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Collaboration between SCK·CEN and JAEA for Partitioning and Transmutation through Accelerator-Driven System

Working Group for Collaboration between SCK·CEN and JAEA
for Partitioning and Transmutation through Accelerator-Driven System

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This technical report reviews Research and Development (R&D) programs for the Partitioning and Transmutation (P&T) technology through Accelerator-Driven System (ADS) at Studiecentrum voor Kernenergie/Centre d'Etude de l'Énergie Nucléaire (SCK・CEN) and Japan Atomic Energy Agency (JAEA). The results obtained in the present Collaboration Arrangement between the two organizations for the ADS are also summarized, and possible further collaborations and mutual realizations in the future are sketched.

Keywords: Partitioning and Transmutation, Accelerator-Driven System, ADS, MYRRHA, Transmutation Experimental Facility, TEF

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加速器駆動システムを用いた分離変換に関する SCK・CEN と JAEA 間の協力

日本原子力研究開発機構

ベルギー原子力研究センター

加速器駆動システムを用いた分離変換に関する
SCK・CEN と JAEA 間の協力のためのワーキンググループ

(2017 年 1 月 18 日　受理)

本報では、ベルギー原子力研究センター（SCK・CEN）と日本原子力研究開発機構における加速器駆動システム（ADS）を用いた分離変換（P&T）技術の研究開発プログラムをレビューする。また、ADS のための現行の 2 機関間の協力取り決めを取りまとめると共に、将来における更なる協力可能性とその実現について概要を述べる。

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1. Introduction

Reduction of the burden caused by radioactive High-Level radioactive Waste (HLW) management is one of the most critical issues for the sustainable utilization of the nuclear power. The Partitioning and Transmutation (P&T) technology provides the possibility to reduce the amount and lifetime of the radiotoxic inventory of the HLW drastically and to extend the repository capacity. The Accelerator-Driven System (ADS) is regarded as a powerful tool to effectively transmute Minor Actinides (MAs) in the “double-strata” fuel cycle strategy.

SCK・CEN has been working on the MYRRHA project for more than 15 years now. MYRRHA is a ~100 MWth research and demonstration facility for the ADS concept. This effort was conducted in the frame of the European Commission strategy for P&T for HLW management called "Four Building Blocks P&T strategy"[1,2)], where ADSs are regarded as the prime candidate for concentrated burning of minor actinides in a double strata approach. In 2010, SCK・CEN received 60 M€ special endowment from the Belgian Government for the further development of the MYRRHA project hence contributing to the 3rd building block of the European strategy. This enabled SCK・CEN to define, develop and implement a large design, R&D and licensing program in support of the different aspects of MYRRHA and inspired or coordinated many European Commission FP5, FP6, FP7 and HORIZON 2020 projects related to P&T and ADS as MYRRHA is very central in the EC strategy. Above efforts are summarized in Chapter 2.

The Japan Atomic Energy Agency (JAEA) has been continuously implementing Research and Development (R&D) on P&T technology. As partitioning technology, the four group separation process was proposed and improved processes with superior extractants are being developed based on the active tests using simulated High-Level Liquid Waste (HLLW) with MA tracer and genuine HLLW. As transmutation technology, JAEA proposes a lead-bismuth eutectic (LBE) cooled, tank-type subcritical reactor with the power of 800 MWth driven by a 30 MW superconducting LINAC. JAEA has done R&D for accelerator design and its reliability, neutronic of the core, plant design, LBE treatment and thermo-hydraulics, materials for beam window and so on. Assuming necessary budgetary steps, JAEA plans to construct the Transmutation Experimental Facility (TEF) that consists of ADS Target Test facility (TEF-T) and Transmutation Physics Experimental Facility (TEF-P). TEF-T is devoted to the target development and material research for ADS and TEF-P is utilized for validation of uncertain nuclear data of MAs and establishment of operation method of ADS. The R&D for fuel design, fabrication and reprocess is also essential to accomplish the transmutation. JAEA is developing a fuel analysis code usable for nitride fuel accumulating experimental data for material properties, compatibility with cladding materials and irradiation behavior. The fuel fabrication and pyrochemical-reprocessing are also designed based on component tests. Above efforts are summarized in Chapter 3.

The two organizations have cooperated in R&D for the ADS under the Collaboration Arrangement between the Japan Atomic Energy Agency and the Belgian Nuclear Research Centre for Cooperation in the Field of Research and Development of Nuclear Energy (CFRDNE) signed on November 23, 2006, renewed on November 24, 2011 and continuing till November 23, 2016. Several results have been obtained in this collaboration and other collaborative activities with Europe through the EURATOM-Japan agreement as described in Chapter 4.

Based on the current R&Ds of the two organizations, the possible collaboration list in the future is organized in Chapter 5.

2. Outline of MYRRHA activities at SCK•CEN in the framework of P&T

SCK•CEN activities in the framework are mainly concentrated around the development of the ADS demonstrator facility MYRRHA presented in Fig. 2-1. The activities are subdivided in MYRRHA R&D activities, MYRRHA design activities and MYRRHA licensing activities. Nevertheless SCK•CEN through the MYRRHA has influenced and coordinates many European Commission projects related to P&T and ADS of the FP5, FP6 FP7 and HORIZON 2020 framework[3].

Fig. 2-1 Global view of the MYRRHA project on the SCK·CEN technical site

2.1 MYRRHA R&D

2.1.1 Objectives of the MYRRHA R&D program

The strategy adopted for the MYRRHA R&D is based on 3 categories:

- Generic research for P&T and ADS through EC Frameworks
- ADS related research through bilateral agreements without or with exchange of money
- MYRRHA Specific design or licensing support R&D through own R&D or bilateral funded research that we are focusing on hereunder

The MYRRHA R&D program to support the design and the licensing activities is divided into six topics:

- Materials selection and qualification including the analysis of the design conditions and hypothetic failure scenarios for the MYRRHA components in order to identify related material property and degradation effects;
- Fuel research and qualification including a preliminary safety assessment phase
- Accelerator design and demonstration of the required reliability.
- LBE Technology development to demonstrate the feasibility of key components in an LBE environment representative of MYRRHA as well as to develop the technology

for coolant chemistry control and to study the release and capture of hazardous volatile impurities

- Instrumentation and Control to set-up the overall control concept and its interfacing
- Computational codes and data sets for neutronic design and safety analysis of MYRRHA.

2.1.2 Infrastructure at SCK・CEN

To perform mechanical and corrosion tests in stagnant and flowing LBE environment new installations have been constructed and commissioned (LIMETS 3, LIMETS 4, CRAFT loop). In case of the CRAFT (Corrosion Research for Advanced Fast reactor Technologies) loop an exposure time approaching 5000 hours has been achieved. The operational experience of the setups used for materials tests is systematically analysed and provides valuable input for defining of the detailed operational conditions of MYRRHA.

A fuel laboratory has been installed to manufacture nuclear fuel pellets on a laboratory scale. An irradiation experiment is in preparation in the TRIGA-reactor of INR (Romania) in order to establish the failure threshold, expressed in deposited energy in the fuel, for fast transients.

The dedicated RHAPTER (Remote HAndling Proof of principle TEst Rig, Fig. 2.1.2-1) set-up has been operated at SCK・CEN since November 2011. Results from the tests are promising: screening tests have identified ball bearings that have operated reliably for tens of thousands of operations under MYRRHA conditions, simulating years of active use. Follow-up tests are in progress that expand the working conditions, widen the material choice and provide even more realistic use scenarios of bearings in LBE. Solutions for cable management in rotary joints are under development, paving the way for reliable signal transmission to sensors on robot arms.

