclear safety. Similarly, China's provisions for responding to a nuclear accident or a terrorist sabotage attack have been considered inadequate due to a shortage of trained staff and expertise.[6]

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[2] 'Cost of Pollution in China: Economic Estimates of Physical Damage', World Bank, February 2007, http://go.worldbank.org/FFCJVBTP40.
[3] 'China's Gen-III – Safe and Reliable?', *Nuclear Intelligence Weekly*, 1 June 2012, p. 4.
[4] Yun ZHOU et al. (2011), 'Is China Ready for its Nuclear Expansion?', *Energy Policy (39)*, p. 779.
[5] Chinese participant at IISS Nuclear Security Workshop, Qingdao, June 2012.
[6] Dean KNOX (2012), 'Nuclear Security and Nuclear Emergency Response in China', *Science & Global Security (20:1)*, p. 30.

On a structural level, China does not have an independent and sufficiently authoritative regulatory body with the purpose of ensuring that new nuclear technology is ready for deployment and of verifying the safe operation of nuclear facilities. The NNSA is supervised by the Ministry of Environmental Protection. In comparison, the National Development and Reform Commission that oversees nuclear development has a much higher authority. Even China's three state-owned operators have a closer connection to the State Council.[7] A Chinese participant at an IISS workshop on nuclear security held in June 2012 noted that the Fukushima accident has not led to an increase of the NNSA's independence or authority.[8] The lack of independence of Japan's regulator was found to be a key permissive cause of the Fukushima accident.

It is noteworthy that that the State Council's freeze of granting approvals to new nuclear projects continues to remain in place more than a year and a half after it was declared. Concerns over a nation-wide decline in public acceptance of China's nuclear ambitions could partly explain this delay. Additionally, the timing of the upcoming 18th National Congress of the Communist Party certainly adds to the sensitivity of nuclear issues. In the run-up to the once-in-a-decade leadership change, the Communist Party is especially wary about making decisions that may prove controversial with the public.[9]

Before the Fukushima accident, China's public was considered to be relatively supportive of nuclear power because it acutely felt the environmental consequences of coal-fired electricity generation.[10] But the accident in neighbouring Japan brought the risks of nuclear power generation into public consciousness. In the days after the accident, when radioactive plumes were thought to be threatening to drift over China, the rumour that consuming iodised salt protects against radiation harm led to the panic-buying of salt across the country.[11] Initial turmoil quickly faded, but China's public has become more sceptical about safety provisions at domestic facilities. No strong and well-organised antinuclear movement like in Germany or Japan has emerged, but there is opposition against individual nuclear projects. In early 2012, for example, a formal request was sent to Beijing to suspend construction of the Pengze reactor in Jiangxi province following public pressure.[12]

This can be seen as part of the wider trend of public protests becoming more frequent and effective in China. Throughout the past years there have been reports of numerous violent public protests against major industrial projects, mainly out of concerns over their local environmental impact.[13] The leadership in Beijing has reasons for concern that a nuclear accident in China could provoke a substantial public backlash.

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[7] Yun ZHOU et al. (2011), p. 779.
[8] Chinese participant at IISS Nuclear Security Workshop, Qingdao, June 2012.
[9] 'What's Causing China's Slowdown?', *Nuclear Intelligence Weekly*, 17 August 2012, p. 3.
[10] XU Yi-Chong (2010), *The politics of Nuclear Energy in China,* Palgrave Macmillian: New York, p. 214.
[11] 'Radiation fears prompt panic buying of salt', China Daily, 18 March 2011, http://www.chinadaily.com.cn/cndy/2011-03/18/content_12189705.htm.
[12] 'China Nuclear Protest Builds Steam', Financial Times, 28 February 2012, http://www.ft.com/cms/s/0/d733c466-5eab-11e1-a04d-00144feabdc0.html#axzz28nNmKett.
[13] 'Recent High-profile Mass Protests in China', BBC News, 3 July 2012, http://www.bbc.co.uk/news/world-asia-china-18684903.

