2017

OYSTER

Annual Report

Developing instruments and start construction

TU Delft Delft University of Technology

REACTOR INSTITUTE DELFT

Foreword

I'm pleased to present you with the 2017 annual report of the OYSTER programme.

The OYSTER programme (*Optimized Yield - for Science, Technology and Education - of Radiation*) has been devised to improve and expand the nuclear research infrastructure of TU Delft. It will enable educational, scientific and societal challenges in the fields of materials, health and energy to be better addressed.

Prof. dr. Bert Wolterbeek

Director of the Reactor Institute Delft

Over the course of 2017, the results of the programme, in terms of both scientific outcomes and the construction of new and upgraded instruments, have become ever more visible. All subcontractors for the Cold Neutron Source (CNS) and CNS-Utility building are now known, and in October 2017, the construction of the CNS-Utility building has commenced. At the time that this report is published, the building should be nearing completion. Installation of the equipment that will enable the cooling of the CNS is ongoing.

Our brand-new flexible irradiation facility 'FlexBeFa' is now fully operational; in December 2017, the first liver cancer patient was treated with special radioactive microspheres produced in this facility. Thanks to the FlexBeFa, there is a longer window of time to get these medical isotopes to hospitals around the world where they are applied for curative purpose to patients.

Our researchers started non-invasive inspection of historical objects with the new neutron radiography and tomography instrument (FISH) in collaboration with Dutch museums. The instrument SESANS was used to characterize the effect of processing of proteins on the microstructure of new food materials which mimic meat. And one of the most notable achievements of the battery researchers was the study of lithium metal plating for higher battery energy densities. This year report gives you an insight into these and many other developments.

For 2018, I'm looking forward to more breakthroughs and to the tests of the eagerly awaited CNS-Utility equipment.

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OYSTER in short

The Reactor Institute Delft (RID), part of Delft University of Technology (TUD), is a nuclear knowledge centre. It operates a research reactor, irradiation facilities and radiation-based research instruments. The OYSTER programme (Optimized Yield - for Science, Technology and Education - of Radiation) has been granted in 2012

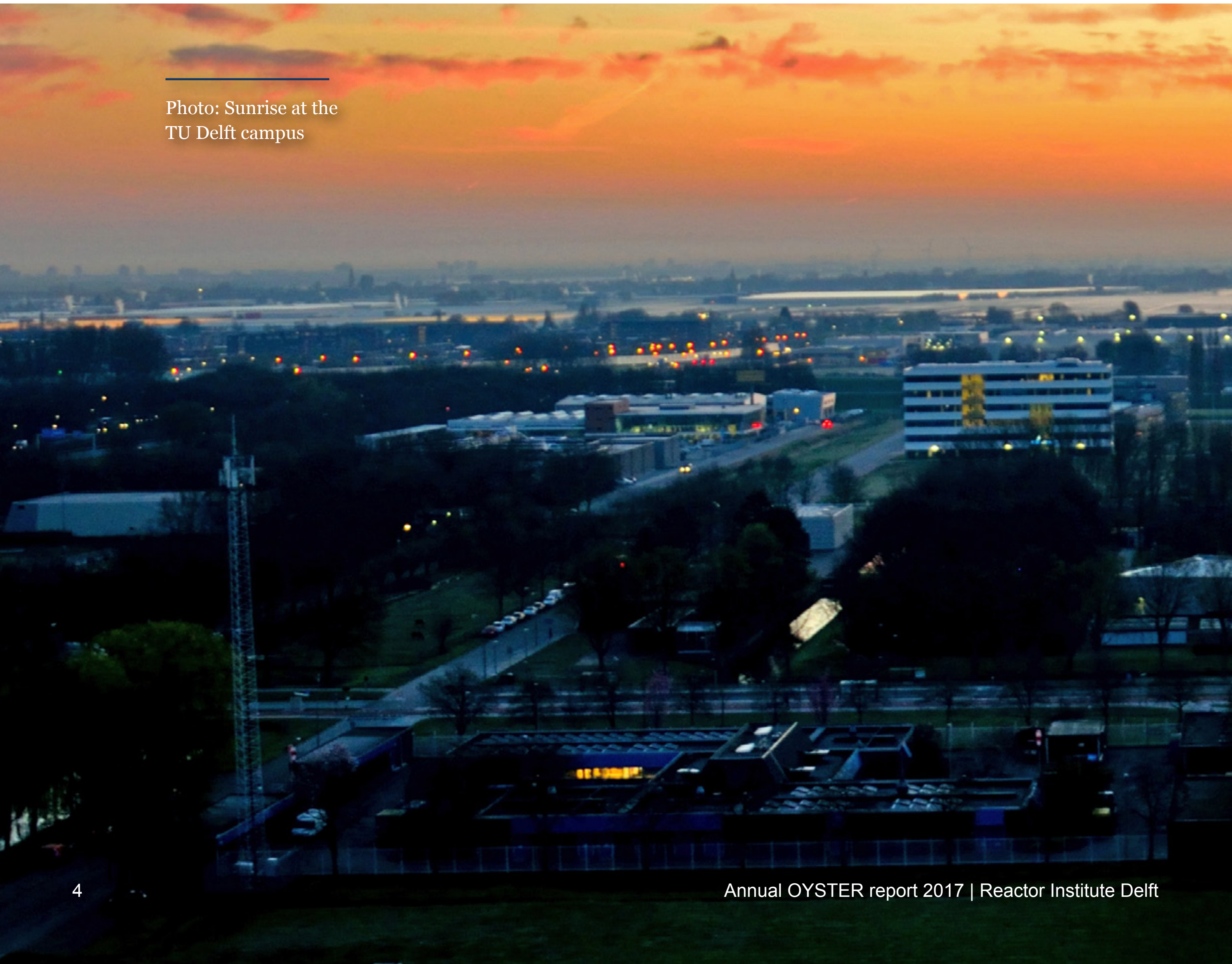


Photo: Sunrise at the TU Delft campus

to improve and expand the RID infrastructure (reactor, instruments, facilities). This will enable current and future educational, scientific and societal questions to be better addressed.

In conjunction with the Department of Radiation, Science & Technology (RST) of the Faculty of Applied Sciences, RID accommodates resident and visiting scientists and other users from a variety of (scientific) disciplines. RID educates students, professionals and scientists, and serves as an independent source of information for society on radiation-and nuclear-related issues.

Main goals of OYSTER

RID is active in the field of neutron, positron, reactor and radiochemistry science. Here, OYSTER has five main goals:

1 To strengthen RID's national coordinating role.

2 To establish RID's European role in research and training.

3 To stimulate ground-breaking innovations.

4 To create a home base for neutron scattering in the Netherlands and secure Dutch collaboration with major international neutron sources, specifically the European Spallation Source (ESS) in Lund, Sweden.

5 To sustain RID's leading role in the use and knowledge of world-class instruments, in the development of new routes for radioisotope production and Instrumental Neutron Activation Analysis (INAA).

OYSTER is an ambitious programme of technological improvements and additions to the RID infrastructure:

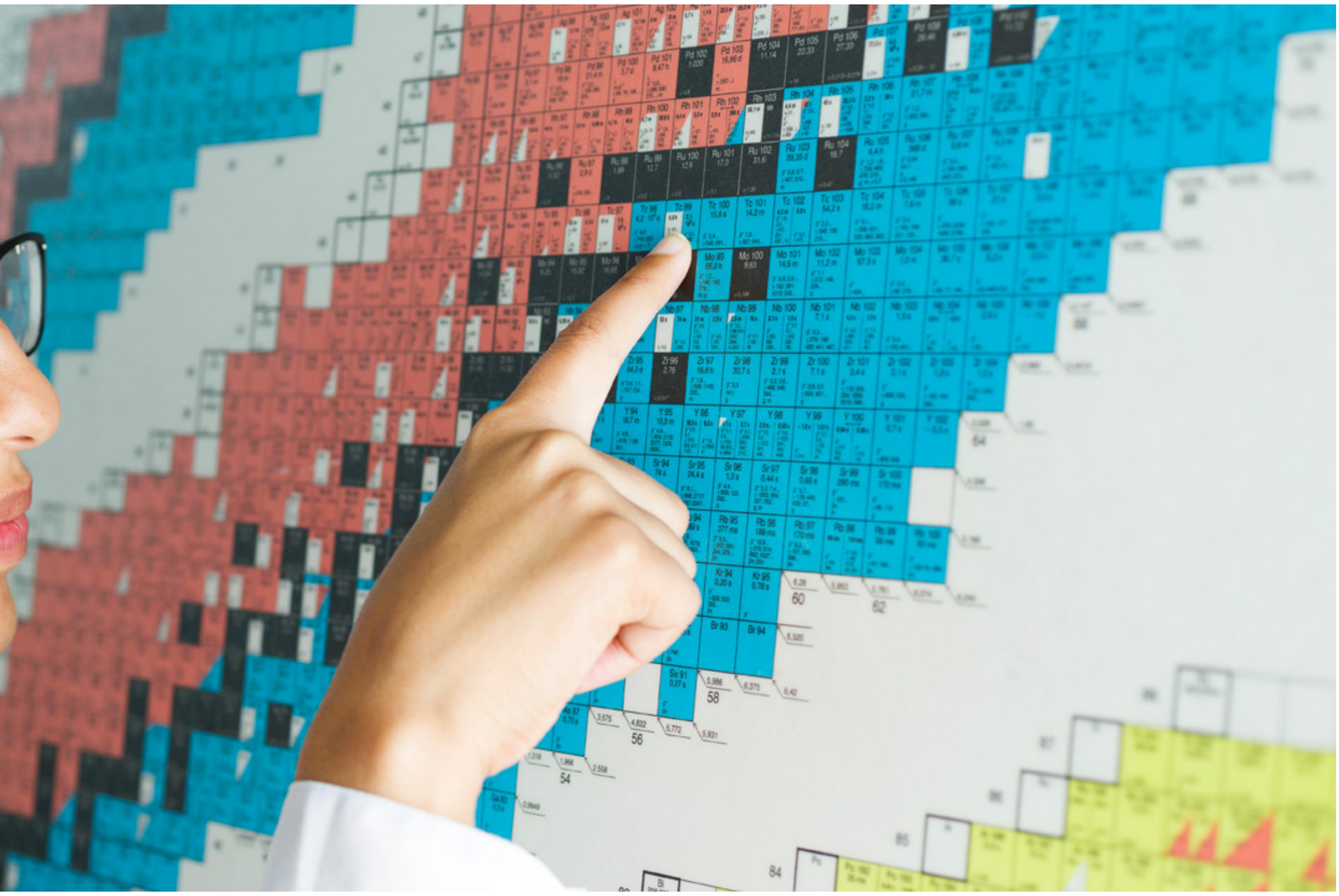
- The installation of a Cold Neutron Source (CNS), cooling neutrons from room temperature to -250ºC, to increase the intensity of low-energy neutrons by more than an order of magnitude and improve the sensitivity of existing instruments.
- The design and construction of new research instruments.

Technological objectives of OYSTER

- The (re-) design and construction of (new) irradiation facilities, to allow the development of production of radioisotopes with unprecedented purity and to boost the sensitivity and opportunities for research with isotopically enriched stable isotopes.

- The design and installation of a miniature hot-cell/decanning facility for submerged access of irradiated samples from the irradiation facilities, to allow innovative production methods of (medical) radioisotopes and studies of radiation damage effects.