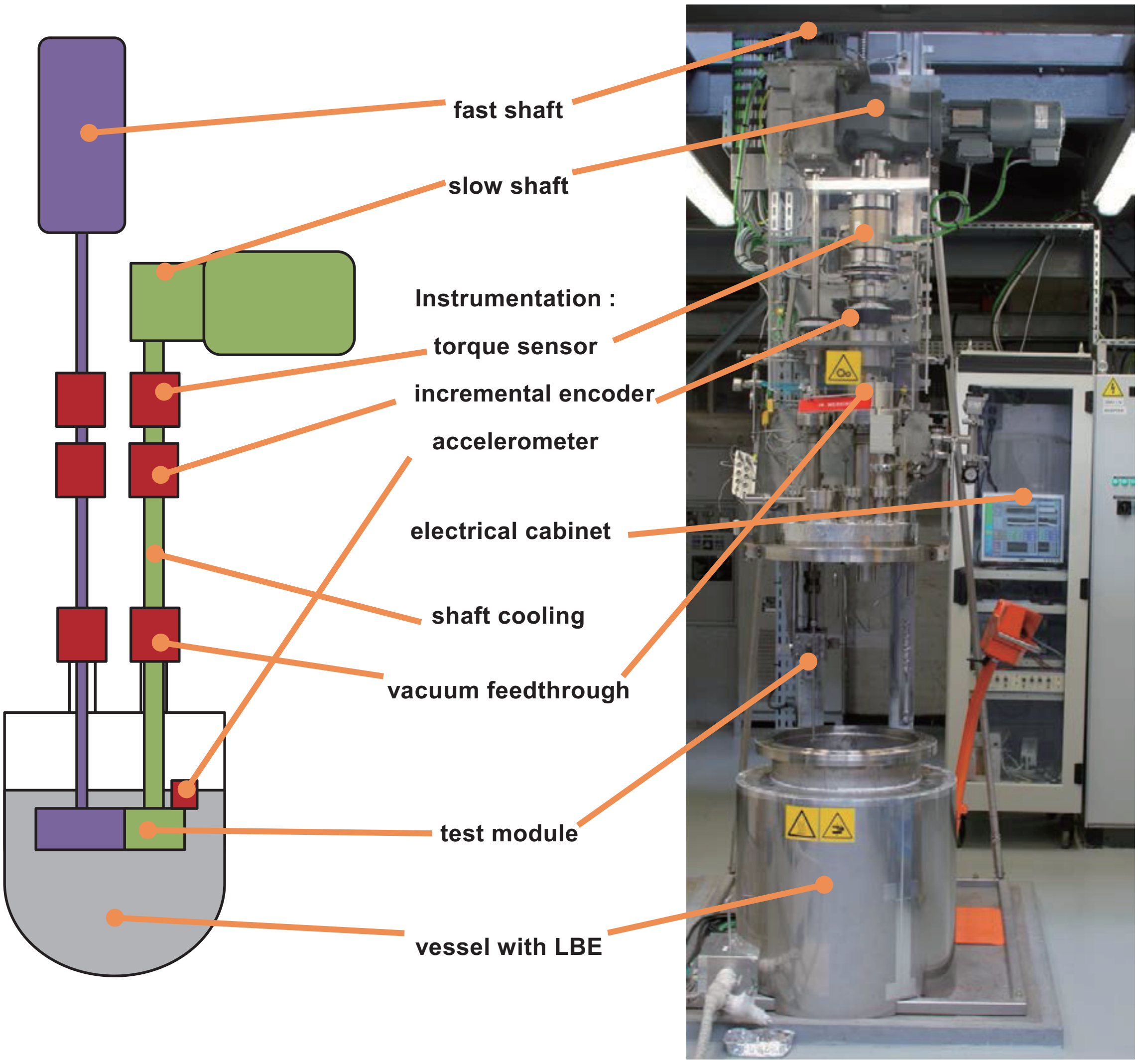

Fig. 2.1.2-1 RHAPTER layout (with, on the right, RHAPTER in open position)

The COMPLOT (COMPonents LOop Tests, Fig. 2.1.2-2) facility is a newly built and operated LBE loop facility at SCK・CEN, designed to characterise the hydraulic and hydrodynamic behaviour of various full-scale MYRRHA components in LBE. COMPLOT has vertical test sections representative of a single MYRRHA core position or in-pile section at full height. A first test campaign for a fuel assembly test section was successfully performed characterizing the pressure loss in the MYRRHA Fuel Assembly at different flowrates. Test sections for the control rod and fuel assembly vibration tests are being assembled. A dedicated experiment for testing innovative heat exchanger design is under preparation.

Fig. 2.1.2-2 COMPLOT Facility in the TCH hall at SCK・CEN

The E-SCAPE (European SCAled Pool Experiment, Figs. 2.1.2-3, 2.1.2-4) experimental facility, in the final phase of construction, consists of a thermal hydraulic 1/6-scale model of the MYRRHA reactor vessel and internals, with an electrical core simulator, cooled by LBE. It will provide experimental feedback to the designers and safety analysts on the forced and natural circulation flow patterns and temperature fields. Moreover, it enables to benchmark and validate the computational methods for their use with LBE.

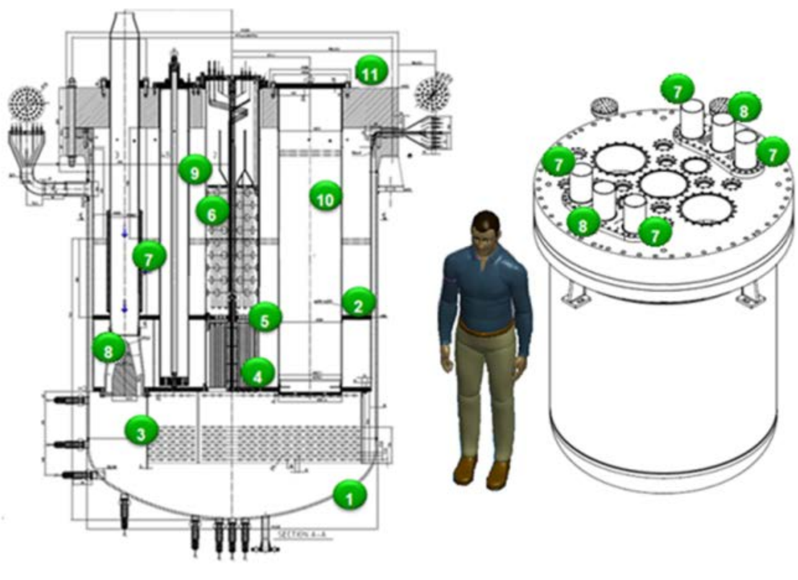

Fig. 2.1.2-3 E-SCAPE – Main vessel with internals

Fig. 2.1.2-4 E-SCAPE – Facility in the TCH hall at SCK・CEN

A one-of-a-kind pilot-scale LBE loop termed MEXICO (Mass EXchanger In Continuous Operation) has been constructed to study oxygen control. Solid lead oxide-based systems for the controlled addition of oxygen to LBE are now being evaluated in MEXICO. A new oxygen control system based on electrochemical oxygen pumping has also been developed. With this unique technology, oxygen in LBE can be controlled precisely in order to master corrosion inside the reactor.

A 220 kg LBE batch system termed HELIOS (HEavy Liquid metal Oxygen conditioning System) was constructed to investigate various gas-LBE interactions. This system was used to characterize and optimize LBE conditioning by gas bubbling or *via* the cover gas, and to investigate gas-LBE interactions relevant for safety studies (e.g. reaction of LBE with water vapor).

A laboratory was constructed and equipped to perform chemical experiments on heavy metals under safe conditions and experiments to study the evaporation and capture of fission products have been initiated.

A laboratory for ultrasonic imaging technique has been set-up. The opacity of the LBE coolant in MYRRHA necessitates the development of ultrasonic techniques. The effect of the fundamental acoustic properties on the performance of ultrasonic systems operating in water and various liquid metals has been studied in detail. An ultrasonic fuel identification system has been developed and validated thoroughly in water.

Neutronic codes have also been validated further based on the experimental data generated by the GUINEVERE facility (Fig. 2.1.2-5). In 2010, it was made critical for the first time and the first coupling with a particle accelerator was achieved in 2011. A full license for exploitation was obtained during 2013. The GUINEVERE-project is also being used to validate the methodology for sub-criticality monitoring. Currently, the FP7 FREYA is being executed and will run till 2016.

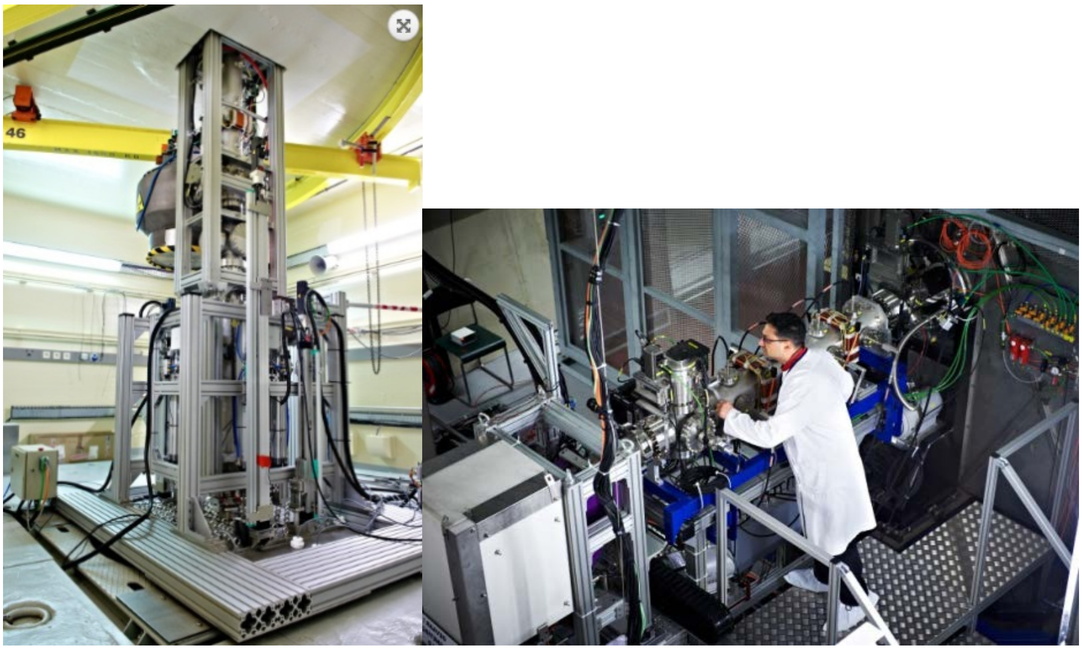

Fig. 2.1.2-5 The GUINEVERE facility with a subcritical assembly (left) and a 14 MeV accelerator (right)

2.1.3 R&D collaborations

Many collaborations have been initiated through several projects of the European framework programme gathering organisations specialised in the Heavy Liquid Metal research or in accelerator development. Table 2.1.3-1 gives an overview of the different European projects where SCK・CEN participated in the frame of P&T. These projects range over different domains such as coupling experiments, fuels for ADS, materials for ADS, design activities of ADS, thermohydraulics of ADS, transverse LFR activities, heavy liquid metal infrastructures, fuel cycle scenario studies and safety studies for ADS.