Long-term plans: reprocessing and fast reactors

Beyond the current emphasis on strengthening safety provisions, China's mid-term and long-term plans for introducing new fuel-cycle technologies harbour proliferation risks that must not be neglected. China has voiced plans since the mid-1980s to re-use the plutonium in spent nuclear fuel for energy production through nuclear reprocessing (thereby 'closing' the nuclear fuel cycle). In another ambitious goal, China hopes to introduce a new type of reactor, sodium-cooled fast-neutron reactors, and powering them with plutonium-containing fuel by around 2030. Fast reactors provide the technological basis for fast-breeder reactors, so called because they can produce ('breed') more plutonium fuel than they consume.

China's achievements with regards to reprocessing so far centre on a small pilot plant that was commissioned in 2010. The plant can process 50 tons of spent fuel per year, albeit this can reportedly be upscaled to 100 tons. In November 2010, China signed an industrial agreement with Areva to build a 800-tons-per-year reprocessing plant which was expected to start operating in 2020. But the deal has since stalled and is unlikely to be finalised soon. Experts familiar with the matter note that the reported price tag (€15 billion) was too high for the Chinese, but France's concerns about a possible use of the plant for China's military nuclear programme was also a factor.[14] It has been suggested that China may consider building commercial reprocessing plants with indigenous technology within the next 20 years, but at the present time, no further details are known as to when and on what technological basis nuclear reprocessing will be introduced on a commercial scale.

Outside China, discussions about the future of China's fuel cycle often centre around concerns over proliferation risks. Just like uranium enrichment, spent-fuel reprocessing is a highly sensitive technology, because it can produce fissile material that is essential for nuclear weapons. Reprocessing involves the separation of uranium, plutonium and highly radioactive fission products from spent nuclear fuel. The plutonium can be re-used for energy production in a nuclear reactor if it is subsequently combined with uranium oxide in a MOX (mixed plutonium and uranium oxides) fuel fabrication plant. Alternatively, just around 5 kilograms of separated plutonium can provide the essential ingredients for a single nuclear weapon. Without the highly radioactive fission products attached, the diversion and transfer of separated plutonium would be relatively easy for state and even non-state actors.

Spoken and unspoken arguments in favour of reprocessing

The main argument for introducing nuclear reprocessing and fast reactors is that both technologies help increase China's self-sufficiency in energy production and thereby strengthen China's energy security.[15] China currently imports a large amount of uranium for

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[14] Mark HIBBS (2010), 'China Should Remain Prudent in Its Nuclear Fuel Path', *Nuclear Energy Brief*, Carnegie Endowment, http://www.carnegieendowment.org/2010/11/22/china-should-remain-prudent-in-its-nuclear-fuel-path/5q8. Personal communication with Chinese expert, August 2012.

[15] GU Zhongmao and ZHOU Zhiwei (2012), 'Converging Nuclear Energy Programs: the View from China', in Lora SAALMAN ed., *The China-India Nuclear Crossroads*, Carnegie Endowment for International Piece, pp. 155-159.

its fleet of LWRs as its domestic supplies are limited. Using MOX fuel in LWRs makes better use of the energy potential of uranium. Further, operating a fast-reactor fuel cycle requires continued reprocessing and so China needs to master reprocessing to take the next step.

Another possible reason behind China's plans for introducing reprocessing might be the view that China should have all major technologies available for its civilian as well as military nuclear programmes. According to one well-respected estimate, China currently holds a military plutonium stockpile of 1,800±500 kilograms, having ceased the production of plutonium for its weapons programme by around 1990.[16] China is estimated to have a stockpile of 240 nuclear warheads.[17] It cannot be entirely ruled out that future changes to China's security environment might prompt decision-makers to restart plutonium production for military purposes. For example, China may wish to have an assured ability to overcome ballistic missile defence systems. An estimate published in 2003 suggests that if China were to update its arsenal of nuclear warheads for long-range missile, it might reach the limit of its current plutonium stockpile without re-using the plutonium inside existing warheads.[18] There is no binding legal commitment that would hold China back from producing more military plutonium. And China is the only P5 country that has not officially declared a moratorium on ceasing fissile-material production for military purposes. In addition, China is believed to support Pakistan in blocking negotiations for a Fissile Material Cut-off Treaty (FMCT), an agreement that would ban the production of fissile materials for nuclear weapons.