- The design of irradiation facilities positioned in the tangential beam tube of the reactor, to undertake research into alternative production methods for e.g. Molybdenum-99 (99 Mo).



Participation in large international and national collaborations

OYSTER will be instrumental in securing or strengthening the role of the RID in various collaborations. For example, the Dutch contribution to the pre-construction phase of the European Spallation Source (ESS[1], an international collaborative facility for materials research using neutron scattering techniques) in Lund, Sweden, is partly financed through OYSTER.
Scientists from Delft work together with ESS scientists in order to develop novel instrument concepts for the ESS.

RID participates in the R&D programme of Holland Proton Therapy Centre (HollandPTC[2]), dedicated to innovative radiation treatment of cancer using proton beams. This programme is a collaboration of TU Delft, Leiden University Medical Centre (LUMC) and Erasmus University Medical Centre Rotterdam (Erasmus MC). HollandPTC is located on the RID premises with first patients to be treated in 2018.

OYSTER research also strengthens the role of RID in supplying innovative ideas towards the envisioned PALLAS reactor[3], which is to become one of the world's leading production sites for medical isotopes.

The OYSTER-initiated new irradiation facilities also enhance RID's position in the Dutch Isotope Valley (DIVA). This is an R&D collaboration set up between URENCO, RID and NRG/PALLAS towards developing, engineering and producing the best-possible medical isotopes for clinical use for both diagnosis and therapy.

Finally, OYSTER underlines the role of RID as an IAEA Collaborating Centre by demonstrating the many innovative scientific opportunities in the utilisation of a medium-sized university research reactor.

1. www.EuropeanSpallationSource.se
2. www.HollandPTC.nl
3. www.pallasreactor.com

Reactor & Utilities

Photo: Martijn Muilwijk (Strukton), Tim van der Hagen, Rik Linssen, Bert Wolterbeek, Ron Goetjaer en Hans Dijkhuizen (Strukton)

OVERVIEW

The modification of the reactor deals with the installation of Cold Neutron Source (CNS) equipment into the beam-tube pipeline between the reactor core and instrument facilities located in the instrument hall. The CNS will be installed in the reactor pool and is therefore designated as the CNS in-pool assembly (IPA). The objective of this modification is to increase the cold neutron flux in order to create better conditions for experiments connected to the neutron beam. To supply the cooling capacity for the proper functioning of the CNS, support equipment will be installed too. Since the available equipment installation surface is limited, a complete new building structure (called CNS-Utility building) will be realised next to the reactor hall. All CNS utility systems will be installed inside this building. Below we provide an overview of the status of this main part of the OYSTER project.

REACTOR MODIFICATIONS

The RID and the Authority for Nuclear Safety and Radiation Protection (ANVS) agreed upon a modification in the license application. The license for OYSTER will now be a "modification license" and includes only the parts to be modified. The revision of the license will be executed during the 10-year periodic safety review (10EVA). For the modification license, an action plan and planning was drafted and provided to the ANVS. Several proposals for the components to be modified and an experiment proposal for the in-pool assembly (IPA) will be issued. Together with this license application and the Environmental Impact Assessment (MER, milieueffectrapportage), a list will be issued of the changes in the current safety report. These documents together form the basis for the license application.

REACTOR MODIFICATION SUBPROJECTS

Reactor Protection System

Safety is essential in the operation of any reactor. RID has a reactor protection system in place to help determine possible risks from a myriad of sensor readouts. Such a smart system can be based on software or hardware solutions. As part of OYSTER, the so-called voting logics of the reactor protection system will be replaced and three Cold Neutron Source (CNS)-related pressure sensor measurements will be added to the new voting logics. We decided to replace the existing relays-based protection system by another hardware-based solution that does not need software to avoid software qualification. The selected solution uses magnetic logic to build the required voting logics.

We started initial discussions with the regulator to explain the design rationale of the current system and the principle of the selected solution that uses magnetic logics and discuss the path to come to a qualified system.

Beam Tube Modification

In order to be able to install the CNS in-pool assembly (IPA), beam tubes R1 and R2 have to be modified. The images on the right show the current situation and the result of the modification of the beam tubes and installation of the CNS-IPA. In 2017, the KHC consortium has selected Bilfinger Noell GmbH as contractor for the construction works. Preparations for the beam tube modifications have started by performing dose-rate measurements inside the reactor pool which form the basis for the design of the shielding of the workers performing the modification activities. In 2018, we will elaborate the beam tube modifications design and working plans in detail.

In-Pool Assembly

KAERI and RID have agreed upon a final design of the moderator cell. The shape was optimised to provide the best possible cold-neutron gain performance. The optimum design was chosen after reviewing the results of KAERI's neutronic, thermohydraulic and mechanical strength calculations by RID staff, RID contractors together with Prof. Robert Mudde, Dr. Robert Williams and Dr. Stuart Ansell of the OYSTER Expert team. The design of the IPA is now frozen and only small modifications based on manufacturing requirements and the mock-up tests are possible.

The nuclear safety authority ANVS has designated the explosion barrier of the IPA as nuclear pressure equipment to be built according to the requirements of the Dutch nuclear pressure directive. This means that the design, fabrication and inspection regime of this part of the CNS will all have to be approved by an independent and qualified third party to be appointed by the ANVS in 2018.

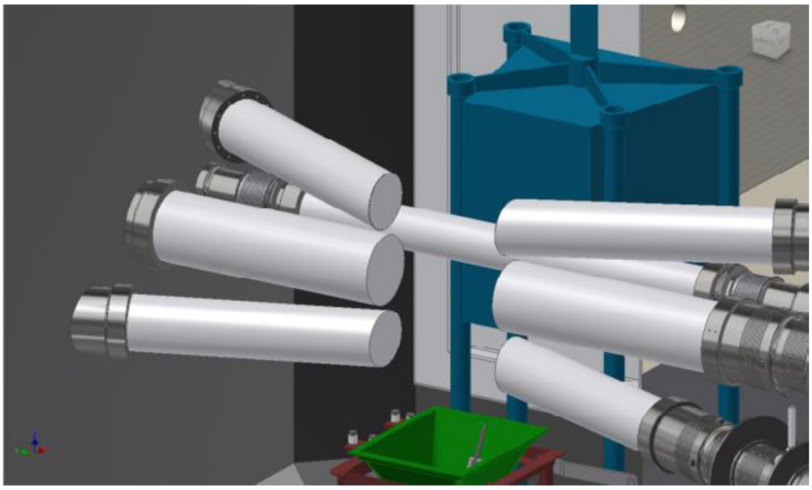


Image: The current situation of the beam tubes in the water basin of the research reactor.

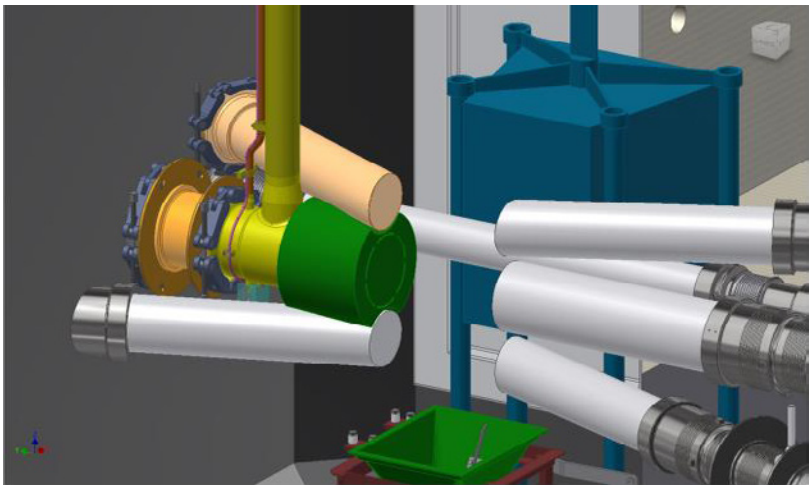


Image: The result of the modification of the beam tubes and installation of the CNS-IPA.

Realisation of the CNS-Utility building

A new building is being realised next to the existing reactor hall housing support equipment to ensure the operation of the in-pool Cold Neutron Source (CNS). This is the CNS-Utility building. In 2017, the detailed design of the CNS- Utility building was prepared. Preparations and calculations for the actual building process were done by Strukton and its subcontractors during the first half of 2017.

Photo: CNS-Utility Building.

The building location was prepared and cleared of obstacles. One obstacle was a bridge located between the north wing of RID and the reactor hall. This bridge contained a pneumatic rabbit system. During autumn 2017, this bridge was removed.

After removal of the bridge, the terrain was handed over to Strukton, who proceeded to prepare the terrain for the foundation works. Eleven pylons were drilled into the soil. Hereafter, the casings for the foundation beams were made and concrete was poured into the casings. The steel frame of the building was constructed and, towards the end of 2017, the first arches of the steel system were erected to form the first floor of the building.

Photo: The first piles of the CNS-Utility Building.

Equipment

The first three process vessels, designed by Kreber, were prepared for fabrication. They will be built and delivered in 2018.

DH Industries started the production of the six cryogenerators needed for the cooling of the process Helium of 20K. Also in 2017, the position of the transformer and 400V powerlines for the cryogenerators and additional equipment were defined. Demaco will prepare all cryogenic lines; the control system is defined and will be prepared by Yokogawa.

Outlook to 2018

The CNS-Utility building will be finished end of April 2018. After the power lines are installed, all necessary equipment will be placed in the building. Mid 2018, the mock-up IPA will arrive and be installed outside the new building and connected to the cryogenerators, vessel and control system. The thermos-syphon principle used to cool the IPA will be tested at cryogenic temperatures.

After installation, there will be a test period to check the cooling power, the response and performance of the IPA system. After the test period, the operators will be trained to work with the installation.

(Sub)contractors

The following executive parties are involved in the realisation of the project-related work packages.

MAIN CONTRACTOR

- **CONSORTIUM KHC**
  This consortium of the Korea Atomic Energy Research Institute (KAERI), Hyundai Engineering and Hyundai Engineering & Construction is responsible for the CNS In-Pool Assembly.
- **ROYAL HASKONING DHV**
  Provides the detailed design of the building structure and supervises the execution

Photo: Celebrating the highest point of the CNS-Utility building.

SUBCONTRACTORS

(involved in the fabrication/installation of materials and equipment)

- **STRUKTON**
  Construction company for the civil works related to the CNS-Utility building structure
- **DH INDUSTRIES**
  Main supplier of the cryogenic equipment that provides the cooling capacity for the CNS
- **KREBER**
  Main supplier of the vessels
- **DEMACO**
  Main supplier of the cryogenic pipelines
- **YOKOGAWA**
  Main supplier of the control systems
- **STRUKTON WORKSPHERE**
  Main supplier of the electrical wire connections
- **PROCESS FLOW SYSTEMS**
  Main supplier of interconnecting piping
- **MOOJIN**
  Supplier of the In-Pool Assembly (IPA) equipment (including CNS and the IPA mock-up)
- **BILFINGER NOELL GMBH**
  Will install the IPA equipment in the beam tube inside the reactor hall

EXTERNAL EXPERTISE AND REVIEW

In 2017, many activities were related to the execution of the non-nuclear work package of the CNS-Utility building structure. The engineering work is focussing on the design and building of steel and concrete structures, walls and floors, where subcontractor Royal Haskoning DHV is the external specialised company providing the detailed design of the building structure.