Table 2.1.3-1 Overview of the different European projects where SCK•CEN participated in the frame of P&T

TOPIC	FP5	FP6	FP7
Coupling	MUSE	DM2 ECATS	FREYA
Fuels	FUTURE	DM3 AFTRA	FAIRFUELS
Materials	MEGAPIE	DM4 DEMETRA	MATTER
	SPIRE, TECLA		GETMAT
Design	PDS-XADS	DM1 DESIGN	CDT
			MAX
	ADOPT	EUROTRANS	SILER
Thermal-Hydraulics	ASCHLIM		THINS
LFR	-	ESLY	LEADER
Infrastructures	-	VELLA, MTRI3	ADRIANA, SARGEN, NEWLANCER
Scenario Studies	-	PATEROS	ARCAS
Safety	-	-	SEARCH, SILER, MAXSIMA

In several of these projects, JAEA has participated as further detailed in the section on the collaboration between JAEA and SCK•CEN.

Collaborations have also been launched on the national level. For example, a new accelerator laboratory has been installed in the buildings of the Université Catholique de Louvain's Cyclotron Research Centre in Louvain-la-Neuve and already the ion source together with the Low Energy Beam Transport line have been realised. The research activities performed in the frame of DEMOCRITOS project in collaboration with von Karman Institute for Fluid Dynamics have led to new development of expertise and construction of new facilities: a 1/5 scaled water model of the MYRRHA reactor with all major internal components (core, heat-exchangers, primary pumps, in-vessel fuel storage, diaphragm) for experimental thermal-hydraulic simulation and studies named MYRRHABelle, another facility TAUPE for the characterisation of ultrasonic pulses in moving liquid at different temperature and the SHAKESPEARE facility for the study of sloshing. Collaborative research on MYRRHA R&D topics has been set up with different Belgian universities mainly through joint PhD work, using the specific expertise of each organisation.

Also, several bilateral collaborations have been set up around specific MYRRHA R&D topics with CNRS/IN2P3, ACS, CEA, IAP Frankfurt, KIT, RIAR-Dimitrowgrad, IUS_KTU, ENEA, INFN, NRG, CIEMAT, NUTRECK-SNU, VKI, UCL, KUL, UGhent, VUB, CERN, ...

2.1.4 R&D main achievements

The structural materials pre-selected for the construction of the MYRRHA reactor have been further studied under working conditions of the MYRRHA conditions. These studies allowed to confirm the pre-selected materials from the point of view of resistance to irradiation conditions combined with liquid metal exposure for all major components except for some rotating components where further R&D is needed. For the resistance to liquid metal corrosion there is still some long-exposure experiments needed.

Based on the present MYRRHA fuel pin and fuel assembly designs, a licensing approach and a preliminary fuel service envelope have been developed and discussed with the regulatory authority. A first batch of 500 MYRRHA fuel claddings has been produced in industrial conditions and delivered to SCK•CEN for further qualification in normal and transient conditions in test reactors in Belgium and abroad. Fuel performances codes needed for the fuel qualifications have been adapted to the MYRRHA specific coolant and conditions in normal and transient situations. Possible routes for fuel procurement have been identified, but in this respect we have to highlight that Japan possesses the only operational production facility for fast reactor MOX fuel.

The MYRRHA accelerator design and support R&D is conducted within the international consortium established since 1999 through EC FP5 and has been continued since then in this form with an enhanced effort within SCK•CEN since the government specific support to MYRRHA in 2010. The main R&D achievements for the accelerator consisted in designing and prototyping the individual components of the MYRRHA linac and individual testing in as representative MYRRHA conditions as possible. The main achieved results are: the construction and testing of the Electron Cyclotron Resonance (ECR) source (prototyped far beyond the MYRRHA specifications namely 20 mA instead of 4 mA), the design of the Low Energy Beam Transport line (LEBT), the partial prototyping of the RFQ needed for the injector of the MYRRHA linac, the prototyping of the Room Temp CH cavity and Supra-Conducting cavity (but with a frequency slightly different from the one chosen for the MYRRHA LINAC) and their testing in vertical cryogenic modules, the prototyping of a SPOKE cavity and testing in a vertical cryogenic module, the prototyping of a high β Supra-Conducting Nb Elliptic cavity and finally the design of a RF solid state amplifier.

Thanks to the large number of Lead-Bismuth facilities constructed at SCK•CEN the basic technology of this liquid metal (preparation, conditioning, chemistry control, impurities filtering, oxygen and temperature monitoring and control) are now mastered. The program of MYRRHA internals component qualification has started in particular for moving parts (such as bearing of in-vessel fuel handling machine) with promising results obtained, but large-scale tests have not been performed yet.

From end 2014, qualification at scale one-to-one in the COMPLOT facility of major components of the MYRRHA core such as the fuel assembly and the control rods has started. The design and construction of the E-SCAPE facility have been performed with commissioning foreseen beginning of 2016.

Based on the established overall control concept and its interfacing for the MYRRHA facility, the R&D, the qualification and validation of the individual specific sensors for MYRRHA coolant (UltraSonic (US) sensors for visualization under LBE and Oxygen-meters in LBE) or instrumentation and procedures for sub-criticality monitoring have been conducted. The main achieved results are development and qualification of US-sensors for MYRRHA conditions for identification of fuel assemblies under LBE, US-visualization in static condition, reliable oxygen-meters under MYRRHA conditions, sub-criticality monitoring in relative mode and absolute value measuring have been demonstrated and validated in the GUINEVERE facility. The execution of the different experimental programmes in the GUINEVERE facility, FFP7 FREYA (2013-2016) and H2020 MYRTE (2016-2018) generates a large database for ADS reactor physics.

The selected simulation and design codes used for MYRRHA design in terms of core neutronics and shielding, safety, thermal-hydraulics and severe accidents are in the process of verification and validation on existing benchmark experiments at SCK・CEN or from other sources such as the NEA data bank of the OECD. The codes Validation & Verification methodology has been discussed and agreed with the safety authority.

2.2 MYRRHA FEED design

The MYRRHA project was started in 1998 by SCK・CEN. Its design has been improved through regular international reviewing panels and during the various framework programs of the European Commission in the context of P&T. In 2011 the design entered the Front End Engineering Phase (FEED), covering the period 2011-2015.

2.2.1 Primary system

The main task to be executed internally within SCK・CEN is to produce the basic design of the primary system with all the peripherals that are directly linked to the system.

The scope of this work concerns the reactor vessel with all its internals, the external LBE-conditioning system, the cover gas and ventilations system, the pressure relief system, the primary heating system and the remote handling for the maintenance activities in the reactor hall.

The design activities started in 2009 as part of FP7 CDT, with the MYRRHA/XT-ADS-design (v1.0) serving as the starting point. During that period, the MYRRHA/XT-ADS concept, initially worked out within IP-EUROTRANS with collaboration of JAEA, was developed further to a more advanced engineering design level MYRRHA/FASTEF (v1.2), again with participation of JAEA as outlined further on. It should be noted that from the MYRRHA/FASTEF design onwards, the requirement for operation in sub-critical and critical modes was added. A staged design approach with regular design freezing points was thus introduced. This allowed the safety engineers to perform, in parallel, analysis on a coherent “frozen” design. The outcome of these analyses became the new input for the next revision. After MYRRHA/XT-ADS (v1.0) and MYRRHA/FASTEF (v1.2), a MYRRHA v1.4 was developed that was the basis for the Front-End Engineering Design.

After finalization of revision 1.4, several issues resulted in the need to redesign MYRRHA. These issues arose from the new safety requirements (FANC/AFCN's guidance on external hazards and severe accident management) and parallel research and development performed during the design phase. In parallel, detailed mechanical and thermo-mechanical calculations for primary system components were performed based on the rules of the RCC-MRx design code. Those calculations indicated unacceptable stresses in some components, which then needed to be lowered by design improvements. New solutions were developed in the period 2012 and 2013, and some problems were avoided by design changes, resulting in the current revision 1.6. The design options for this revision were finalized at the beginning of 2014. Revision 1.6 is therefore the first detailed coherent and consistent design of the primary system, as illustrated in Fig. 2.2.1-1. In this sense, the original objective for the primary system for the period 2010-2014 has been reached to a significant extent.

