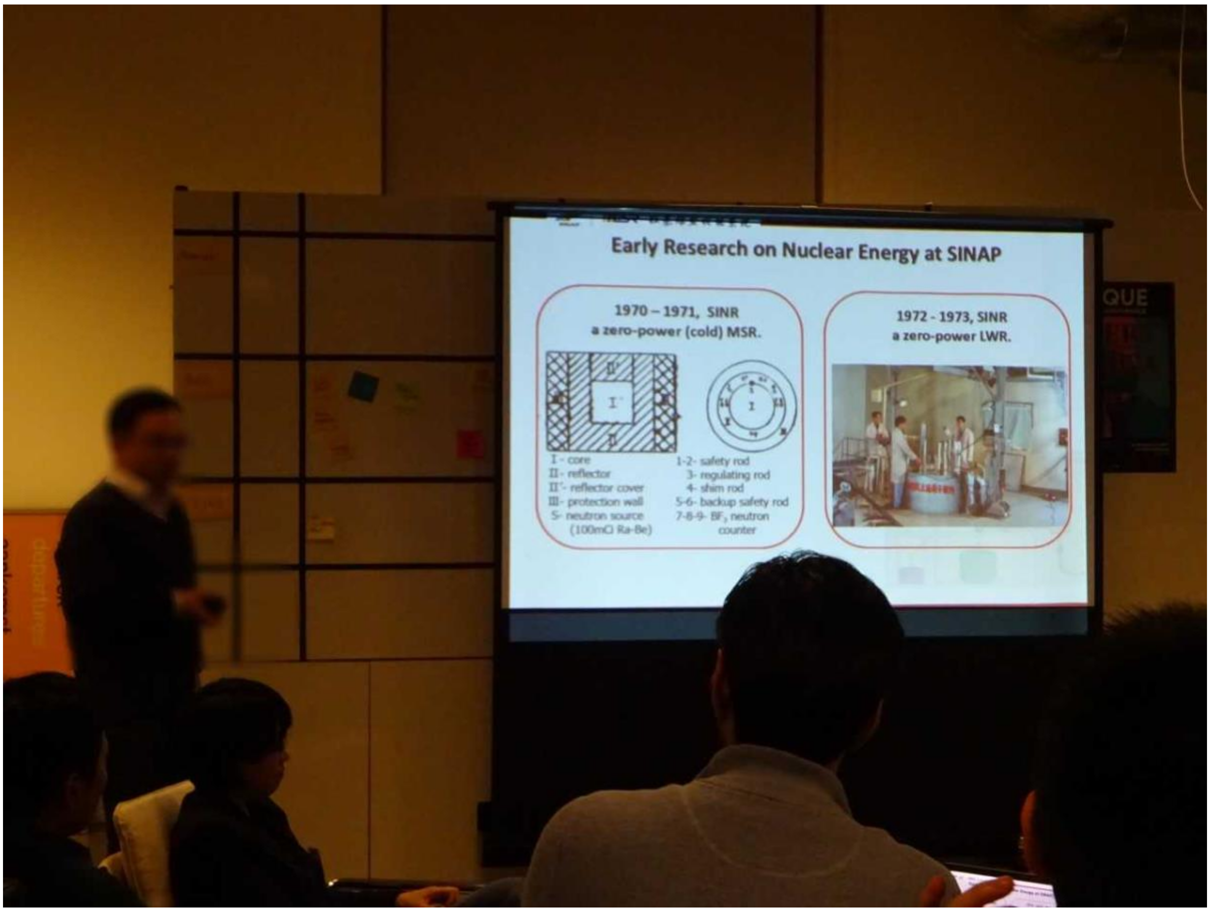
Why China's 600 fte MSR program wants to cooperate with Delft TU and NRG in Petten

Sometimes, on rare occasions, I just love social media. One such occasion was when I discovered a very enthusiastic response that we got upon the publication of our article about the start of the SALIENT experiments. Now, we DID get a lot of response to that. But this one was special, as it apparently came from a professor at the Shanghai Institute of Applied Physics, SINAP. He told us that he and his colleagues were, I quote 'very excited' about the start of the experiments in Petten, Netherlands.