With respect to the nuclear part of the project, the CNS In-Pool Assembly, Prof. Robert Mudde, Dr. Robert Williams and Dr. Stuart Ansell of the OYSTER Expert team were involved with the results of KAERI's neutronic, thermohydraulic and mechanical strength calculations.

EXTERNAL EXPERT TEAM

As part of the OYSTER project, many technical discussions are taking place between RID, supplier and contractors. In order to have sufficient knowledge available to judge their proposals an "External Expert Team" has been established. The team became operational in 2014 and is comprised of external specialists who assist RID in handling the various technical issues.

In 2017, the External Expert Team (EET) consisted of:

TONI SCHEUER
Affiliation: Nuclear Technology Consultant at the TÜV Rheinland Group
Expertise areas: Licensing issues, and material- and component qualification
Focus within EET: Welding procedures, materials, codes & standards

STUART ANSELL
Affiliation: Neutron Scientist at the European Spallation Source (ESS) in Lund
Expertise area: Cold neutrons equipment design for research reactors
Focus within EET: Optimisation processes neutronics

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STEPHAN WELZEL
Affiliation: Chief coordinator of the reactor upgrade at the Helmholtz-Zentrum Berlin
Expertise areas: CNS process technology and operational aspects
Focus within EET: CNS process technology

ROBERT F. MUDDE
Affiliation: Professor of Multiphase Flow, Department Chemical Engineering, Delft University of Technology.
Expertise area: Multiphase flows
Focus within EET: Heat and mass transfer, hydrodynamics

ROBERT WILLIAMS
Affiliation: Nuclear Engineer and Cold Neutron Source Team Leader at the National Institute of Standards and Technology (NIST), Gaithersburg, Maryland, (USA)
Expertise area: Cold Neutron sources, calculations and new reactor designs
Focus within EET: CNS performance calculations, operations and safety

In the context of Dutch legislation in the area of nuclear safety, RID holds a permit to operate the reactor and the various instruments. With OYSTER, this permit is going to be updated. Therefore, an important aspect of the OYSTER project concerns the licensing of the new instruments and reactor modifications. Since 2013, RID has been working on the licensing procedures and associated review schedules with the relevant regulatory body, the Dutch Authority for Nuclear Safety and Radiation Protection (ANVS). Key parts of the formal license application were to create a Safety Report, a Safety Analysis Report (SAR) and an Environmental Impact Assessment (MER, milieueffectrapportage).

Apart from planning this license revision, the ANVS has reviewed the license request for the CNS-Utility building with its non-nuclear instruments in 2017. This license was granted in October 2017. Although one person objected to the license, RID did start building the CNS-Utility building. The objection was rejected by the Council of State (Raad van State) in November 2017.

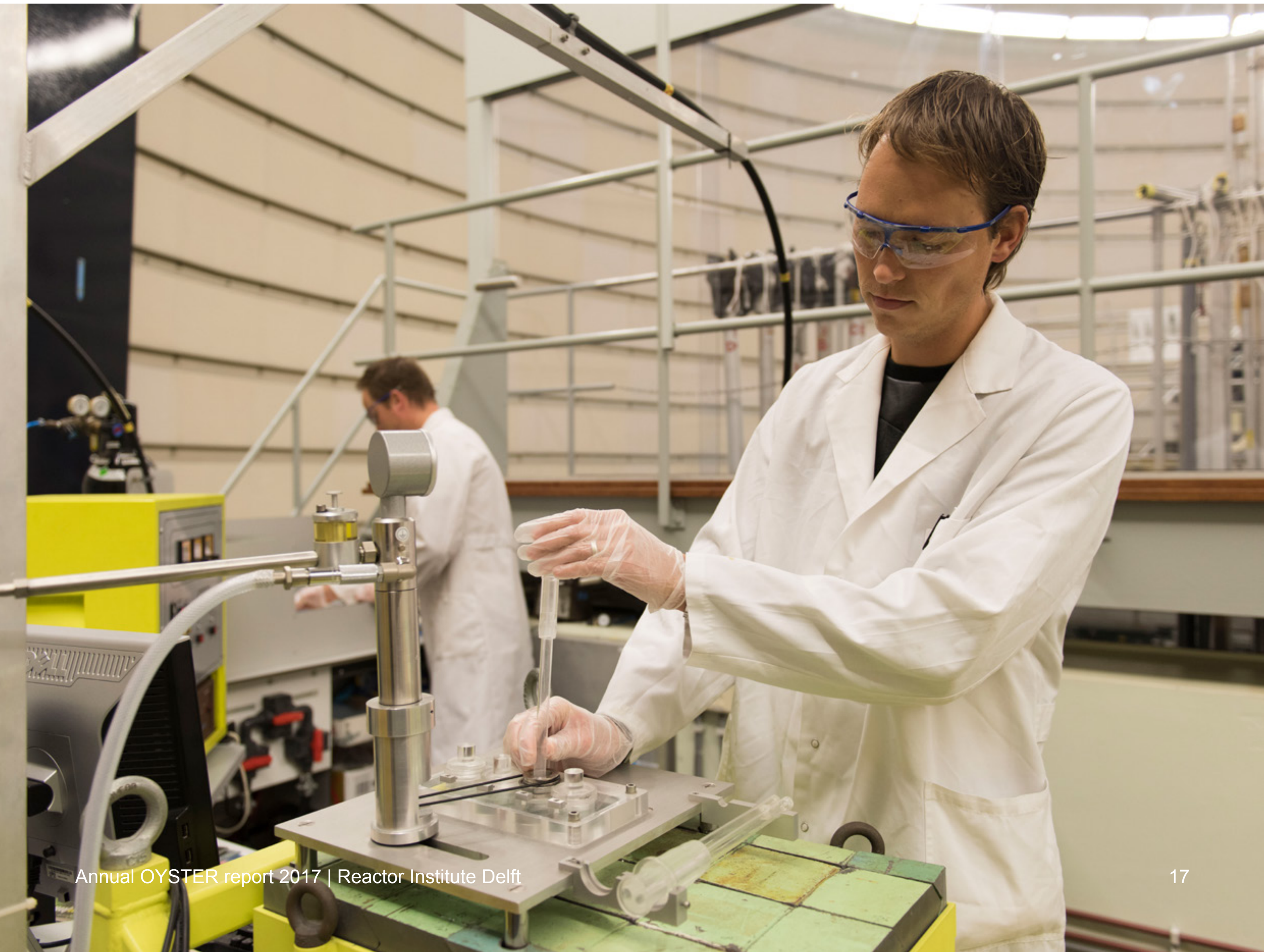
In 2017, RID and ANVS agreed upon modifying the current permit

Licencing

with respect to the nuclear part of the OYSTER project. Instead of creating a full Safety Report, Safety Analysis Report and Environmental Impact Assessment, the focus for 2018 is to get the permit modified to accommodate the OYSTER changes; this will be done by creating a Safety Report and Environmental Impact Assessment on the reactor modifications only. The modification licence is expected to be issued in March 2019.

Further on, from 2020 onward, a 10-yearly safety evaluation will be carried out (10EVA), including the creation of a new Safety Analysis Report (SAR) on the HOR. The 10EVA and SAR will serve as the fundament for RID to apply for a complete licence revision.

Photo: Operators at work in the reactor hall.



Instruments

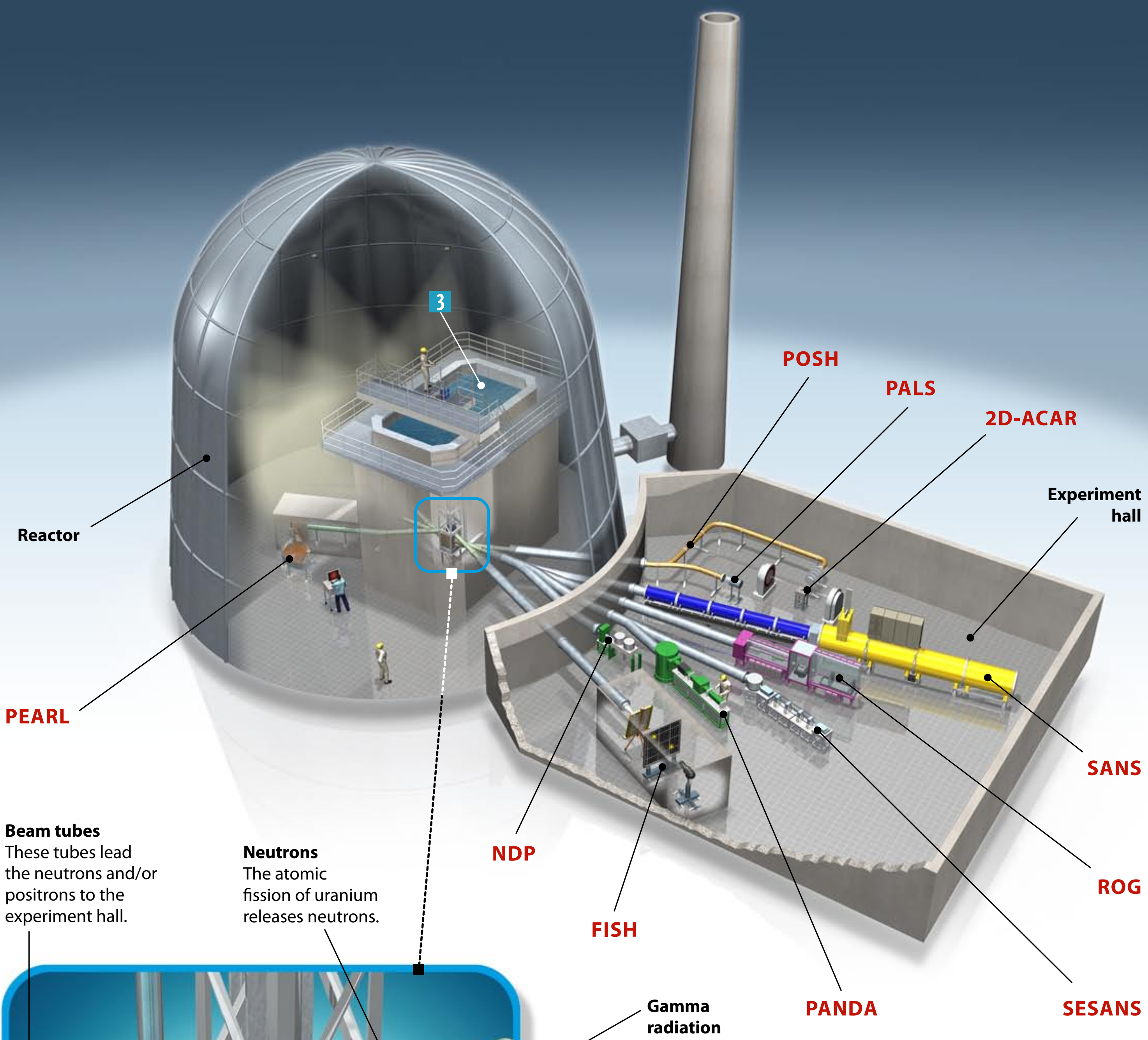
As part of OYSTER, RID will develop new or upgrade existing instruments that exploit the (cold) neutron and positron radiation produced by its reactor. The instruments are:

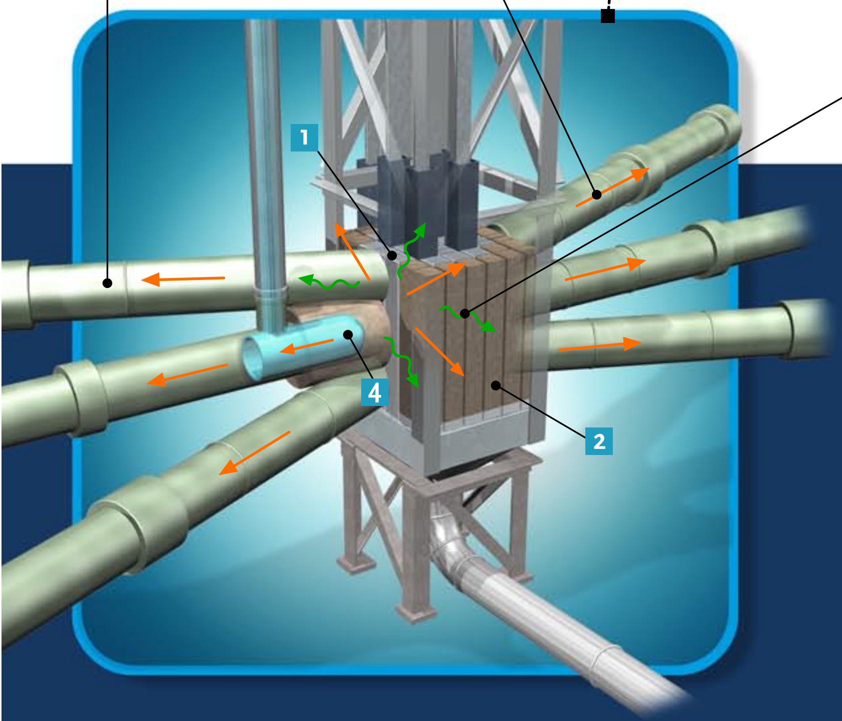
- PEARL – a new neutron powder diffractometer
- POSH-PALS – new positron annihilation lifetime spectroscopy, using positrons by POSH
- ROG – upgrade and relocation of the time-of-flight neutron reflectometer to a cold beam line
- SANS – a new small-angle neutron diffractometer with a dedicated cold beam line
- NDP – upgrade of the neutron depth profiling spectrometer
- FISH – a new multi-purpose neutron imaging facility
- SESANS – upgrade of spin-echo labelled SANS
- Mössbauer Spectroscopy – upgrade of the existing spectrometer

On the next pages we describe what each of the instruments does (or will do), the progress achieved in 2017 and the prospects for 2018.

Measurement instruments

around the research reactor





1 Fuel element
This element (8 x 8 x 60 cm) comprises 19 airtight aluminium boxes each enclosing a thin plate of uranium silicide.

2 Reflector elements
Beryllium (a metal that absorbs almost no neutrons) elements are used to reflect neutrons that do not fly directly into the beam tubes back to the fuel elements.

3 Water pool
The water slows down fast neutrons and cools the reactor core.

4 Neutron cooler

Neutron powder diffractometry – PEARL

(new instrument since 2015)

The PEARL neutron powder diffractometer was built in 2015 mainly to determine the crystal structures of energy-materials, like batteries. Neutron diffraction and X-ray diffraction complement each other in the sense that neutrons are particularly sensitive to light elements and can distinguish light elements in crystal structures that contain both light and heavy atoms. In addition, magnetic structures and magnetic moments in the crystal can be accurately determined. PEARL is a unique facility within the Netherlands and one of the few in Europe.

Lectures in basic crystallography during the hands-on powder diffraction school at the RID, November 2017

Progress 2017

In 2017, PEARL beam time was distributed over in-house and collaborative experiments as well as education and instrument development. The in-house research on PEARL focussed mostly on battery materials, both for purely academic research and for projects with industry. Several collaborations from the previous years were continued and new collaborations were started, within the Netherlands and abroad. Instrument development focussed mostly on cryogenics and software extensions, and the first high-temperature desorption experiment was performed, too. First explorations were done to apply PEARL on nanocrystalline materials. The scientific output of PEARL has increased as expected.

In November 2017, we organiszed and hosted the first national hands-on school for powder diffraction in collaboration with the Dutch Crystallographic Society. The school was fully booked with 40 PhD and postdoc participants. Lectures were provided by experts from TU Delft, the Dutch Crystallographic Society, Radboud University and Shell Technology Centre Amsterdam. The participants came from 6 Dutch universities and several companies.

Prospects 2018

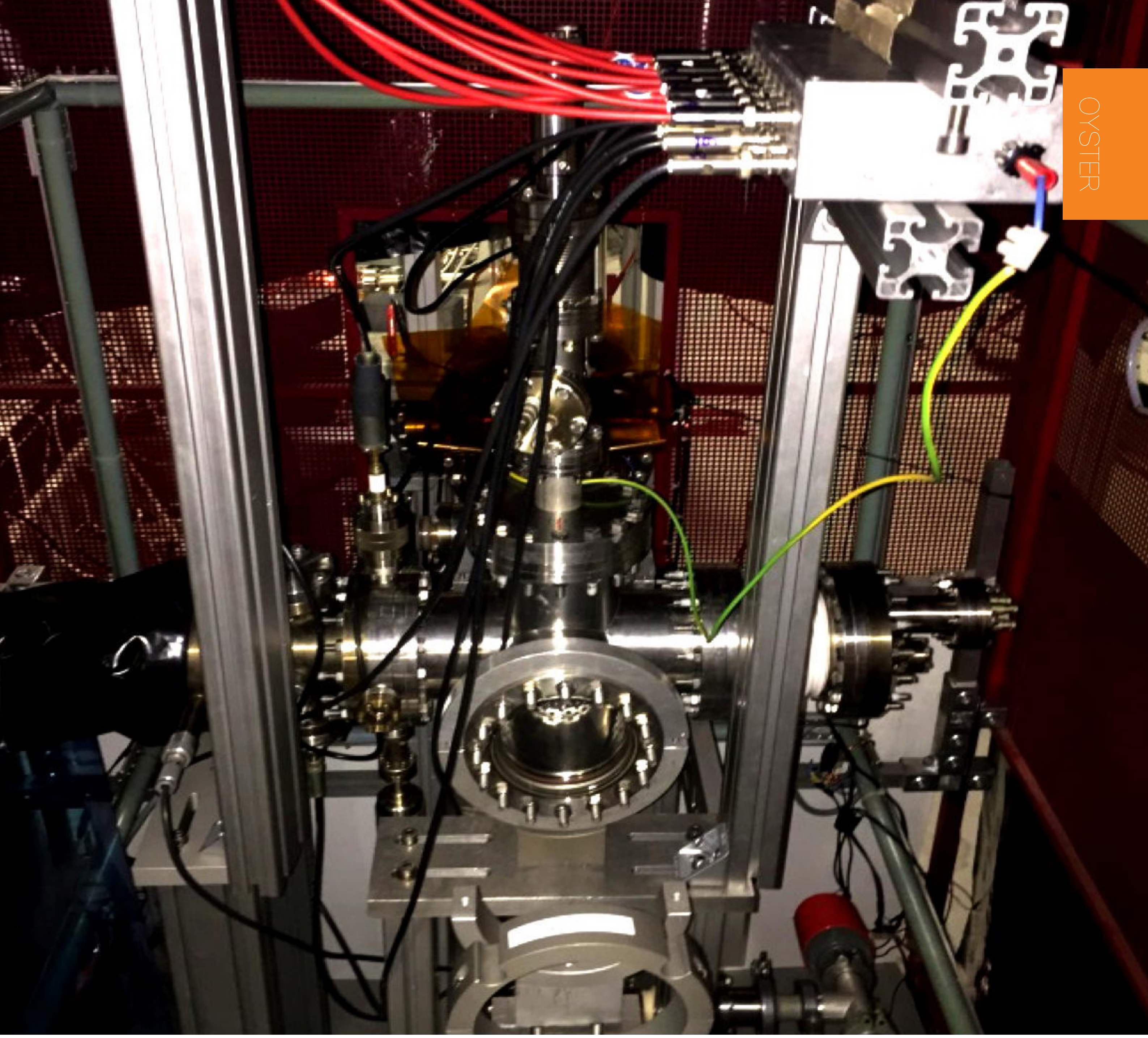
For 2018, we expect to have a cryostat in operation as well as a cryofurnace. Accurate temperature control is expected to greatly benefit both in-house research and the capabilities for external/foreign collaborations, with the aim to improve the scientific output of PEARL in quantity and/or in quality.

Photo (right): Picture of the focussing and deflection system of the POSH-PALS setup

Positron Annihilation Lifetime Spectroscopy — POSH-PALS

(new instrument)

Positron Annihilation Lifetime Spectroscopy (PALS) is a unique method for identifying open-volume defects and determining their abundance in materials. These defects, with sizes ranging from atomic vacancies to nano-voids may influence the properties and functionality of materials used in photovoltaics, perovskite-based solar cells and energy storage mediums like lithium and hydrogen. Moreover, they are often too small to be observed by other techniques. Positrons are highly sensitive probes for open-volume defects because their annihilation lifetimes are inversely correlated to the local electron density and thus an indication for the presence of open-volume defects. By tuning the energy of the incoming positrons, the probe depth can be adjusted from few nanometres up to several micrometres below the sample surface.



Progress 2017

In 2017, we performed the first beam-optimisation experiments with moderated low-energy positrons in a fully electrostatic beam-guiding system. Special effort was put into the enhancement of the moderation efficiency and into the focussing on and transport of the positrons through a 25-nm thick carbon film necessary for the successful generation of secondary electrons.

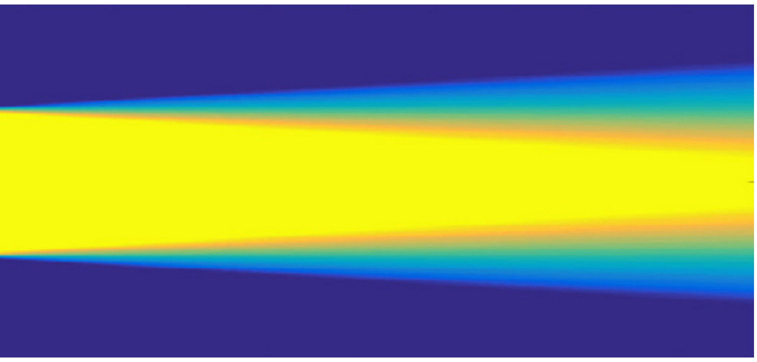
Prospects 2018

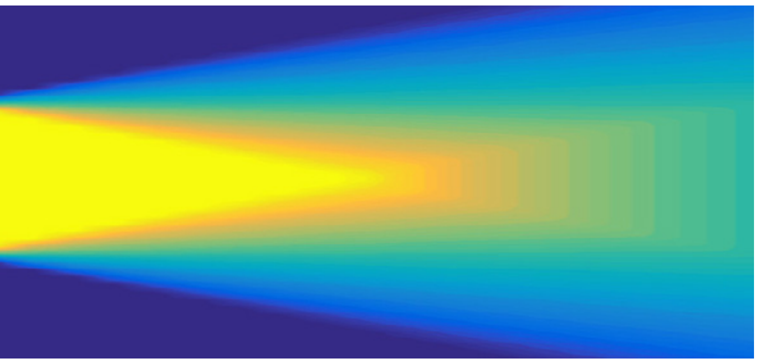
For 2018, the implementation and optimisation of the secondary-electron detection system (based on a microchannel plate detector) is foreseen, as well as testing of the overall timing system of the positron lifetime spectrometer using dedicated annihilation gamma detectors. At a later stage, high-efficiency detectors with a 100-ps timing resolution will be installed. These are currently being developed in-house.