However, the current MYRRHA design, rev. 1.6, is, characterized by a diameter of about 10.4 m and a height of 13 m. These dimensions constitute a manufacturing and transportation challenges, and together with the volume of LBE required affect the cost of the facility.

In 2015, several options to reduce the size and to solve safety issues with regard to the single-wall heat exchanger concept were investigated. Three major have been identified that will be the focus of the following design activities:

- Innovative double-wall heat exchanger concept with increased heat conduction between the two walls
- Innovative In-Vessel Fuel Handling Machine with an additional joint
- Long-shaft mechanical pump

Close collaboration with industry and manufucturers is recommended for these items.

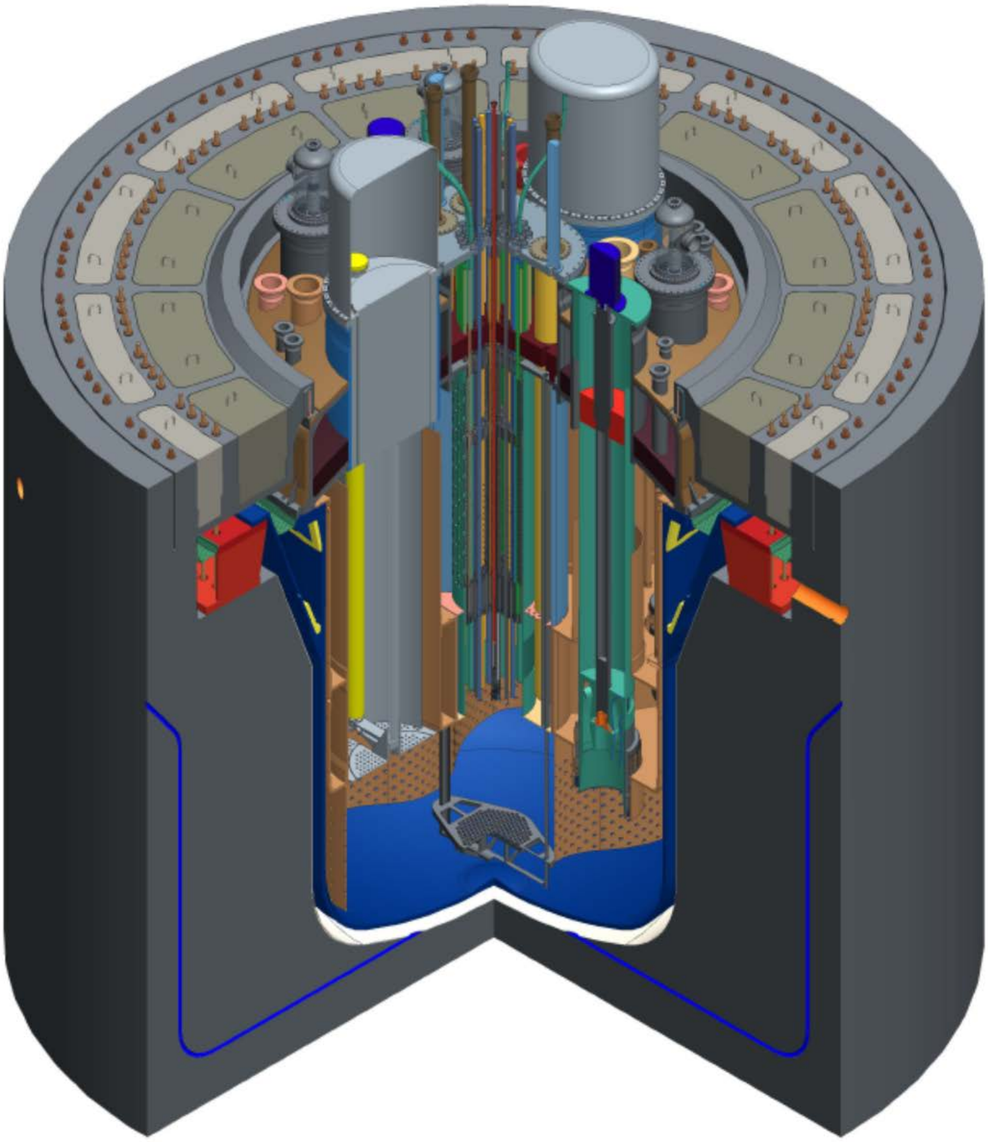

Fig. 2.2.1-1 MYRRHA design (rev. 1.6)

2.2.2 Accelerator design

The FP7-MAX project (2011–2014)[4] has delivered a consolidated design of the MYRRHA proton accelerator. It is consistently based upon the original philosophy that was adopted in order to allow for a significant increase of its reliability with respect to comparable existing machines:

- Superconducting LINAC
- Doubling of the injector (17 MeV)
- Conservative electric fields
- Fault tolerant beam optics and coherent associated architecture
- Accurate control of the delivered beam

The global accelerator may be subdivided in 3 sections. Each of them will be briefly introduced.

The injector

The MYRRHA injector line is designed to provide optimal acceleration efficiency, yet high reliability in a low energy CW context. The doubling of the whole 17 MeV injector provides a hot stand-by spare that is able to quickly resume beam operation in case of failure in the active one. The fault-recovery procedure is based on the use of a fast switching dipole magnet connecting the two injectors through a “double-branch” Medium Energy Beam Transport (MEBT) line. Each branch of the injector consists of the following elements:

- a 30 kV ECR proton source followed by its 2 meters long LEBT magnetic line featuring a beam chopper
- a 4 meters long 176.1 MHz 4-rod RFQ accelerating the beam to 1.5 MeV and operating with a conservative inter-vane voltage and a linear power dissipation density of 30 kW/m,
- a 15 meters long booster consisting of a matching section followed by several β-profiled multi-cell CH-type cavities with external quadrupole doublets

Following the recommendations of the mid-term International Design Review, the layout of the injector has been significantly upgraded during the final period of the MAX project.

The SC-LINAC

The MYRRHA main superconducting linac brings the beam from 17 MeV to its final energy of 600 MeV over about 240 meters. It is composed of a periodic array of independently powered superconducting cavities with moderate energy gain per cavity and regular focusing lattices. Three distinct cavity families are used to cover the full energy range: the first section (81 MeV) uses 352.2 MHz single spoke cavities, the second section (185 MeV) double spoke cavities at the same frequency, while the high energy section uses 704.4 MHz elliptical 5-cell cavities (β_{opt}=0.70). In these sections the fault tolerance capability is brought by serial redundancy, and therefore the linac is designed so as to increase as much as possible the tuning flexibility and to ensure a large beam acceptance. The present adopted strategy is to compensate for RF failures (cavities and their associated power and control systems) by using a local compensation scheme: the faulty cavity (respectively cryomodule) is compensated by acting on the RF gradient and the phase of the 4 nearest neighboring cavities (respectively cryomodules). Such a retuning scheme requires significant accelerating field overhead capacity throughout the 3 superconducting sections.

In the present design, this operational margin is evaluated to be about 30%.

It is foreseen to feed the entire linac with RF power making use of Solid State amplifiers.

The HEBT

A final High Energy Beam Transport (HEBT) line injects the proton beam onto the spallation target located inside the reactor. Through 3 bending magnets this line brings the beam up from the linac tunnel and then down through the reactor hall to the sub-critical core. It has achromatic and telescopic optics in order to guarantee the beam stability on target and to ease the tuning. AC magnets are installed in order to scan the beam on target with the specified shape. Beam commissioning will occur on a dedicated full power beam dump. The HEBT provides room for a fast beam kicker and associated beam extraction elements allowing to send a fraction of the main beam to the ISOL@MYRRHA facility, taking advantage of the regular 200 μs beam interruptions that serve the on-line subcriticality monitoring of the core.

Figure 2.2.2-1 shows a schematic view of the MYRRHA linac accompanied by a snapshot overview of some ongoing R&D activities with regard to the different linac components.