A commercial-scale reprocessing plant naturally provides a theoretical ability to produce military plutonium faster. During the above-mentioned talks between China and Areva about the 800-tons-per-year reprocessing plant, France insisted on technical and political assurances that plutonium could not be used for military weapons. Specifically, the French were concerned that the reprocessing plant was to be built close to the facilities where China originally extracted plutonium for its weapons programme.[19]

In another argument in favour of reprocessing, some Chinese experts point out that all other P5 countries plus India and Japan have current or past commercial reprocessing programmes, and so China should also master this technology.[20] (In Japan a major reprocessing plant in Rokkasho has been completed but has yet to start operations due to technical problems.) Particular reference has been made to India, as Chinese experts see their country lagging behind their South Asian rival in implementing fuel-cycle technologies.

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[16] 'Countries: China', International Panel on Fissile Materials, accessed 28 September 2012, http://fissilematerials.org/countries/china.html.
[17] 'Status of World Nuclear Forces', Federation of American Scientists, 7 May 2012, http://www.fas.org/programs/ssp/nukes/nuclearweapons/nukestatus.html.
[18] David WRIGHT and Lisbeth GRONLUND (2003), 'Estimating China's Production of Plutonium for Weapons', *Science & Global Security (11:1)*, p. 75.
[19] Mark HIBBS (2010).
[20] Personal communication with Chinese expert, June 2012.

Delays in closing the fuel cycle

While outside observers are worried about proliferation risks, China has two other good reasons to further delay plans to close the nuclear fuel cycle. The first reason is that following the Fukushima accident, it makes more sense to direct financial resources and nuclear engineering expertise towards improving safety provisions of current and planned LWRs and towards accelerating the transfer from generation II to generation III LWR technology. From a long-term perspective, a closed nuclear fuel cycle makes it more difficult to keep nuclear-energy production safe and secure. Additional nuclear facilities and longer transport routes of highly radioactive spent nuclear fuel and plutonium-laden MOX fuel increase vulnerabilities to a sabotage attack and require more resources to guarantee safety.

Secondly, many international experts have concluded that a closed nuclear fuel cycle makes little economic sense in the foreseeable future for any country.[21] Nuclear fuel costs currently account for around five percent of the generating cost of a nuclear reactor.[22] The 2011 'Red Book' concludes that identified uranium resources are sufficient for more than a century, based on current requirements.[23] As a significant increase in uranium prices in the coming decades is unlikely, there are no economic benefits in recycling spent fuel utilising highly expensive reprocessing and MOX fuel production facilities.

A cost estimate published in 2011 that considers various development scenarios of China's future nuclear fuel cycle illustrates this point. The cumulative cost of placing all of China's spent fuel into storage until 2035 is estimated to be $319m.[24] The cost of recycling plutonium and making MOX fuel is estimated to be $29,069m.[25] This estimate is based on the assumption that only as much MOX fuel as required is produced (as opposed to running facilities at 100% capacity, which would cost more) and it takes into account some foreseeable delays to the programme.

Fast reactor development

The attraction of a closed fuel cycle with fast reactors is that this would significantly increase energy utilisation from a given amount of uranium – up to a factor of 50 to 60 according to senior Chinese experts.[26] This is because fast-breeder reactors have an astonishing ability to produce more plutonium fuel than they consume, making it theoretically possible to have a fuel cycle that does not depend on access to uranium resources. A study by the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), a forum for member states of the International Atomic Energy Agency (IAEA), goes as far as saying that a

[21] See for example: 'The Future of the Nuclear Fuel Cycle', MIT, April 2011, http://mitei.mit.edu/publications/reports-studies/future-nuclear-fuel-cycle.
[22] Yun ZHOU (2011), 'China's Spent Nuclear Fuel Management: Current Practices and Future Strategies', *Energy Policy (39)*, p. 4365.
[23] 'Global Uranium Supply Ensured for Long Term, New Report Shows', NEA Press Release, 26 July 2012, http://www.oecd-nea.org/press/2012/2012-05.html.
[24] Yun ZHOU (2011), p. 4367 (table 9). Assumptions: based on 2008 US rates and a 0 percent discount rate.
[25] Yun ZHOU (2011), p. 4368 (table 11).
[26] GU Zhongmao and ZHOU Zhiwei (2012), pp. 157.

closed breeder-reactor fuel cycle 'might de facto be considered as a renewable energy source'.[27] China would achieve a very high degree of energy security, if it was to overcome the substantial technical barriers that stand in the way of commercialising fast reactors.