Neutron reflectometer – ROG

(upgrade instrument)

Neutron reflectometry is a neutron diffraction technique that yields information about material structure and composition at surfaces and interfaces, probing areas on the nanometre scale. Applications are found in a very broad range of research, from protein adsorption at liquid-air interfaces for the stabilisation of foams to hydrogen adsorption in metallic films for detection purposes. It will contribute to many scientific challenges, such as hydrogen sensing storage systems, drug-delivery systems and magnetic films for information storage and read out.
The reflectometer ROG will be one of the instruments to achieve a huge increase of performance due to the neutron spectrum provided by the cold neutron source. To that end, ROG will undergo a major upgrade and will be moved from its present position to a beamline facing the cold source.





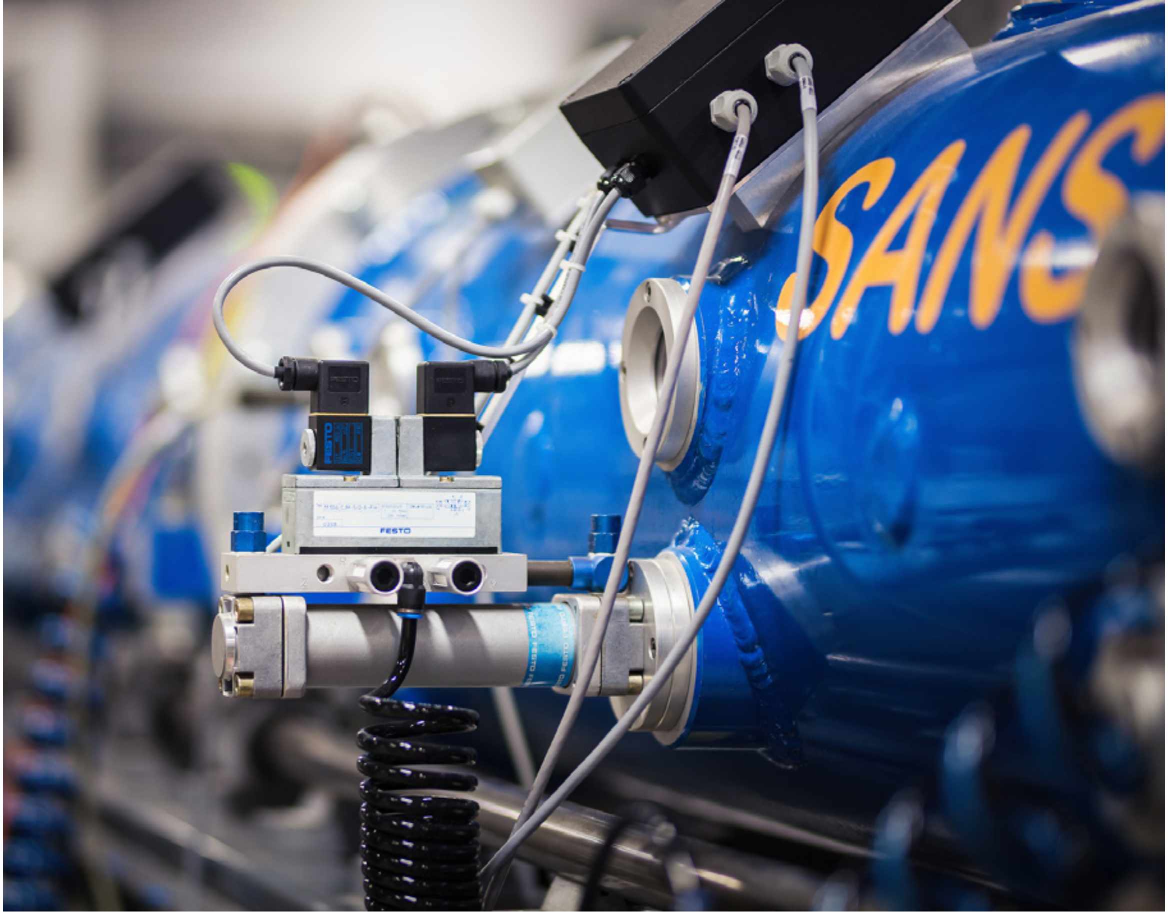
Images: ROG neutron beam at the exit of the new neutron guide for two different neutron wavelengths

Progress 2017

- We studied the hydrogen-detection performance of different thin metallic films, such as hafnium, tantalum and palladium-gold alloys.
- We studied a poly-electrolyte coating on titanium that will serve as a matrix for anti-bacterial drugs for dental implants.
- We optimised the new optical components for ROG and started negotiations with potential suppliers.
- We designed new mechanical components, such as a neutron chopper and sample-environment equipment.

Prospects 2018

- We plan to finish the design work and the major part of the fabrication of all new mechanical components.
- All necessary changes in instrument-control electronics and software will be made.
- We foresee the installation at the new beam position late 2018 or beginning 2019.



Small-Angle Neutron Scattering instrument — SANS (new instrument)

The small-angle neutron scattering instrument (SANS) allows researchers to investigate structures with particles of sizes from 1 up to 100 nanometres. The neutron scattering is a direct result from a local variation in chemical composition or magnetisation. For larger particles, the neutrons scatter under smaller angles. This allows for a direct characterisation of the particle size distribution within the material. Using this technique, typically proteins, micelles, polymers, porous media and precipitates are investigated, which are of interest for the development of new products in the field of polymer science, colloids, emulsions, food science and metal alloys.

Progress 2017

In view of the start of the construction of the CNS-Utility building, some further technical improvements in the instrumentation of the SANS instrument were made.

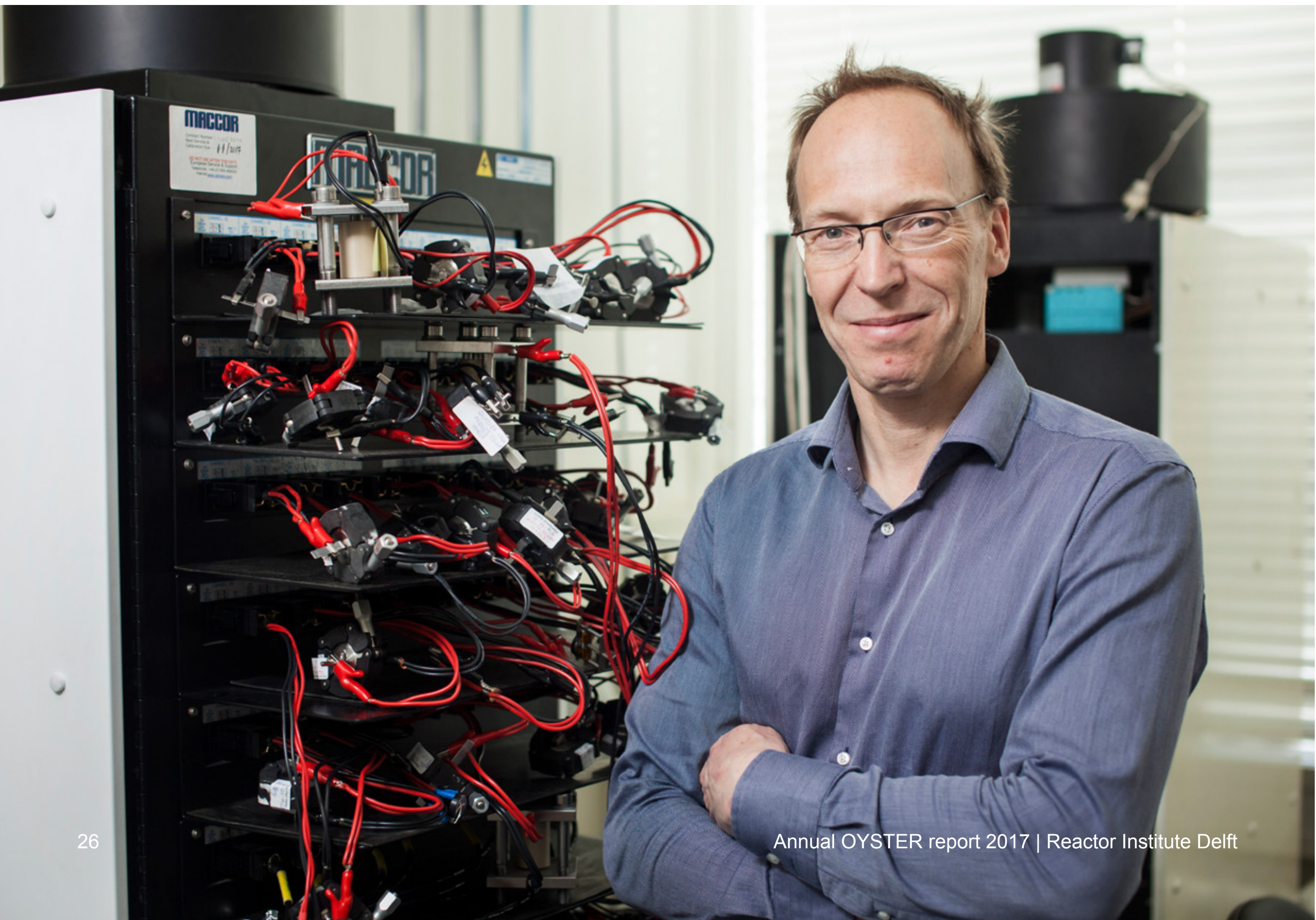
Prospects 2018

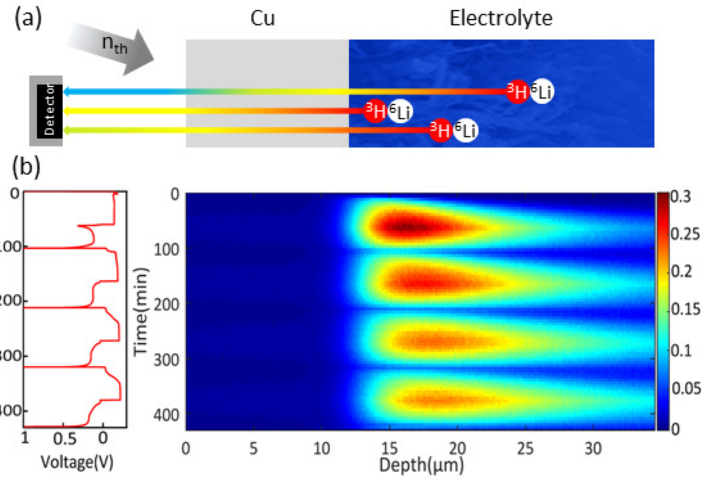
In 2018, a calibration of the instrument will be performed using the thermal neutrons of the current reactor source. In the period before reactor shutdown (for the installation of the CNS), several tests will be performed to evaluate the performance and to compare it to expectations. Based on these tests, the period of reactor shutdown can be used to further develop the instrumentation and sample environment.

Neutron Depth Profiling — NDP

(upgrade instrument)

Neutron Depth Profiling (NDP) is a near-surface analysis technique revealing distributions as a function of depth for specific light elements. The technique is particularly relevant for the development of electric vehicles and handheld devices, where electrical energy storage is the dominant hurdle. Lithium, one of the lightest and most reactive elements in the periodic table, is the most obvious choice to meet the challenge. Because lithium is so light, neutrons have been shown to be powerful in detecting lithium where photons fail to do so. NDP exploits the neutron capture reaction of the lithium-6 isotope yielding high-energy particles that allow scientists to study the position and movement of lithium atoms in any application, regardless of their oxidation state.