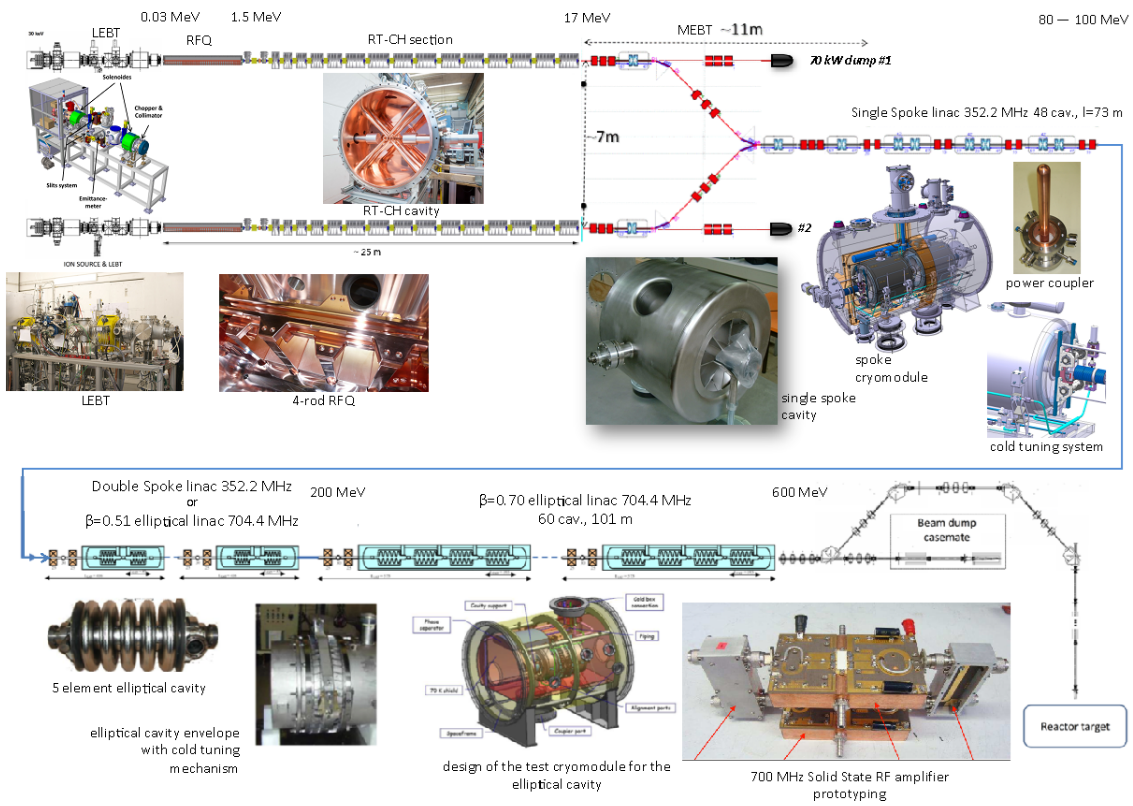

Fig. 2.2.2-1 Schematic view of the MYRRHA linac and R&D activities for components

2.2.3 Balance of plant

Balance of Plant activities were initiated by SCK•CEN and then elaborated further within the CDT project by industrial partners. This preparatory work served as an input to the work performed by the FEED contract from 2013 onwards. The contract was awarded to a consortium of AREVA TA, Ansaldo Nucleare and Empressarios Agruppados with Grontmij as subcontractor. The FEED-contract deals with all the peripheral systems outside of the primary system and the buildings and its supporting systems and utilities.

Secondary and tertiary systems

The design has stabilized to be a system capable of:

- Removing reactor heat through four independent loops, constituting a strong line of defense
- Removing decay heat in a passive manner, with quadruple redundancy
- Integrated water volumetric control
- Providing heat to the primary system to avoid freezing

Each loop consists of a primary heat exchanger, a steam separator, an aero-condenser and a volumetric water control system. A number of peripheral sub-systems complete each loop. The secondary and tertiary system has been conceived to offer the potential for heat recovery in case this might become an economic opportunity.

Buildings

The “buildings design” of the MYRRHA project consists of four disciplines that interact closely with each other:

- Master plan
- Architecture
- Civil engineering
- Building equipment

To give an indication of the extent to which buildings design is crucial, it is sufficient to mention that cost estimates indicate buildings design amounts to more than 1/3 of the total cost.

The FEED-contract was suspended at the end of 2014 to allow to identify reactor design options to cope with unforeseen R&D results and the size increase of primary system version 1.6. The FEED Engineer wrote the functional specifications of all high priority systems. For the systems that are not impacted by the exercise of reactor design options, technical specifications were written by the FEED-Engineer. In 2015, the FEED-Engineer also provided dedicated support to the reactor options exercise.

2.3 MYRRHA licensing

2.3.1 Framework

Following the decision of the Council of Ministers of the Belgian Federal Government in March 2010 regarding the support for realizing the MYRRHA project, one of the three main tasks to be performed was to secure the licensing by preparing all legal requirements for the regulator, the Federal Agency for Nuclear Control (FANC/AFCN). At this stage, the emphasis has been set on the safety aspects but also Environmental Impact Assessment (EIA), security and safeguards, as well as decommissioning are being considered.

It appeared desirable for the regulatory authority (FANC/AFCN) to organize and implement a pre-licensing phase in order to communicate from an early stage and in a timely manner during project development, its expectations in terms of nuclear safety, security and safeguards. BEL V as the technical support organization is directly involved in the process starting beginning of 2011.

Demonstration should be provided, to the extent necessary for this phase that the design options and provisions under development are in line with regulatory expectations. At the end of the pre - licensing phase, the regulator should be in a position to issue a first evaluation report on the licensability of the MYRRHA project.

Towards the latter drafting of a Preliminary Safety Assessment Report (PSAR) during the licensing phase itself, two main tools have been implemented in the pre-licensing phase: the definition and evaluation of "focus points", issues specific to the innovative character of the MYRRHA project, potentially affecting the safety of the installation, and the Design Options and Provisions File (DOPF) demonstrating how adequate provisions have been made at each level of "defence in depth", a safety concept applied to provide enveloped protection against various transients resulting from equipment failure, human errors, internal or external events and hazards.

2.3.2 Progress and achievements

The first 2 years (2011/2012) have been mainly devoted for the owner:

- To the drafting of the technical description of the primary system, and
- To the definition of a safety approach to be implemented,

for the regulator:

- To the drafting of a strategic note covering the safety aspects as well as the security requirements and safeguards obligations applicable to MYRRHA (design, operation), and
- To the elaboration of a guidance document for the format and content of the DOPF.

The process of identifying Focus Points (FPs) has been initiated and the first corresponding FP's sheets have been drafted and discussed. The results of several safety studies, carried out for a large part in the framework of EC FP6 and FP7 projects, could be shared with BEL V representatives (e.g. CDT/SARGEN IV projects).

In 2013-2014, the owner developed further the 2 first volumes of the DOPF (technical description, safety approach) and finalized the MYRRHA project note, a first report requested in the frame of the EIA, to be approved jointly by a working group composed of the Federal regulatory body and a dedicated division of the regional government. From the regulator side, we can mention the finalization of the safety strategy and associated guidelines (airplane crash, seismic, flooding, safety requirements).

Considerable efforts were devoted to the discussion and drafting of the last FP sheets so that all of them (35) could be approved and issued by the end of 2013. At this stage (end 2015), about 50 deliverables on 160 have been issued of which some 35 are still the subject of Q&A.

3. Outline of R&D activities in JAEA

3.1 Partitioning

Separation process for MAs (Am and Cm) has been developed at JAEA using new innovative extractants to improve the partitioning process from the viewpoints of the economy and the reduction of secondary wastes. The MA separation process consists of three solvent extraction steps (Fig. 3.1-1). Phosphorus-free compounds consisting of carbon, hydrogen, oxygen and nitrogen (CHON principle) were applied to the all separation steps.

At the first step, MA and Rare Earth elements (RE) are recovered together from HLLW by solvent extraction process using *N,N,N',N'*-tetradodecyldiglycolamide (TDdDGA) (Fig. 3.1-2). The performance of the process was verified by continuous extraction test using simulated HLLW containing MA tracers. The MAs were recovered over 99.99% from simulated HLLW. The MAs, Am and Cm, are separated from RE at the second step by solvent extraction using new hybrid type extractant such as *N, N, N', N', N", N"*-hexaoctylnitrilotriacetamide (HONTA) or podand type soft-donor extractant such as *N,N,N',N'*-tetrakis(pyridin-2-ylmethyl)- decane-1,2-diamine (TPDN) (Fig. 3.1-2). The potential of separation performance of the separation process using HONTA has been verified with continuous extraction test using MA tracers. At the last separation step, Am are separated from Cm by the new hybrid type extractant. The extractant has high separation performance between Am and Cm. The separation factor between Am and Cm is 5.5 with no complexing agent in aqueous phase.

The hot test using genuine HLLW for principle demonstration of the MA separation process started in FY2015.

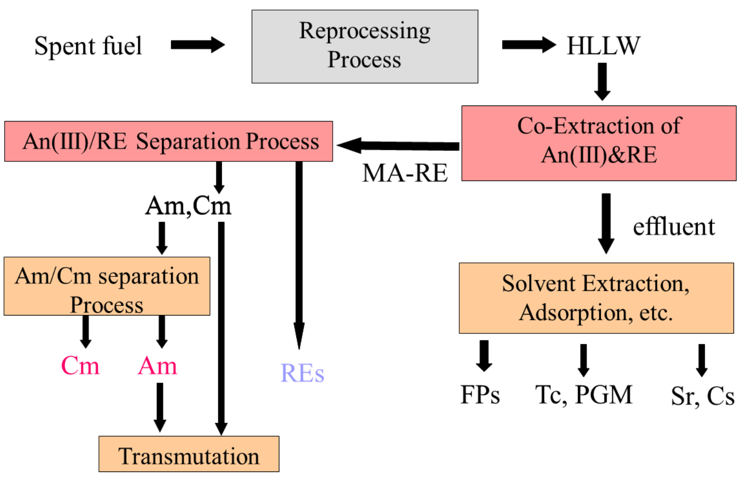

Fig. 3.1-1 Block flow of MA separation process

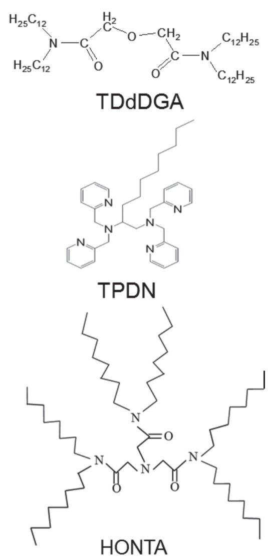

Fig. 3.1-2 Extractants for MA separation

3.2 Transmutation system

3.2.1 R&D for ADS

JAEA's reference design of the industrial ADS is a tank-type subcritical reactor, where LBE is used as both the primary coolant and the spallation target as shown in Fig. 3.2.1-1.