Fast reactors fundamentally differ from conventional LWRs in terms of fuelling, neutron moderation, and cooling. Fast reactors require fuel with a much higher content of fissile material and for that reason MOX or plutonium-based metal fuel (for example uranium-plutonium-zirconium alloy) are preferred. LWRs need water as a neutron moderator to slow down the neutrons that maintain the nuclear chain reaction, whereas fast reactors use unmoderated (or 'fast') neutrons. In a LWR, water also functions as the core coolant, but in a fast reactor a material that can absorb heat more efficiently is needed. Liquid sodium is the standard choice in fast reactors.

In 2011, the 20 MWe China Experimental Fast Reactor (CEFR) was connected to the grid. It has since operated without problems and supplies 8 MWe of power, with a 100% power output expected by the end of 2013. The CEFR is currently fuelled with highly enriched uranium, but by that time it is also expected to irradiate MOX fuel.[28] The next step in China's fast-reactor programme will be the construction of the China Demonstration Fast Reactor (CDFR), which is likely to be based on a 600 MWe design.[29] Before Fukushima, the CDFR reactor was expected to become operational by 2020, but at the present time it is hard to say when this will be achieved.[30] As an alternative to developing an indigenous CDFR design, in 2009 China agreed with Russia to start preparing the purchase of the Russian BN-800 reactor. But this year it emerged that China is postponing the purchase due to disagreements over the price.[31]

Major technical hurdles remain

The development of fast reactors has a long history, with a number of countries having started down that path. But even though 400 reactor-years of experience in operating experimental and pilot fast reactors have been collected globally, fast reactor technology remains a long way away from its commercial deployment. Only four countries other than China today seriously consider further investments in their fast reactor programmes. France is conducting studies on a future pilot fast reactor called 'Astrid' with a decision on its construction expected in 2017. In India, a prototype breeder reactor is due to become operational in 2013. Japan's prototype breeder reactor 'Monju', which previously ran into

[27] IAEA INPRO (2010), 'Assessment of Nuclear Energy Systems Based on a Closed Nuclear Fuel Cycle with Fast Reactors', IAEA-TECDOC-1639, p. 1, http://www-pub.iaea.org/MTCD/publications/PDF/TE_1639_web.pdf. It should be noted that this INPRO report was prepared by five countries with active interest in the further development of fast reactor technology (China, France, India, Japan, Russia) plus three additional countries (Canada, South Korea, Ukraine).
[28] Personal communication with Chinese expert, June 2012.
[29] Personal communication with Chinese expert, June 2012.
[30] Personal communication with Chinese expert, June 2012.
[31] 'China Delays Purchase of Russian Fast Neutron Reactors', IPFM Blog, 18 May 2012, http://fissilematerials.org/blog/2012/05/china_delays_purchase_of_.html. Personal communication with Chinese expert, June 2012.

safety and technical difficulties, is currently shut down. In Russia, the BN-600 fast reactor is operational and a BN-800 is under construction and scheduled to operate in 2014.[32]

One of the main reasons why past fast-reactor programmes have a poor record on safety and reliability is their liquid-sodium cooling mechanism. Sodium reacts violently if it comes in contact with water and it burns in air. Even minor leaks in the cooling cycle can cause damage to the facilities. Russia's BN-600 recorded 27 sodium leaks between 1980 and 1997, 14 of which resulted in fires.[33] A high level of redundancy in the BN-600 design allowed it to operate with relatively few interruptions. The BN-600 has three parallel primary cooling loops and so if one cooling loop needs repair following a sodium leak, the other two allow for continuing operations.[34]

In order to achieve a degree of reliability and safety that other countries have so far failed to attain, China will need to overcome major technical challenges and make substantial investments. There is no guarantee for success, even though China has some unique advantages that might help in overcoming the necessary barriers. Outside China, further efforts to develop fast reactors have stalled because high capital costs of new facilities deter investors and operators. In China, however, funding for research and development would be provided by the central government. Strict regulatory requirements for new nuclear technologies and a generally uncertain future for nuclear energy that applies to Western countries do not apply to China to the same extent. While a state-controlled nuclear regulator may undermine nuclear safety, it can help accelerate approval processes for new technologies.