The principle of NDP and operando measurement of Li-plating.

(a) Thermal neutrons from the reactor fall on the battery in which they are captured by 6Li producing charged 3H+ with a well defined starting energy. The 3H+ loses energy while flying to the detector, which can be used to determine the depth of the 6Li. (b) Reversible Li plating monitored by NDP showing at the left the voltage while plating an stripping and on the right the reversible appearance of the signal representing the plated Li density. From the amount of Li at each moment we learn at what rate Li is plated where, giving insight in Li transport and reactivity, necessary to develop future Li-metal anodes for future high density batteries.

Progress 2017

One of the most notable achievements is our study of lithium metal plating. Using lithium metal as anode material for rechargeable batteries would yield the most energy-dense battery architecture and is considered as the next step in unlocking the high energy density of oxygen and sulphur-based cathodes. Our study showed that the properties of the metal layer, such as the porosity, highly depend on the rate of plating. We showed that lithium-anode batteries should be cycled at higher currents in order to store more lithium and prevent detrimental side reactions. Moreover, the positive effects remain visible as the battery is cycled further, even at different rates. NDP is especially powerful here as it allows the study of the lithium anode as well as the electrolyte and side reactions as a function of depth with accuracies beyond the parts per million (ppm) level.

Prospects 2018

Three-dimensional (3D) particle trace detection, which will enable 3D imaging of Li-ions in battery electrodes, has shown good progress last year and we hope to demonstrate a proof of principle in coming months. Also, experiments are on the way with a new set-up to allow measurements outside vacuum, which will increase the ease of operation for operando battery research work with NDP.

Photo (left): Marnix Wagemaker in the battery lab.

First Imaging Station Holland — FISH

(new instrument)

Image (right): With FISH we investigated the casting process of this small brass statue of a seated Ganesha.

Neutron imaging can be used for non-invasive inspection of metal structures such as historical statues, of cooling channels in 3D-printed metal objects, or for monitoring water uptake in roots of plants and lithium transport in batteries. All these investigations are of vital importance for both academic research and industrial applications, and can now be performed at the specialised neutron radiography and 3D-tomography station FISH.

Progress 2017

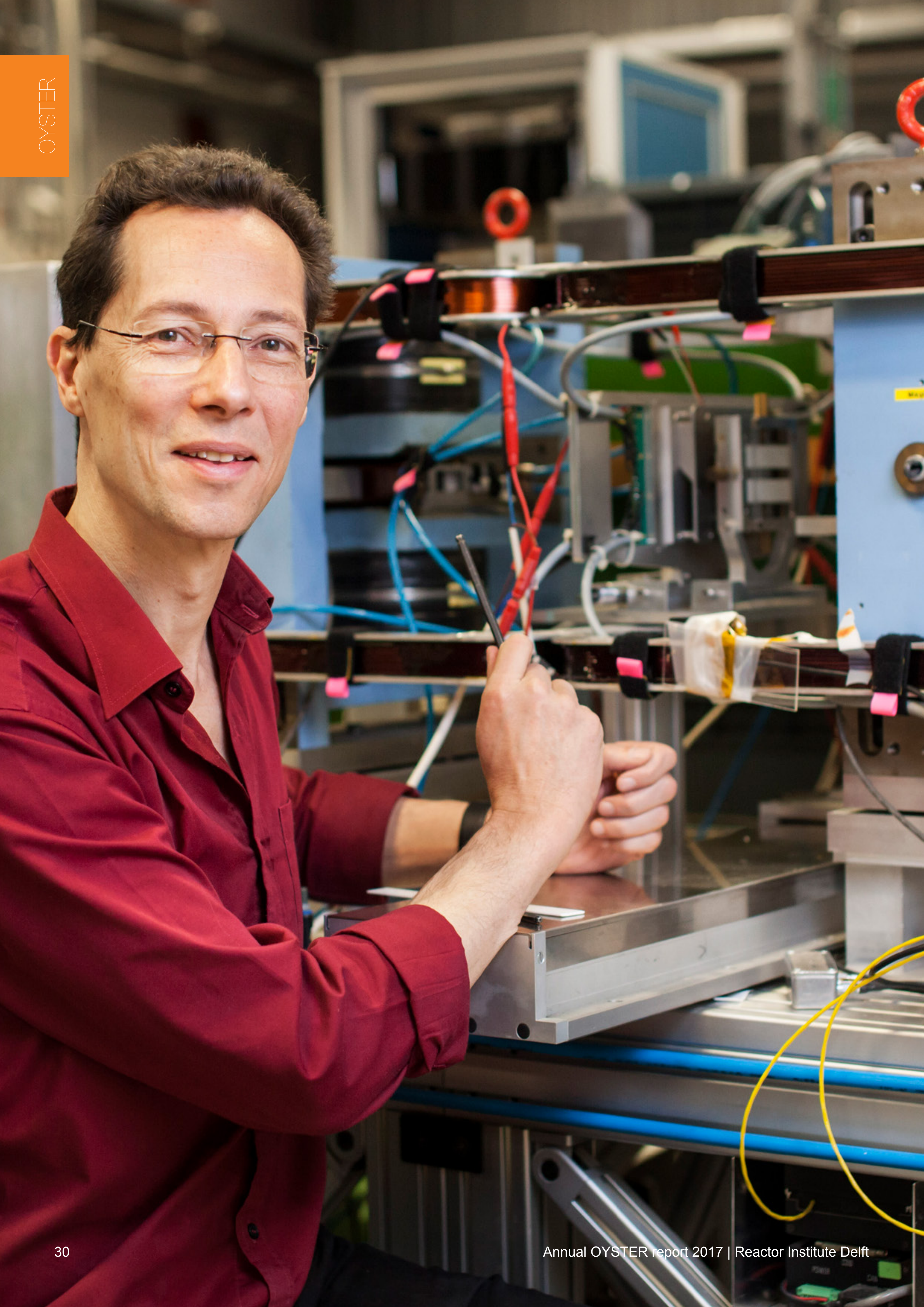
Over the past years, a test neutron imaging setup was installed, called Baby-FISH. In 2017, the performance of this setup was evaluated in collaboration with our colleagues of the imaging group at the Paul Scherrer Institute in Switzerland. The conclusion was that the test beamline is of excellent quality and very competitive.
The next step was to convert Baby-FISH to a permanent and mature imaging station, called

Images (below): 3D reconstruction of the interior of a classical watch. All metal parts are imaged in detail highlighting the complex mechanical design. More examples can be found under: https://vimeo.com/user54014065

FISH. For this purpose, we collected funds for a Swiss state-of-the-art camera system and new commercial software. In parallel, we tested an extremely efficient camera system, developed by the company Photonis, which may have great potential for future upgrades. A new collaboration with Rijksmuseum and the Cultural Heritage Agency of the Netherlands resulted in a PhD and postdoc grant from NWO, as part of the ‘Imaging’ programme of the Netherlands Institute for Conservation and Art Science (NICAS). The multidisciplinary team that has been formed around FISH provides a solid connection between this instrument and the Dutch museums and the cultural heritage field.

Prospects 2018

In early 2018, we will install the new high-resolution Swiss camera system. We will continue the tests of a highly efficient camera system developed by Photonis. We will operate new commercial software and further increase the data-analysis capabilities. Finally, we will seek additional funding in collaboration with external users.



Spin-Echo Small-Angle Neutron Scattering - SESANS

(upgrade instrument)

Spin-echo small-angle neutron scattering (SESANS) is a technique that allows users to investigate structures on length scales from 20 nanometres up to about 20 micrometres, which is two orders of magnitude larger than small-angle neutron scattering (SANS). These length scales are especially relevant for many food materials. In contrast to traditional scattering methods, SESANS data are in real space, rather than reciprocal space, which makes their interpretation easier. These properties make SESANS a powerful tool for the study of structural properties of materials.

Photo (left): Wim Bouwman working on the SESANS instrument.

Progress 2017

In 2017, we used SESANS to characterise the effect of processing of proteins on the microstructure of new food materials; these materials mimic meat but are animal friendly and more sustainable. We determined the effect of mechanical processing of cellulose to improve the conversion into biofuel. We installed new pole shoes from softer iron on the electromagnets to have better and faster control of the magnetic fields, which yields a higher polarisation and thus a higher information content of the measurements. We built rotating sample cells to be able to study creaming or sedimenting dispersions.

Prospects 2018

In 2018, we will investigate composite polymers for use in electronic shielding and new battery materials. We plan to have adjustable angles on the neutron spin flipping foils, in order to be more flexible in the wavelengths used in SESANS experiments. This will allow for the measurement of weaker-scattering samples.

Mössbauer spectroscopy

(upgrade instrument)

The high penetrating power of the gamma rays makes Mössbauer spectroscopy a very versatile technique to study catalysts in their working state, providing promising routes to better understand catalytic sites, opening new ways to synthesise novel or improved catalysts. The Mössbauer laboratory at RID is the only one of its kind in the Netherlands and has been leading – in the past 30 years – in the application of Mössbauer spectroscopy, one of the few techniques that can be used to investigate catalysts under real industrial conditions.

Progress 2017

The development of the neutron in-beam Mössbauer spectroscopy facility was successfully initiated within an NWO Post-Doctoral project, in collaboration with Johnson Matthey and Dow Chemical. Development work has proceeded with the establishment of collaborations with groups with existing in-beam Mossbauer stations. This cooperation has revealed how sensitive the technique is to stray gamma background and neutron flux. Furthermore, a prototype detector has been commissioned

Photo: Instrument scientist Iulian Dugulan

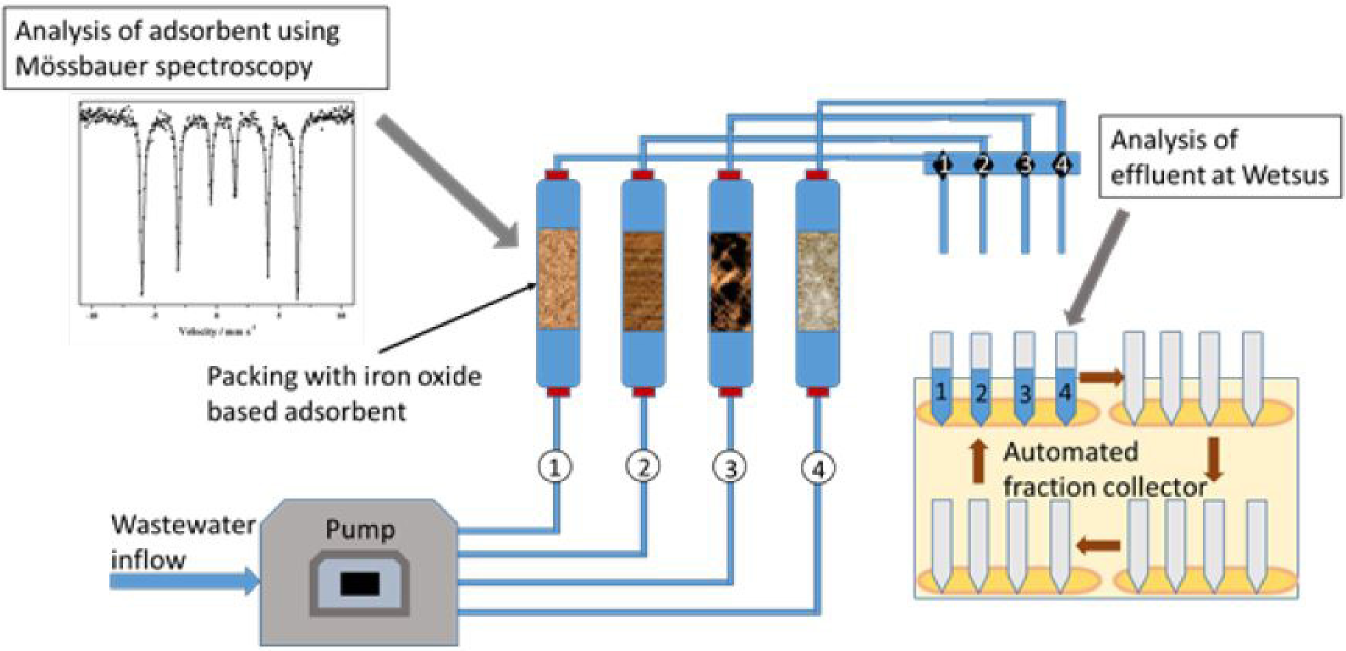


Figure: Mössbauer characterization of materials and their phosphate adsorption testing with real wastewater, in rapid small scale columns, used to automate adsorption and desorption cycles.

to utilise secondary electrons produced in the gamma absorption process after neutron capture; this approach is insensitive to the gamma background from the reactor. Calculations for shielding and signal-to-noise ratio are currently being undertaken.