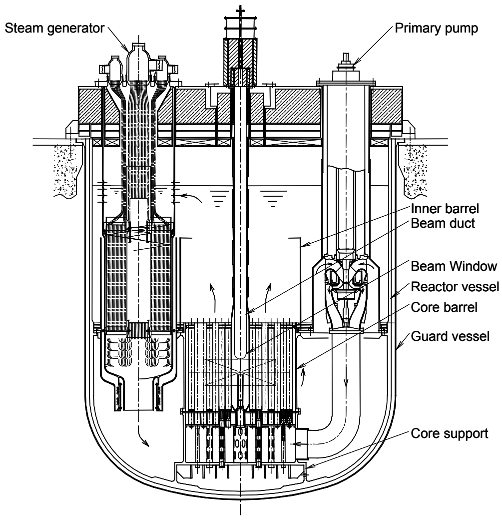

Fig. 3.2.1-1 LBE-cooled 800 MWth ADS for transmutation of MA proposed by JAEA

For ADS to play important roles in the nuclear fuel cycle, several critical issues have to be resolved. Items of R&D are divided into three technical areas peculiar to the ADS: (1) superconducting linear accelerator (SC-LINAC), (2) LBE as spallation target and core coolant, and (3) subcritical core design and technology. For these technical areas, various R&D activities are progressing in JAEA as described below.

(1) R&D on SC-LINAC

The proton accelerator for the industrial ADS should have high energy of 1.5 GeV and high intensity of power of 30 MW, with good conversion efficiency from electricity to proton with high reliability to assure the self-sustainability for electricity of the whole system. Taking account of these requirements, SC- LINAC is regarded as the most promising choice. The SC-LINAC consists of a series of cryomodules, which contain two units of superconducting cavities made of high-purity niobium. JAEA fabricated a prototype high beta elliptical cryomodule to test the performance of the electric field and the helium cooling. In addition to the development of the cryomodule, the system study of the SC-LINAC with high conversion efficiency was also performed.

(2) R&D on LBE as spallation target and core coolant

The beam window, which forms a boundary between the vacuum proton beam tube and the subcritical core, is one of the most important technical issues in the engineering feasibility of ADS in terms of thermal-hydraulic and structural design. The beam window will be used in the severe conditions; (a) external pressure by LBE, (b) heat generation by the proton beam, (c) creep deformation by high temperature, (d) corrosion by LBE and (e) irradiation damage by neutrons and protons. The engineering feasibilities of the beam window were shown assuming unirradiated condition. The irradiation effect must be estimated by the proton irradiation test.

While LBE is regarded as the prime candidate for the spallation target and the core coolant of the ADS, the technology to use LBE in the nuclear system is not well-established. Some small test loops using LBE were built in JAEA to investigate the corrosion of structural material and the thermal-hydraulics characteristics.

(3) R&D on subcritical core design and technology

Neutronic design is important issue for R&D of ADS. In the reactor physics characteristics of ADS, the multiplication factor (k_{eff}) that is usually limited below 0.97 is a significant parameter. A design study was performed to reduce the variation of k_{eff} during operation (reactivity swing) that deteriorates other design parameters such as power peaking factor and maximum proton beam current. In addition to the optimization of fuel components, an adjustment mechanism of k_{eff} (control rods or neutron absorber) is being developed.

The calculation accuracy for k_{eff} is also important in neutronic design of ADS. Among various sources of uncertainty, one in nuclear data is considered to have a significant impact. The uncertainty from nuclear data was evaluated based on covariance data in JENDL-4.0, and specified were nuclides and reactions needed to be verified. Experiments to verify inelastic scattering cross section of lead among them were and will be performed.

As basic safety analysis for ADS, investigations for abnormal events and safety analysis were performed from a view point of the possibility of Core Disruptive Accident (CDA). The investigation for abnormal events was carried out by Level 1 Probabilistic Safety Assessment (PSA). The safety analysis was performed by the transient analysis code SIMMER-III.

3.2.2 TEF project

As shown in Fig. 3.2.2-1, TEF consists of two individual buildings: ADS Target Test Facility (TEF-T)[5] and Transmutation Physics Experimental Facility (TEF-P)[6]. Two buildings are connected by beam transport line with a low power beam extraction mechanism using a laser beam to extract 10 W beam for TEF-P. TEF-T is planned as a material irradiation facility which can accept a maximum 400 MeV-250 kW proton beam on a LBE spallation target. It also has a possibility to be used for various basic research purposes. TEF-P is a facility with critical/subcritical assembly to study neutronic performances and controllability of ADS.

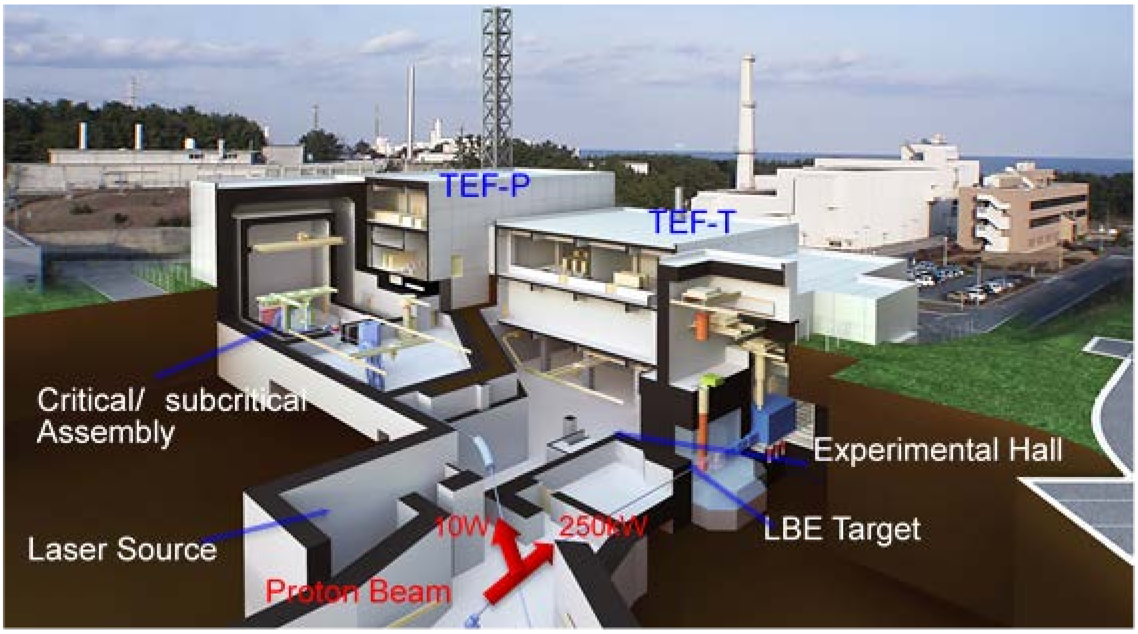

Fig. 3.2.2-1 Transmutation Experimental Facility

3.2.2.1 Outline of TEF-T

The main purpose of TEF-T is to obtain the data to evaluate the actual lifetime of beam window. The facility mainly consists of a spallation target, a LBE cooling circuit, and hot cells to handle the spent target and irradiation samples.

A high power spallation target, which will be used for irradiation of structural materials for future ADS, is an essential component to realize TEF-T. To set up the beam parameters, future ADS concepts are taken into account. The target has an annular structure which contains a specific area to install the irradiation samples in flowing LBE environment. Both operation temperature and temperature gradient can be varied according to the requirement for the preparation of irradiation database for future ADS design. The oxygen concentration in flowing LBE will be added as a parameter of irradiation database.

To evaluate a feasibility of a designed beam window of TEF target, numerical analysis was performed. In the analysis following items were considered: a current density and shape of the incident proton beam, and, flow rate and inlet temperature of LBE. The structural strength of the beam window was also determined to evaluate a soundness of the target. The prototype design of the beam window for TEF target system is shown in Fig. 3.2.2-2[7].