Now it's one thing when Dutch experts tell you that Petten's High Flux Reactor (HFR) has become a uniquely rare research facility in the world – due to, amongst other things, disappearance of nuclear research facilities in the West. It's quite another thing if this assertion is confirmed by a spontaneous response from Shanghai on a publication one has posted just a few days before. So why are the Chinese researchers excited about a few crucibles of salt, presently irradiated in the HFR, Petten? Essentially, because they want to get their own stuff in. The HFR offers something that the Chinese at the present time do not have: the possibility to test materials in contact with salt in real life reactor conditions.

A few months after this online encounter, we got word that three Chinese experts where going to visit the Netherlands. On the program were TU Delft and, of course, the Nuclear Research and Consulting Group, NRG, in Petten, that operates the HFR. The scientists hoped they could meet us on the occasion. For the Thorium MSR Foundation, this presented the ideal opportunity to learn more about the Chinese MSR program, and the visiting party immediately agreed to transform the proposed meeting into a Meet&Greet with an audience, organized by the Thorium MSR Foundation.

As it turned out, the only evening available for Chinese delegation was December 5. As everybody in The Netherlands knows, the 5th of December is Santa Claus' eve, which is a Big Family Thing in the Netherlands, so although we were only too happy with the visit, we were slightly concerned about our ability to present any visitors outside ourselves. We were wrong. After having dinner with our guests – in which we learned that the researchers at SINAP had been aware of the planned SALIENT experiments, as they had met Dutch researchers at conferences at ORNL in Oak Ridge, but had not been aware of the actual start of the experiments – more than thirty people showed up to hear what the three specialists in respectively nuclear fuel irradiations, materials irradiations and nuclear graphites were willing to share. The audience got three informative talks about the progress the specialist's research in the context of the Chinese MSR program.



The first speaker presented an overview of the Chinese MSR program as a whole. Already in the first slides, it becomes obvious that China has high ambitions regarding their future energy system. The Chinese government is dead serious about clean energy, the role therein of nuclear power in general and the role of molten salt reactors in particular. Although I'm usually not a big fan of starting presentations with the buildings where the research takes place, in this case the picture is telling. Three modern buildings (the one on the top right is for the thermal hydraulics research where several salt loops are housed, the ones at the bottom are used as offices and materials research) are the home of the roughly 400 SINAP scientists that are working on molten salt reactors. Together with about 200 colleagues working on the same subject but in different institutions, they have an estimated budget of about 500 million USD to spend (source of these figures is World Nuclear, the Chinese government does not provide this information).

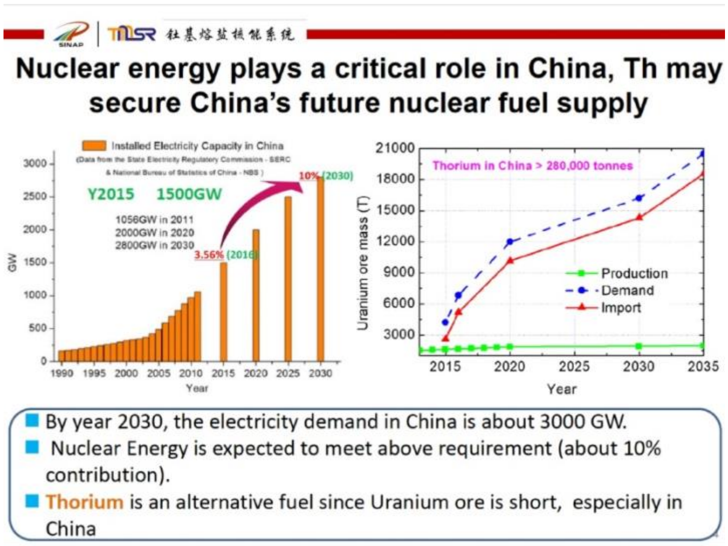
The presentation adds a nice historic perspective, that makes clear how the Chinese program was originally inspired by the Molten Salt Reactor Experiment (MSRE) in the US. The dates preceding the first Chinese efforts are 1954 (the Aircraft Reactor Experiment) and of course 1965 (Molten Salt Reactor Experiment). The Chinese then had their own molten salt reactor in 1970, the SINR Zero Power MSR experiment. Due to corrosion problems the Shanghai Institute of Nuclear Research gave up the program, and switched to the Light Water Reactor, in line with the worldwide developments of the time.