A new grant has been awarded in 2017 to the Mössbauer laboratory, for the development of effective methods to recover phosphorus from wastewater through manipulation of iron phosphorus chemistry. This NWO project is a collaboration between TU Delft, Wetsus and the following partners in the "Phosphate Recovery" research theme: Kemira, ICL Fertilizers, Green Water Solutions, Oosterhof Holman, STOWA and Waterschap Brabantse Delta.

Prospects 2018

Over the next year, an instrument design will be produced for the neutron in-beam Mössbauer spectroscopy facility. To test this design, we will perform extensive viability measurements using both a normal and the prototype detector.

In addition, a new project will be started in collaboration with Eindhoven University of Technology – under the supervision of Shell Global Solutions – employing 57Co-Mössbauer emission spectroscopy to study the sintering and oxidation of cobalt as a deactivation mechanism of Fischer–Tropsch catalysts for the gas-to-liquids process.

Irradiation facilities

Irradiation facilities are primarily used to produce radioisotopes that find applications in various fields among which medicine. Besides the production of radioisotopes, the irradiation facilities can also be used to study the effect of radiation on matter, which in turn can be used to design better irradiation facilities according to the customer needs. For a research reactor it is essential to design irradiation facilities in a flexible way so that the radiation field can be adjusted to fit to the purpose of each irradiation. We have designed such a flexible irradiation facility, called "FlexBeFa", which can be used for instance to shield gamma radiation and activate metals enclosed in organic compounds such as Ho-165 polymeric microspheres used in liver radioembolisation. Another example of possible application of this facility is the production of Cu-64, a so-called theranostic radioisotope, i.e. it can be used for imaging as well as therapy. Our flexible irradiation facility allows exploring two production routes for Cu-64, both requiring tuning of the radiation field but which have the potential for achieving high yields and high specific activity necessary to meet the customer needs. >>

"The new flexible irradiation facility has brought the production of isotopes for medical applications closer to the patients."

Quote and photo (right):
Head of the research project
Antonia Denkova

>> **Progress 2017**

In 2017, the flexible facility was built and tested. The first test concerned lead shielding which was used to protect polymeric microspheres containing Ho-165 from gamma radiation during neutron activation. The results were positive and the facility was used for the first time to produce materials for actual patient treatment. The production and distribution of short-lived medical isotopes is a race against time. To be able to get medical isotopes with the required level of radioactivity to the patient, we have been working closely with Quirem Medical. In December, in Italy, the first liver cancer patient was treated with special radioactive microspheres that were produced in Delft. This innovative liver cancer treatment is conducted using tiny spheres – about the thickness of a hair – that are packed with the radioisotope Holmium-166. The microspheres were activated in the new flexible irradiation facility.

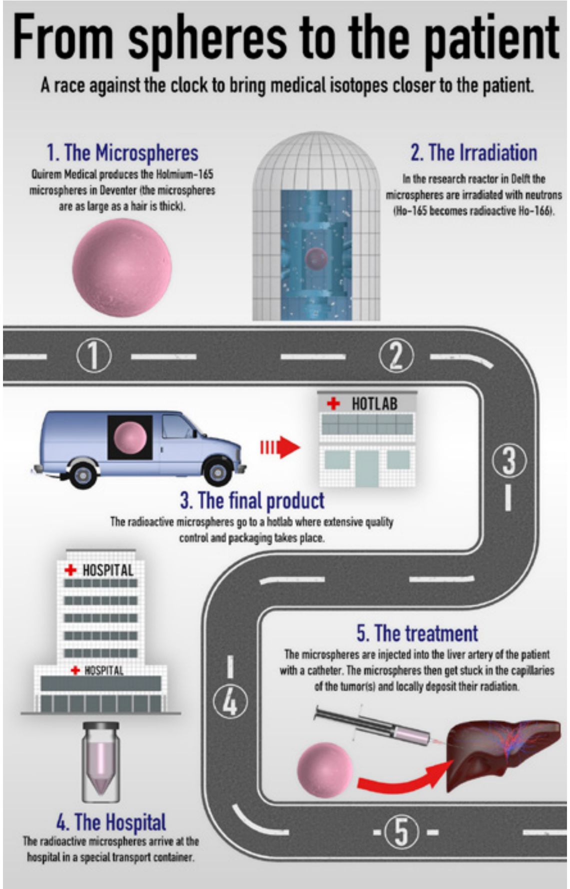
Prospects 2018

In 2018, we plan to continue with new applications of the FlexBefa (e.g. Cu-64 production) including the use of new shielding materials. Simulations are currently being carried out to optimise the design of each shielding option. We expect that simulation work will need about 1.5 year, of which 9 months are already funded.

FASTER AND CLEANER MOLYBDENUM-99 (99MO) PRODUCTION ROUTES

Isotopes are used for a wide range of medical applications. Worldwide, each year, about 30-40 million clinical radiodiagnostic scans are made using technetium-99m (99mTc). 99mTc can be derived from its parent isotope molybdenum-99 (99Mo). The challenge therefore is to produce sufficient 99Mo in an efficient and reliable way. Most 99Mo is currently produced by fission of uranium-235 (235U). To do so, solid targets containing 235U are irradiated in a nuclear reactor. 6.1% of the fission reactions lead to 99Mo.

Researchers at the RID now investigate the feasibility of producing 99Mo by irradiating a uranyl nitrate solution in a U-shaped loop located near the core of the reactor. Recent research has shown that the uranyl nitrate solution inside such a U-shaped loop could run continuously for more than 20 years without the need for refilling. In contrast with irradiating solid targets, this innovative approach supports online



Furthermore, we will design two new pneumatic FlexBefas which will be implemented after the CNS has been installed in the reactor. Finally, we plan to make the in-core facility ("SmallBeBe") pneumatic, which will increase its applicability tremendously. For the realisation of these plans we will need to finance part of the design work as well as the materials needs.

Infographic

extraction and therefore significantly reduces the post-processing time. Future research will concentrate on optimising microfluidic solvent extraction to selectively and continuously extract 99Mo from the irradiated uranyl nitrate solution.

To maximise production, the concentration of uranyl nitrate should be as high as possible. Due to the high concentration, however, the produced heat (a consequence of fission heat and the interaction of gamma radiation with construction material) in the facility will result in the temperature of the solution exceeding the boiling point. Therefore, another focus of further research is enhancing the heat-transfer process and cooling the U-shaped loop more effectively, so that higher uranyl nitrate concentrations can be used.

After the research and demonstration phases, the new production process of 99Mo is aimed to be implemented in large-scale facilities.

INTERVIEW:

"The Mössbauer facility helps us look for environmentally friendly catalysts."

Principal Scientist Dr. Leon van de Water

In Mössbauer spectroscopy, gamma rays produced by a radioactive source pass through a material under test. By analysing the gamma-ray resonance absorption spectra, scientists learn about iron atoms and their chemical environment inside the material. One of the projects heavily relying on the Mössbauer facility at RID is a collaboration of TU Delft, Eindhoven University of Technology and Johnson Matthey, a British multinational producing speciality chemicals and sustainable technologies. Their joint project aimed at using Mössbauer spectroscopy techniques to accelerate the development of environmentally friendly catalysts started in 2015.

Hydrogen production

One of the chemicals Johnson Matthey provides catalyst technology for is hydrogen. Produced from carbon monoxide and water, hydrogen is not only used as intermediate in the large-scale production of chemicals such as ammonia and methanol but also plays a role in sustainable energy technologies such as fuel cells. Dr. Leon van de Water, Principal Scientist at the company's Billingham site, explains: "To speed up the production of hydrogen, we use a catalyst, most often based on iron oxide. In our Research and Development departments we are continuously working to improve the properties of the catalyst to meet our customers' demands."

Fundamental questions

Although the catalyst produced by Johnson Matthey has a proven performance and is being used in large quantities at production sites worldwide, there is still much to learn. "Although we have been producing this catalyst for over 10 years, some questions about the detailed working mechanism of the catalyst remain. For example on the exact role of the chromium additive on the iron oxide phase where the catalytic reaction takes place. Fundamental research is needed to shed more light onto the current catalyst if we want to develop a new generation of catalysts." >>

Photo: Dr. Leon van de Water of Johnson Matthey's Technology Centre in the UK and Maxim Ariëns (PhD student RID) in front of a high-throughput catalyst testing system.

"We're working with the Mössbauer team in Delft towards joint scientific research as well as proprietary R&D."

>> **Realistic environment**

"The Mössbauer facility in Delft allows us to look at catalyst materials in a realistic environment: the correct gas mixture composition (carbon monoxide, carbon dioxide, hydrogen and steam) at realistic pressures (up to 40 bar) and temperatures (up to 500°C). It has been shown before that a catalyst in a simplified lab environment behaves differently than the same material under actual process conditions. For example, small crystal particles tend to agglomerate, a factor that is absent when you don't mimic the real industrial process parameters."

Smooth collaboration

How is the collaboration working out? "It's a cliché, but the project is a win-win situation for all involved." Asked about the results thus far, Van de Water can't say too much, as the team are preparing multiple publications. But he can say they've already had some very interesting results. Of course, the project will not single-handedly replace the current catalyst standard. "We're combining fundamental research into the current catalyst with in-house R&D into alternative materials. It's hard to predict what will come out. Changing such a high-volume chemical production route is not easy. It will take years of trials at increasing scales to convince industry that a new process is the way to go."

Unique facility

The project has strengthened ties between Johnson Matthey and RID. "We've already started up another collaboration, which is more in the area of contract research measuring proprietary samples." As a final note, Van de Water remarks: "We enjoy working with the Mössbauer team at RID. From our perspective, it appears this unique facility is mostly used by the materials science and physics disciplines. I hope the chemistry community will discover it too!" The upgrade of the existing Mössbauer facility as part of the OYSTER project will open up even more capabilities: it is expected to allow the development of catalyst materials that emit the gamma rays needed for Mössbauer analysis themselves, sending out messengers from deep within the catalysis process.