An irradiation sample holder, which is installed in the inner tube, holds eight irradiation specimens in the horizontal direction. The size of each specimen is 40×145×2 mm. The rectification lattice having the aperture of the plural squares type is installed at the front-end of the sample holder. A slit of 2 mm in width is arranged along the side of the rectification lattice to cool off the sample holder by flowing LBE. The irradiation performance of the reference case was evaluated as around 8 DPA/yr by 400 MeV-250 kW proton irradiation. This value is about 20% of DPA considered in the beam window of JAEA-ADS.

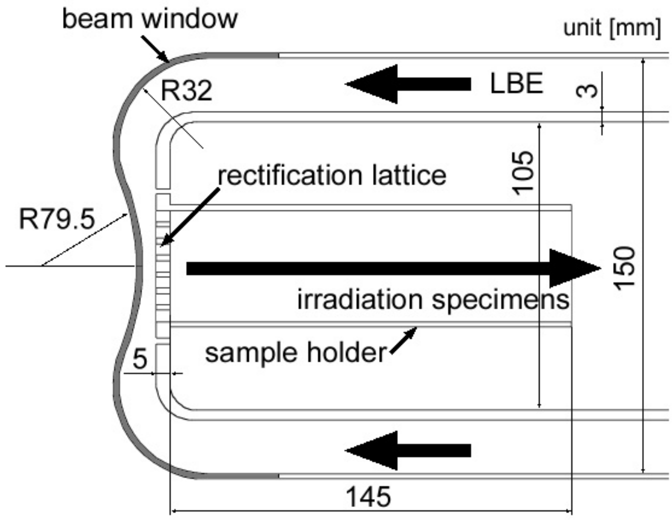

Fig. 3.2.2-2 Prototype LBE spallation target for TEF-T

3.2.2.2 Outline of TEF-P

Although several neutronic experiments for ADS have been performed worldwide, there has been no subcritical experiments combined with a spallation source installed inside the subcritical fast-neutron core that contains certain amount of MA. The purposes to build TEF-P are (1) study on reactor physics aspects of the subcritical core driven by a spallation source, (2) demonstration of the controllability of the subcritical core including a power control by the proton beam power adjustment, and (3) investigation of the transmutation performance of the subcritical core using certain amount of MA and Long-Lived Fission Products (LLFP).

TEF-P is designed with referring to the Fast Critical Assembly (FCA), the horizontal table-split type critical assembly with a rectangular lattice matrix, to utilize operation experiences and existing experimental data of FCA. In this concept, the plate-type fuel for FCA with various simulation materials such as lead and sodium for coolant, tungsten for solid target, ZrH_x for moderator, B_4C for absorber, and AlN simulating nitride fuel, can be commonly used at TEF-P. The proton beam will be introduced horizontally at the center of the assembly and various kinds of spallation targets can be installed at various axial positions at the radial center of the subcritical core. In the experiment with a 10 W proton beam, the effective multiplication factor of the assembly will be kept less than 0.98. From the viewpoint of the accuracy of neutronic analyses for subcritical systems, it is desirable to make the core critical in order to ensure the quality of experimental data of the subcriticality and the reactivity worth. So, the subcritical core can be critical when the proton beam is suppressed.

One of the main purposes of TEF-P is to perform integral experiments using MA because the present accuracy of nuclear data is not sufficient for ADS design[8]. To improve the accuracy of the nuclear data especially for MA, both the differential experiments and the integral experiments are necessary, while the integral experiments on MA are more difficult than those on the major actinides. The effectiveness of MA-loaded experiments with a certain amount of MA was discussed[9]. By using a certain amount of MA, which is an order of kg, effective improvement can be obtained.

3.3 Fuel cycle for transmutation system

3.3.1 MA-bearing fuel

3.3.1.1 Fuel design

In JAEA, the MA-bearing nitride fuel in conjunction with the pyrochemical reprocessing is considered as the prior concept for MA recycling with the ADS. MAs and Pu nitrides are diluted with an inert matrix of ZrN, which forms single phase solid solution, (MA, Pu, Zr)N. The ZrN content approximately varies from 60 to 80 mol% depending on the core position.

3.3.1.2 Fabrication technique

Schematic diagram of the nitride fuel pellet fabrication process is shown in Fig. 3.3.1-1. There are two routes for the synthesis of (MA, Pu)N. One is the carbothermic nitridation of (MA+Pu) oxides. The oxide mixture blended with a certain amount of carbon powder is pelletized and heat treated at 1300 °C under a nitrogen gas flow for nitridation, followed by a heat treatment at 1500 °C under N_2+H_2 mixed gas flow. Formation of a (Np, Pu, Am, Cm)N solid solution from the oxide mixture by this technique was demonstrated[10-12]. This method is applied for MAs separated from HLLW of commercial fuel reprocessing.

The other route is nitridation of Pu and MAs recovered in Cd cathode by the pyrochemical reprocessing of the spent nitride fuel. Cd is distilled under a nitrogen atmosphere and the powder of (MA, Pu)N remained as the nitride product. Formation of PuN and AmN from Cd-Pu and Cd-Am system was demonstrated, respectively[13,14].

The (MA, Pu)N powder obtained by both the route is blended with the highly-pure ZrN, fabricated from reactor-grade Zr metal through the hydride. The mixture is pelletized and heat treated at ~ 1600 °C for solid solution formation, (MA, Pu, Zr)N. The solid solution is grounded to fine powder and pelletized again for sintering. Sintering is performed at ~1650 °C under the nitrogen gas flow to achieve 85~90 % of theoretical density. Small pellets and disk specimens with numerous compositions were fabricated for thermal properties measurements[15,16].

The solid solubility of lanthanide and actinide nitrides into ZrN matrix was experimentally evaluated. The solid solubility curves were determined as a function of the Relative Lattice Parameter Difference (RLPD) of solute to the solvent ZrN[17]. Single-phase solid solution formalism with ZrN for various MA compositions can be now simulated using lattice parameter of each component.

3.3.1.3 Material properties

Essential thermal properties of MA nitrides and (MA, Pu, Zr)N have been measured in this decade, and a material properties database has been constructed[18]. The lattice thermal expansion of NpN, PuN, AmN, CmN and their solid solutions including ZrN was measured by high-temperature X-ray diffraction method[19,20]. The thermal expansion coefficients of the nitride solid solutions can be approximated by a linear mixing rule.

Specific heat and thermal diffusivity were also measured by drop calorimetry and laser flash method, respectively, to evaluate thermal conductivity. Because of the electrical conduction of the nitrides, the thermal conductivity of (MA, Pu, Zr)N increases with temperature, and it is much higher than that of actinide dioxides. Thermal conductivity of (Pu, Am)N–ZrN system was organized as a function of ZrN content[15] as shown in Fig. 3.3.1-2.

Measuring of some mechanical properties of nitrides pellets (elasticity, hardness, thermal creep, etc.) has just been begun using simulated nitride fuel pellets (lanthanide nitrides and ZrN) to understand the interaction with cladding material under irradiation.

3.3.1.4 Irradiation test and fuel behavior analysis code

Irradiation test of Am-bearing nitride fuel pellets with a small-pin scale in JOYO is under planning to understand the irradiation behavior. Development of a fuel behavior analysis code for ADS nitride fuel is also ongoing based on the FEMAXI-7 code. The material properties and phenomenon models for nitride are to be included in the code step by step.