The corrosion issue is interesting, as the MSRE reported no such problems, even after 4 years of operation. The explanation may be a simple one: molten salts at high temperatures need to be kept under inert atmosphere at all times. As long as that condition is fulfilled, the salt is not very corrosive. It's not the salt that causes the trouble, but the oxygen and any water vapor that may be in the air. The confusion about whether the salt is or is not corrosive is widespread.

Not much later, in the early 70s, China's first Light Water Reactor was developed by SINR. For 40 years, the MSR program was suspended. Then, in 2002, the MSR was appointed as one of the concepts of Generation IV. And in 2011, China re-embarked on the MSR-quest. I remember reading a post by Kirk Sorensen around 2010, that his webmaster told him that 'somebody in China is downloading all our documents'. No offence to the Chinese, researchers at NRG in the Netherlands have done the same thing. Kirk Sorensen's initiative to publish the old Oak Ridge reports online will one day be in the history books of both China and the West.

300 GW of nuclear power by 2030

The development of the Chinese MSR needs to be placed within the context of China's ambition to realize clean electric power on an unprecedented scale. Presently, the country is already generating



1500 GW's of electricity (2015 figures). In 2016, the share of nuclear energy in the mix was 3,56 per cent. By 2030, China wants this percentage to be raised to 10 per cent nuclear. By that time, the total output of China's electricity system is targeted at 3000 GW. If we recalculate this to 1GW plants, by the year 2030, 300 nuclear power plants will be spinning out clean power in China. The researcher remarks that he expects the percentage will be higher than this 10%. And although after Fukushima, the Chinese public has been doubtful about their acceptance of nuclear power, according to the presenter, this attitude has been changing a lot in favor of nuclear. For obvious reasons: the Chinese public is just fed up with having to breathe air that is brown from coal pollution. And power from sun and wind is not constant enough, is the straightforward assessment the researcher makes.

But China has a challenge. If all those 300+ gigawatts of nuclear energy are to be produced by uranium in light water reactors, China will depend heavily on imports of huge amounts of uranium. And although China has large reserves of a wide variety of minerals, its uranium inventory is limited. The graph presented speaks clearly on China's hunger for uranium. Here's where the thorium comes in. A big reason for China to embark on the development of thorium molten salt reactors is to save on uranium imports. The thorium reserves of China are estimated to be above 280,000 tons. While that number may not appear to be large, a ton of natural thorium in an MSR in principle could produce 100 times the energy of a ton of natural uranium in a light water reactor. This means that thorium could really become the alternative fuel for nuclear power in China.

Two MSR-concepts under development, one with solid, one with liquid fuel

Starting in 2010, China is now working on two very different thorium based molten salt reactor programs. One is based on liquid fuel, the other on molten salt cooled solid fuel. Both are designed for specific application areas.

The solid fuel MSR, named ThMSR-SF, is a high temperature reactor, intended for industrial heat, hydrogen-production and electricity production. The ThMSR-SF uses fuel pebbles similar to the ones we know from the gas-cooled High Temperature Reactors. The difference is that in the ThMSR-SF the fuel pebbles are cooled by molten salt. One area of research is the optimization of the fuel elements. The pebbles are graphite spheres that contain solid fuel kernels, of which several compositions are tested, including thorium kernels.