Review by NWO

In June 2017, the fifth visit of the "NWO OYSTER Advisory Committee" took place.

In comparison with 2016, the composition of the Advisory Committee has changed; Dimitri N. Argyriou has left while Shane Kennedy and Christiane Alba-Simionesco have joined. In view of the development of the project, the Committee focussed its recommendations on reactor status, licensing and programmes, missions & strategy and instruments.

Looking back at the review meeting, the OYSTER organisation highly appreciates the positive cooperation between NWO and RID/RST and invited the Committee to participate in the next review meeting of 2018.

The following Committee members attended this meeting:

CHRISTIANE ALBA-SIMIONESCO
Laboratoire Léon Brillouin (LLB), France

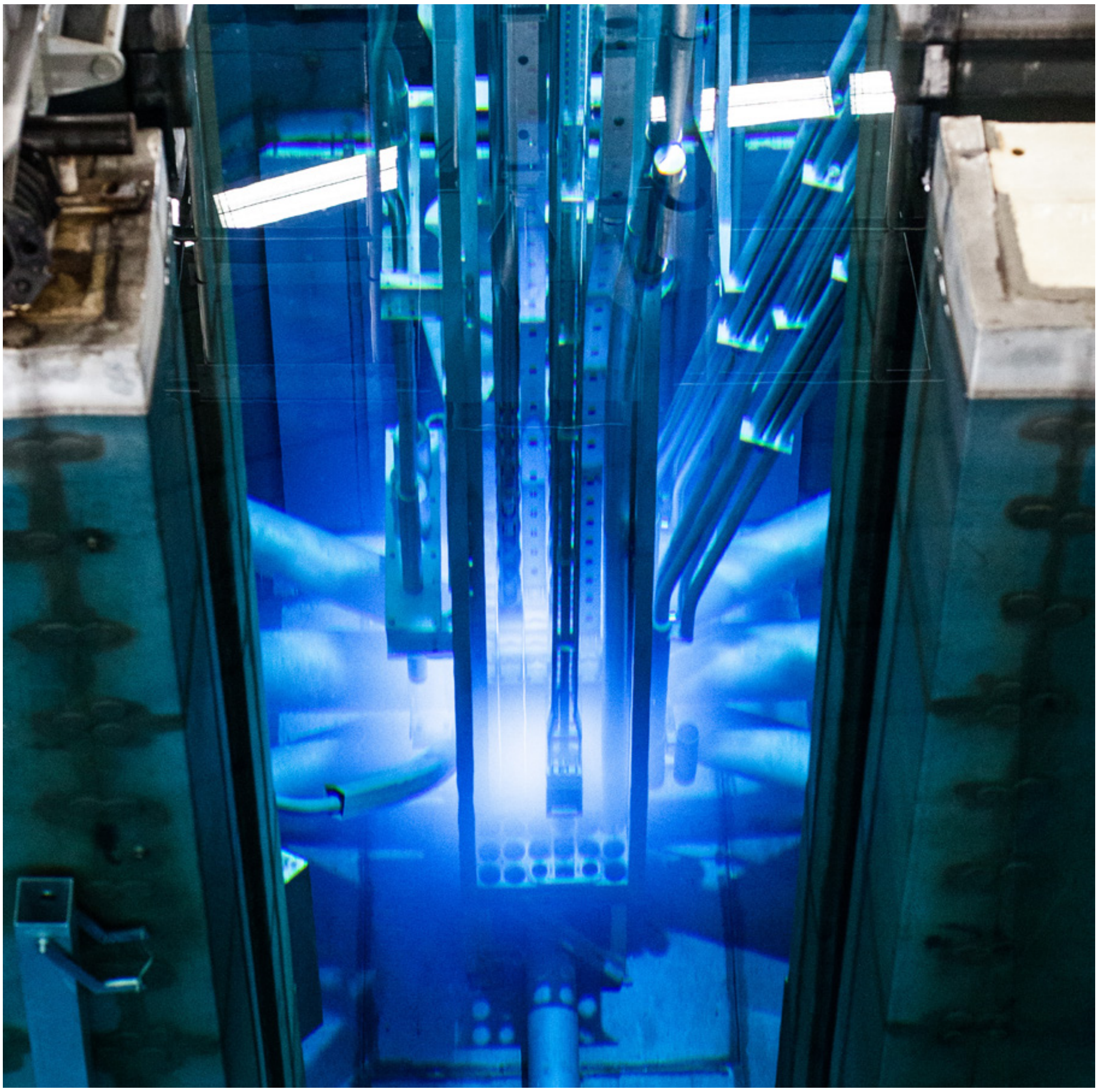
KURT CLAUSEN (CHAIRMAN)
Technical University Denmark (DTU)/Paul Scherrer Institute, Switzerland

SHANE KENNEDY
European Spallation Source (ESS), Sweden

FRED VERZIJLBERGEN
Erasmus University Medical Centre Rotterdam (Erasmus MC), Netherlands

NICO KOS
Netherlands Organisation for Scientific Research (NWO), Netherlands

	COMMENTS/RECOMMENDATIONS OF THE NWO OYSTER ADVISORY COMMITTEE	IMPLEMENTATION/SOLUTIONS BY THE OYSTER TEAM
1	The committee recommended to capture the reactor cold source delivery scope and licensing according to plan and within budget.	The original scope of work for the Korean main contractor is unchanged and the pertaining licencing procedures are still according to schedule. For the non-nuclear part, the execution works have started already and for the nuclear work package, the licencing permit procedure is continuing. Regarding the budget development, up to now no price escalation is foreseen.
2	RID/RST is recommended to formulate the mission and strategy for the neutron scattering programme as soon as possible.	RID and RST are going through reorganisations. RST is being restructured from 5 to 8 research groups, while RID will comprise a dedicated instrument group. In addition, the mission of RST/RID are being reformulated. These aspects are all under development. Arranging funding for instrument scientists is in progress, as is the search for the scientists themselves. Strategy and organisation are being developed in further detail.
3	The scientific outcomes of the new instruments will become ever more visible. The committee recommended to arrange financing, consolidation with the community and involvement of right staffing personnel.	These aspects are all under development. Arranging funding for instrument scientists is in progress, as is the search for the scientists themselves. Strategy and organisation are being developed in further detail.
4	Managing expectations is still key for starting successful operations by 2020.	RID/RST is fully committed to manage expectations of the stakeholders.



"We observed good and open discussions as basis for our work. In view of the progress of the project we anticipate to have one more meeting."

Quote: NWO OYSTER Advisory Committee

The Integral Management System (IMS)

Crucial to OYSTER, the Integral Management System (IMS) is a coherent system of processes, procedures, work instructions and performance indicators, in which the contributions of every part of the RID organisation are denoted. As a tool to achieve organisational goals without compromising safety, the (International Atomic Energy Agency) IAEA considers an IMS to be an essential part of the safety culture around nuclear reactors. The IMS also ensures that permit, safety, legal and customer requirements are met. The IMS for RID has been under construction for years, speeding up considerably when a Quality Manager was appointed.

The IMS is based on the 'plan-do-check-act' (PDCA) cycle. This means that a cycle of establishing goals, making plans, doing the work, measuring, analysing, improving and anchoring is performed. Insight is obtained as to whether the goals are achieved, the needs for means are met, and the structure and processes of the organisation are suited for the purpose. If not, changes can be made, resulting in continuous improvement.

Progress 2017

In 2017, the main process of RID ("To make radiation and to do measurements") was identified and mapped. The necessary staff and means, control measures, performance indicators, clients and customers were identified for each partial process. A management review was performed as part of the PDCA cycle. The document control system was designed with respect to structure and formats, together with the quality coordinators. It was made accessible to all staff members needing access.

Prospects 2018

In 2018, we will continue expanding the IMS. Amongst others, the partial process "To irradiate targets & samples" will be enclosed in the IMS. Also, the "Newcomers" process to admit a new colleague or guest to the building and to get all the work permissions will be streamlined. A management review will be performed.

Financial overview

Budget summary

The available OYSTER project budget amounts to €117 million, covering the initial investments as well as the basic reactor-associated operational costs for a period of 10 years. In 2012, the Dutch government awarded €38 million for OYSTER. TU Delft will contribute a total of €74 million in kind.
Furthermore, TU Delft stands surety for an additional €5 million. This is part of the co-funding (industrial, scientific etc.) needed to fund the development, commissioning and exploitation of instruments and facilities over the total 10-year OYSTER programme period and beyond.

Photo (left): programme manager IMS Menno Blaauw and Quality Manager Eric Buzing

Update 2017

In 2017, works have been started on the CNS Utilities (Work Package 2). In addition, improvements according to the Dutch Safety Requirements (DSR), which started in 2016, continued in 2017. This amounts to €5,8 million. In total €12,2 million was spent on engineering (including DSR), licensing process and positioning of OYSTER. Furthermore, TU Delft contributed €9,0 million in kind to OYSTER in 2017.

As part of the start on the CNS Utilities three main subcontractors (Strukton, Kreber and DH Industries) have signed their contracts. About 50% of the total estimated contract value of the CNS Utilities Work Package has been signed. Expenditures within the CNS IPA work package amount to 40% of the contract value of the total work package.

Several OYSTER instruments have already been realised. The neutron diffractometer PEARL, which is used by scientists from the Netherlands and abroad to carry out energy research into, for example, hydrogen storage and new battery materials, still needs further improvements. The funding for PEARL and for the instruments SANS and ROG also comes from the OYSTER project itself. For FISH, Mössbauer and the irradiation facilities, plans are being formulated for further improvements in order to attract additional external funding.

Quote: NWO OYSTER Advisory Committee

Planning

The closing out of the OYSTER project is expected at the beginning of 2020 instead of December 2019. This is a few months later than anticipated in the planning in the previous

Task name	Contractor	2017								
		Q1			Q2			Q3		
		J	F	M	A	M	J	J	A	S
OYSTER Project										
Milestones										
KEW Non-Nuclear License										
Building Permit										
KEW Nuclear License										
Reactor Downtime										
Project Finish										
Regulator										
KEW Non-Nuclear License (ANVS)										
KEW Nuclear License (ANVS)										
Additional Scope										
Construction Site Layout	Strukton									
Entrance Experiment Hall	Strukton									
Primary & Secondary Cooling System										
CNS Utilities										
Civil & Infrastructure	Strukton									
Electrical Systems	Worksphere									
System Descriptions	KAERI									
Helium Refrigeration System	**DH Industries**									
Helium Transfer Lines	Demaco									
Vessels & Tanks	Kreber									
Gas Blanket Systems	Process Flow Systems									
Instrumentation & Control	Yokogawa									
Reactor Modifications										
Basic Design	KAERI									
Test In-Pool Assembly	Moojin Keeyeon									
Main In-Pool Assembly	Moojin Keeyeon									
Beam Tube Modification	Bilfinger - Babcock Noel									
Reactor Protection System	Yokogawa									
Commissioning										
Procedures & Protocols	KAERI									
System Performace Test (SPT)	KAERI - RID									
Integrated System Test (IST)	KAERI - RID									
Reactor Integrated Test (RIT)	KAERI - RID									
Training & Documentation	KAERI - RID									

year report. The delay is caused by the planning of the detailed engineering phase and the availability of the KEW Nuclear Licence permit (Kernenergiewetvergunning). The construction of the CNS-Utility building started in October 2017 and the building will be finished in April 2018 according to planning. The reactor modifications (In-Pool Assembly) will start in Q2 2019.