Proliferation resistance

A fast-neutron reactor fuel cycle significantly increases the accessibility to weapons-usable fissile material as fast reactors typically run on either MOX or plutonium-metal fuel. This is another reason why the further development of fast reactors has fallen out of favour in many countries.

There are some technical barriers that can be implemented that make the illicit diversion of fissile materials harder. The IAEA INPRO report cited above notes several advantages in the proliferation resistance of a hypothetical fast breeder fuel cycle. Crucially, however, technical barriers can at best delay a determined proliferator and they do not alleviate the proliferation vulnerabilities of a fast-breeder system. For example, INPRO suggests that reprocessing could be made more proliferation resistant if alternative technologies to the PUREX process were used that do not produce a stream of separated plutonium, such as pyroprocessing.[35] But pyroprocessing has never been tested on a commercial scale, and the

[32] 'Fast Neutron Reactors', World Nuclear Association, May 2012, http://world-nuclear.org/info/inf98.html.
[33] O. M. SARAEV (2000), 'Operating Experience with Beloyarsk Fast Reactor BN600 NPP', in *Unusual Occurrences during LMFR Operation: Proceedings of a Technical Committee meeting held in Vienna, 9-13 November 1998*, IAEA-TECDOC-1180, p. 114, http://www-pub.iaea.org/MTCD/Publications/PDF/te_1180_prn.pdf.
[34] IAEA (2007), 'Liquid Metal Cooled Reactors: Experience in Design and Operation', IAEA-TECDOC 1569, p. 103, http://www-pub.iaea.org/MTCD/Publications/PDF/te_1569_web.pdf.
[35] IAEA INPRO (2010), p. 33.

extent to which pyroprocessing increases proliferation resistance has been put into serious question since plutonium can still be extracted in a separate step.[36] The PUREX process is well-documented and relatively straightforward and so it is no surprise that China is favouring this technology for any future reprocessing facility.[37]

Other advantages noted by the INPRO report are that a fast-breeder fuel-cycle system does not require uranium enrichment and that less plutonium would be accumulated over time in disposed LWR spent fuel.[38] However, China and other countries that may in the future operate a fast-breeder fuel cycle will not give up enrichment technologies that they already possess. While a reduction in the amount of spent fuel that eventually has to go into long-term storage has many advantages, these appear minor when compared to the large amount of relatively accessible plutonium in circulation in a fast-breeder fuel cycle.

Conclusion

China's nuclear power generation capacity will undoubtedly continue to expand for several decades, and so it plausible and justifiable to research technologies that promise a high degree of energy security and to decrease the volume of radioactive waste that has to be put into long-term storage. Additionally, China may have a strategic interest in developing a full range of fuel cycle technologies for both its civilian and military nuclear programmes.

On the other hand, the economic rationale of reprocessing and using MOX fuel is questionable. Technical success in commercialising a fast-reactor programme will be hard to achieve, and if fast reactors fail to materialise, any plutonium that has already been separated can become a legacy problem. Following the Fukushima accident, it makes sense to prioritise the strengthening of nuclear safety provisions and accelerating the transfer from generation II to generation III LWR technology.

If China manages to become the first country to demonstrate that fast reactors can be safe, reliable and commercially viable, it may naturally be interested in exporting its technology to countries that equally seek a high degree of energy security. However, the spread of reprocessing technologies and reactors operating with plutonium-based fuel goes contrary to global non-proliferation goals.

Chinese nuclear experts have acknowledged that moving towards a fast-reactor fuel cycle is extremely expensive and internal debates have taken place over whether the plutonium path should be pursued.[39] However, it should be expected that China will eventually achieve a closed nuclear fuel cycle. At the very least, China should take the opportunity to learn from the mistakes made by other countries. For example, safety, security, and safeguards considerations should be taken into account in the design phase of nuclear facilities and the unnecessary build-up of separated plutonium should be avoided at all cost.

[36] Christopher HOBBS and Matthew HARRIES (2009), 'South Korea and Spent Fuel Reprocessing', *RUSI Journal (154:5)*, p. 95.
[37] Personal communication with Chinese expert, June 2012.
[38] IAEA INPRO (2010), p. 33.
[39] Personal communication with two Chinese experts, June 2012.