The liquid fuel MSR, named ThMSR-LF, is optimized for the use of thorium. Key to realizing a closed fuel cycle, thus unlocking the full thorium potential, requires mastering the salt chemistry. Adequate salt cleaning is even a prerequisite for the establishment of a closed thorium fuel cycle.

The Chinese development plan for the chemistry of the salt cleaning processes has three distinctive phases. The first phase is the deployment of an online batch process. Here the fuel cycle starts with fuel loading based on low enriched uranium and thorium. There will be online refueling and removal of gaseous fission products, and after several years of operation, the whole core fuel salt will be discharged. Uranium and thorium will be extracted and reloaded to the reactor core. Fission products and minor actinides will be temporarily stored.

In the next stage, the online removal of gaseous fission products will be continued, added will be online extraction and reloading of uranium to enhance the fuel utilization ratio. Fission products and minor actinides will still be stored temporarily.

In the third stage, a fully closed fuel cycle will be realized. The researchers foresee offline extraction of transuranics, that will be reloaded to the reactor. This may evolve into a full recycling mode in which all heavy elements are recycled until they fission. Once this is realized, geologic disposal will be limited to fission products and small amounts of uranium and minor actinides, basically limited to losses in the reprocessing.

And what is the time frame for these reactors, the audience wants to know? “We aim at having a 2MW experimental liquid fuel molten salt reactor in 2020 in Gansu”, says the researcher. The remark is followed by surprised responses from the audience. This obviously is a very ambitious goal, but the scientists seemed very determined to achieve it.

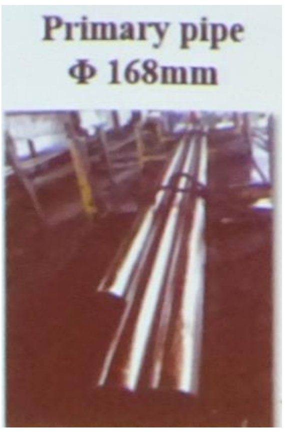
And the first commercial reactor? “We estimate that will be 15 to 20 years from now. We expect that to be true both for the solid fuel reactor and the liquid fuel reactor, as there are many similarities between the two.” This remark is met by a new round of surprises responses. This goal too seems quite ambitious. But the Chinese program means business, and the government has put the utmost pressure on the researchers to get thorium MSR energy available as soon as reasonably possible. In the remaining presentations, the researchers report about technological developments that are as remarkable as the time frame that has been set.

How the future is created in China

SINAP is investigating some remarkable techniques to realize the objectives described, like the use of fluorination for uranium recovery, combined with frozen-wall technique to mitigate corrosion, due to free fluorine (F2) during the fluorination process. The frozen wall technique basically means having some salt freeze on the reactor or piping walls, thus protecting the walls from free fluorine during periods of fluorination. Another area of interest is the demonstration of salt distillation, intended for carrier salt purification. FLiBe salt (a mixture of lithium and beryllium fluorides), especially when made from enriched Li7, is expensive, and the researchers want to demonstrate a controllable distillation device that is capable of processing 6 kg salt per hour, in which most neutron poisons can be reduced with a factor of hundred. Another promising technology is electrochemical separation for uranium recovery. Electro-deposition of uranium metal from the FLiBe-melt can yield a separation ratio of more than 99%.

Introducing China's 'homemade' alloy for molten salt reactors

The next presenter specializes on materials irradiation. The presentation expands on how tests are conducted on alloys, graphites and composites. China has already developed what this researcher calls a 'homemade' version of the well-known alloy that was used in Oak Ridge in the 1960s, Hastelloy N. In China, they've given it the rather modest name GH3535. All of the materials investigated are tested on aspects like strength, embrittlement, creep and swelling.



The Hastelloy is, according to the researcher, quite similar to the original, but there's differences in for instance trace elements. The group has already discovered that the amount of silicon in the composition has considerable influence on the susceptibility to corrosion. Also, in corrosion tests it became clear that the presence of certain impurities in the salt had a big influence on its corrosive behavior. The researcher expresses confidence in the quality of the alloy: 'we have better manufacturing than the US company'. As proof, pictures are presented of GH3535 plates, piping and tubes.

Why the Chinese are excited about 'Petten'

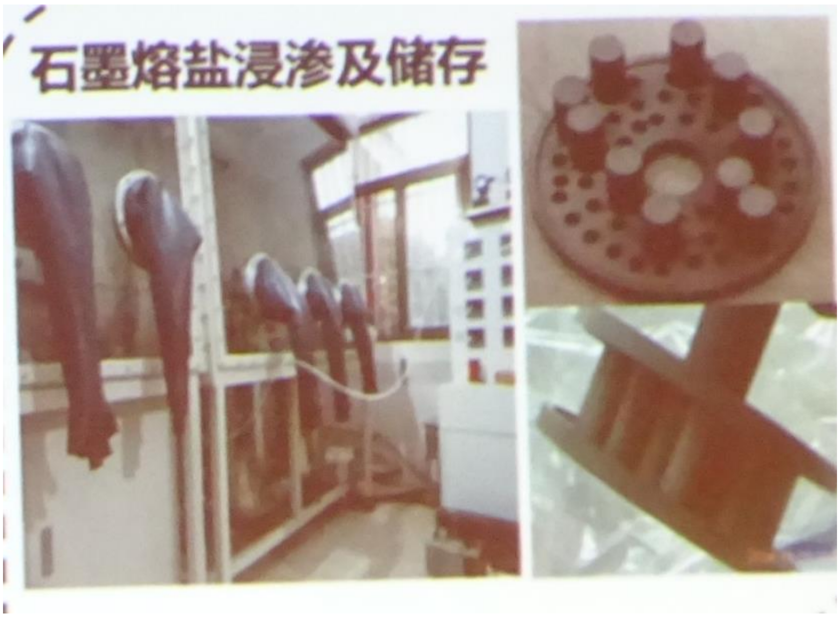
Irradiation tests have also started for the Chinese program, but still at low doses: graphites have been irradiated at temperatures of 650C, with neutron fluxes of 2,5*10^19 neutrons /cm2. Higher dose irradiation tests of graphites in combination with molten salts are planned for 2018 at the Paul Scherer Institute at the Proton Irradiation Facility, with fluxes of 10^20. These figures may help to explain the enthusiasm of the Shanghai researchers about the start of the experiments at the HFR in Petten. Here, the neutron flux is about 20 to 40 times higher (about 2,5*10^21 neutrons/cm2), plus the fact that the irradiation in Petten is done in combination with actual fission.

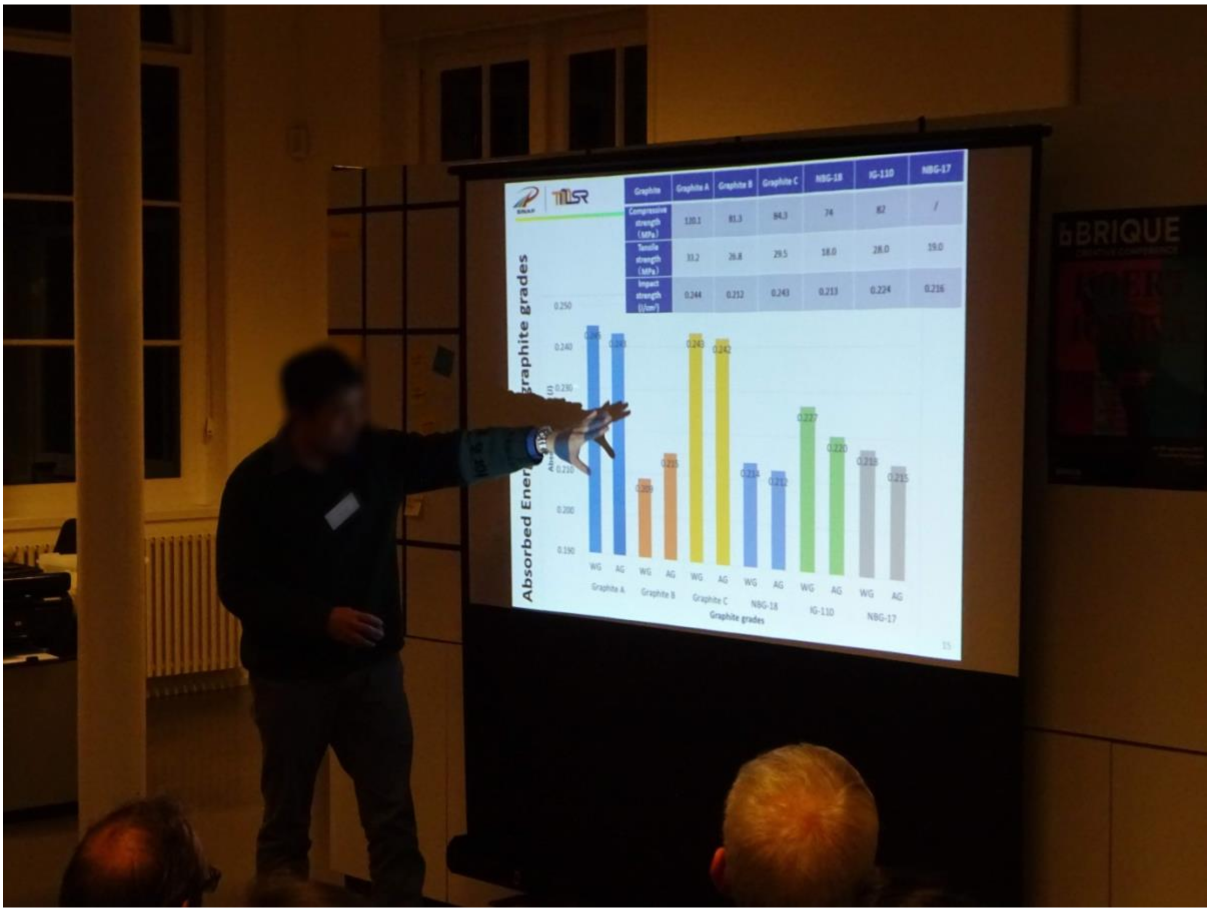
It is clear the Chinese researchers are as passionate about creating a future of clean energy as I know their colleagues in the West are. The researcher expresses this by a little poem, with which the presentation is finished:

To see a world in a grain of atom
And a blue light in a reactor
Hold infinity in the palm of your hand
And the energy for the future.

Rewriting the ASTM paragraph on nuclear graphites

As everybody with a more than superficial knowledge of molten salt reactors is aware of, the graphite is one of the most challenging subjects of the necessary materials development for the MSR. The graphite is a necessary component of molten salt reactors that operate in the thermal spectrum. The operation of this type of reactor depends on the slowing down of neutrons, in the nuclear jargon these are called 'thermal' neutrons. In the 'neutron economy', many processes are counter intuitive, and this is one of them: slower neutrons are better in causing certain elements to fission. The graphite is what is called a 'neutron moderator': it slows them down. In many ways, graphite is an ideal material to use in combination with molten salt: it can endure incredibly high temperatures, and is virtually insensitive to the chemicals in the melt. It also has some properties that make it challenging to use. One of these is its brittleness, the other is its peculiar behavior in a neutron field: after long periods of irradiation, the graphite tends to first shrink, then swell. And although these properties can be compensated for in appropriate use – think of structural design and periodic replacement – the properties themselves also depend of the grade of graphite that is used and need to be well known.





In his presentation, the third of the three researchers mainly focusses on nuclear graphite. He immediately confirms China's dedication to develop the first molten salt reactors: two brand new grades of nuclear graphite, simply called Graphite A and Graphite B, have already been developed for the molten salt reactor. One crucial aspect of these new graphites is their pore size: industrial graphite is porous, and the pore size matters, because the pores should be small enough to prevent any salt from entering. The Chinese researchers have discovered that to achieve this, the mean pore size should be under 0.9 micron. Both of the new Chinese graphites meet this standard: graphite A averages on 0.8 micron, graphite B on 0.7 micron. Both satisfy the size requirements; D. the graphite research team is assessing their other relevant properties, like their heat conductivity and tensile strength.

"Presently, only NRG can do irradiation tests with molten salt."

In his presentation, the researcher reveals China's role in the nuclear world order: SINAP is rewriting the whole chapter on nuclear graphites in ASME, and is setting new ASTM standards, for instance for testing impregnation of nuclear graphite by molten salt. ASME and ASTM are, shortly put, the worldwide reference standards describing materials properties for engineering applications. The fact that the Chinese are now adding new entries to the chapter on nuclear materials, illustrates how the center of gravity in nuclear development is shifting from the West to non-Western countries. As for the graphite for molten salt reactors, it's not just pore size and pressure that determines how well the graphite resists the salt. It's also the behavior of the graphite in a high neutron flux that will ultimately determine the technical lifetime of the moderator. After this presentation, the audience, aware of the challenges that the material incorporates for the design process of the liquid fuel reactor, poses many questions about the graphite. Whether the researchers think it's possible to make the graphite strong enough, what shape it should be, and what lifetime they are counting on. The researchers agree that the material is a challenge. "It's difficult", says the Chinese specialist. "With a nuclear reactor, safety is an absolute necessity." And apparently, this is exactly the reason for visiting NRG. "Presently, only NRG can do graphite irradiation tests in combination with molten salt."

In other words, the complex behavior of graphite can only be tested in real life reactor conditions, which means testing in a high flux materials test reactor, and in the presence of a molten salt stream that contains all the fission products that will be produced in an operating reactor. Petten's HFR can offer all these conditions: the reactor offers a high flux, and its Pool Side Facility offers the space to place big experimental objects, like the LUMOS-loop that NRG is designing, in which molten salt reactor conditions can be integrally created. And thanks to the HFR's high flux, a year in the test reactor can model ten years of reactor life: a feature that can save a lot of development time.

Chinese researchers see broad cooperation possibilities between the Chinese MSR program, NRG and TUD

At the date of the presentation, the Chinese delegation had not yet visited NRG: the Meet&Greet took place on Tuesday, the visit to NRG was scheduled for Wednesday and Thursday, and the flight back home on Friday was early, so the possibility to have an after-talk was limited. But the Chinese delegation told us they see broad possibilities for cooperation between them and the Dutch research that takes place at TU Delft and NRG. But on Tuesday evening, he was not yet able to give details about specifics of this cooperation. Fortunately, for the time being, the Dutch-Chinese cooperation is already possible and relevant within the context of the SALIENT experiments. Fortunate in any case for the readers, that is, as SALIENT is funded by public money and hence everything about SALIENT is, in principle, public knowledge. Senior researcher Ralph Hania confirms that the Chinese 'homemade' Hastelloy will be part of near future SALIENT experiments. As for the two new nuclear graphites, he is not yet able to confirm this, as the Chinese graphite would have to fit into a limited irradiation schedule.

Although, as an afterthought, I'm pretty confident that the Dutch researchers can't wait to see how these graphites perform in the conditions only the HFR can offer.

And I'm pretty sure the Chinese researchers can't wait either…