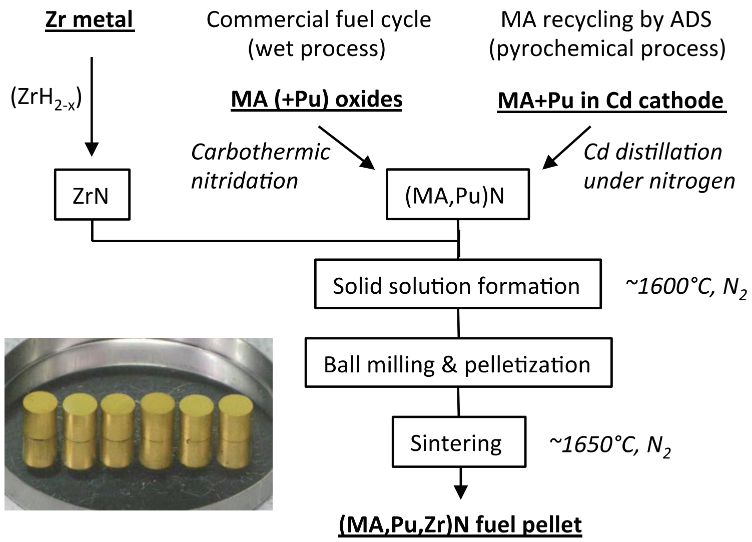

Fig. 3.3.1-1 Schematic diagram of the (MA, Pu, Zr)N fuel pellet fabrication

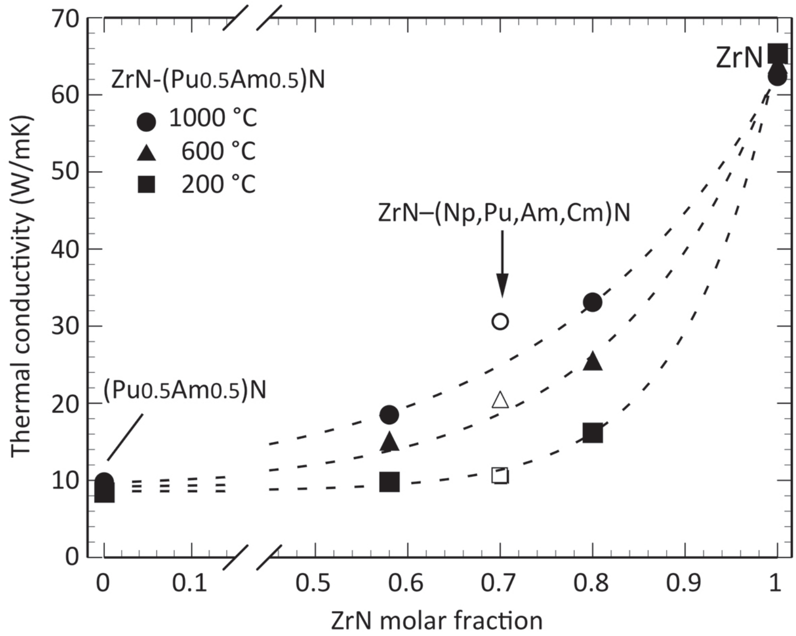

Fig. 3.3.1-2 Thermal conductivity of (MA, Pu, Zr)N as a function of ZrN molar fraction

3.3.2 Reprocessing

A typical weight ratio of the spent nitride fuel is MA:Pu:Zr:RE:U:Platinum group metal (PGM) = 0.21:0.21:0.49:0.03:0.02:0.01; other Fission Products (FPs) such as alkali metals and iodine also will exist in the spent fuel. We have developed a basic concept of the main process for pyrochemical reprocessing of spent nitride fuels based on the pyrochemical processing of metal fuels. The proposed pyrochemical process includes the molten salt electrorefining of spent nitride fuels (Fig. 3.3.2-1) and renitridation of actinides recovered in Cd cathode. A process flow diagram with a mass balance calculation of the process has been reported[21].

3.3.2.1 Molten salt electrorefining of the nitrides

Basic studies on the dissolution behavior of pure actinide nitrides have been carried out. The potential of the actinide nitrides (vs Cl_2/Cl^-) derived from ElectroMotive Force (EMF) values of the cell (AnN | $(LiCl\text{-}KCl)_{eut.}\text{-}AnCl_3$ | $(LiCl\text{-}KCl)_{eut.}\text{-}AgCl$ | Ag) (An=U, Np, Pu, Am) at 773 K[22] shows similar values (-1.94 ~ -2.2 V (vs Cl_2/Cl^-)). These potentials of the actinide nitrides correspond to the equilibrium between AnN and An^{3+} in the molten salt phase expressed with

$$AnN=An^{3+}+3e^-+1/2N_2.$$

Their dissolution potentials measured by voltammetry also shows similar values, as expected from their rest potential.

The dissolution of ZrN, which is used as an inert matrix of the fuels, can occur at anode potentials higher than -1.0 V (vs Cl_2/Cl^-). The difference of the dissolution potential of ZrN and those of AnN is about 1 V. The dissolution potentials of (An, Zr)N (An=U or Pu) solid solution shifted to positive direction with increasing ZrN contents. We need to clarify the dissolution behavior of the solid solution of AnN and ZrN more in detail[22].

The formal standard potentials, $E^{0'}(An^{3+}/An)$ (vs Cl_2/Cl^-) measured with Cd electrodes in $(LiCl\text{-}KCl)_{eut.}\text{-}AnCl_3$ at 773 K indicate similar values for the actinides (An=U, Np, Pu, Am)[22]. This fact supports that all the actinides can be recovered into cadmium cathode simultaneously.

Lanthanides will accompany the actinides in the electrorefining process as reported for Nd[23]. The contents of lanthanides into recovered actinides should be minimized because some of the isotopes of lanthanides absorb neutrons when transmutations are carried out. To lower the contents of lanthanides in the recovered actinides, removal of lanthanides from the molten salt bath by the multi-stage counter current reductive extraction between molten salt phase and liquid Cd phase is proposed[21].

3.3.2.2 Renitridation of actinides recovered in Cd

The actinides recovered in the liquid Cd cathode by the electrorefining process are converted to nitrides to be used as recycled fuels. The nitridation-distillation combined process, in which the Cd alloys containing actinides are heated in nitrogen gas flow, has been developed. Nitridation of actinides and the distillation of Cd have been reported to occur simultaneously by heating alloys typically at 973 K for Pu-Cd, Pu-U-Cd, and Am-Cd systems. Behavior of Zr and FP elements in this process should be studied for development of the reprocessing of the nitride fuels for ADS[22].

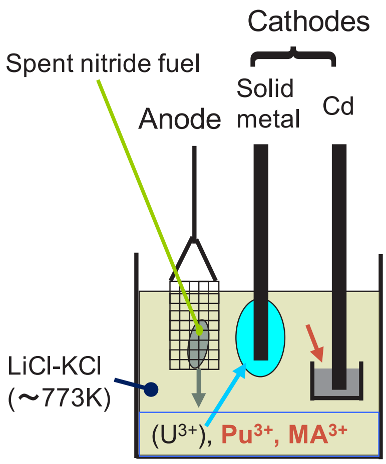

Fig. 3.3.2-1 Schematic diagram of the molten salt electrorefining set up for spent nitride fuels

4. Past collaborative studies

Given the mutual interest of SCK・CEN and JAEA for P&T, a long standing relation and collaboration exists between both institutes. This has been put into practice through multilateral collaborations in European Framework Programs and bilateral collaborations.

4.1 Multilateral collaboration through FP6 EUROTRANS project

The Integrated Project EURopean Research Programme for the TRANSmutation of High Level Nuclear Waste in an Accelerator Driven System (EUROTRANS) was conducted within the EURopean ATOMic Energy Community (EURATOM) 6th European Commission Framework Programme (FP6) to the study of transmutation of high-level waste from nuclear power plants. The work is focused on transmutation by ADS.

The R&D work and the innovation effort to be performed within EUROTRANS were integrated into five technical DoMains (DMs).

<u>DM1: DESIGN</u> (Development of a detailed design of XT-ADS and a conceptual design of EFIT with heavy liquid metal cooling)

The objective of this Domain was to proceed by a significant jump towards the demonstration of the industrial transmutation through the ADS route. This was carried out with two interconnected activities. The first activity was to carry out a detailed design leading to a short-term eXperimental facility (realization in a short-term) demonstrating the technical feasibility of Transmutation in an Accelerator Driven System (XT-ADS). The MYRRHA/XT-ADS design was based on the MYRRHA Draft 2 design File. The total power level of the MYRRHA/XT-ADS ranged between 50 and 100 MWth. This facility was intended to be as much as possible a test bench for the main components and for the operation scheme of the European Facility for Industrial Transmutation (EFIT).

<u>DM2: ECATS</u> (Experimental activities on the Coupling of an Accelerator, a spallation Target and a Sub-critical blanket)

With a view to assisting the design of MYRRHA/XT-ADS and EFIT, DM2 ECATS provided validated input from relevant experiments at sufficient power (0-20 kW) on the coupling of an accelerator, a spallation target and a sub-critical blanket.

<u>DM3: AFTRA</u> (Advanced Fuels for TRAnsmutation Systems)

The main objective of this Domain was the design, the development, the characterisation and the qualification in representative conditions of the most promising U-free fuel concept, and to give recommendations about fuel design and performance for the EFIT. The U-free oxide fuel concept was considered in Europe as the reference candidate. The U-free nitride fuel concept was considered as a backup solution and is investigated with a limited effort in EUROTRANS.

<u>DM4: DEMETRA</u> (DEvelopment and assessment of structural materials and heavy liquid MEtal technologies for TRAnsmutation systems)

The objectives of DM4 were the development and assessment of heavy liquid metal technologies, materials characterisation in design relevant conditions, and the thermal-hydraulic experiments to support the design of the spallation target and the sub-critical blanket.

<u>DM5: NUDATRA</u> (NUclear DAta for TRAnsmutation)

The objective was the improvement of the simulation tools for ADS core, shielding and fuel cycle design, essentially through the improvement of the evaluated nuclear data libraries and reaction models for materials in transmutation fuels, coolants, spallation targets, internal structures and reactor and accelerator shielding, relevant in particular for the MYRRHA/XT-ADS and the EFIT designs.

The contributions of SCK・CEN to each domain were as follows.

<u>DM1 DESIGN</u>

- ✓ SCK・CEN has been the general coordinator of this domain, with large contributions in neutronics and safety calculations. The development of the mechanical part of the XT-ADS has been largely based on the existing so-called “MYRRHA Draft-2” design, made available by SCK・CEN in the beginning of the project.

<u>DM2 ECATS</u>

- ✓ Conception, implementation and realization of the GUINEVERE facility as refurbishment of the existing VENUS facility.

<u>DM3 AFTRA</u>

- ✓ Contributions for the fuel pin and fuel assembly design of the EFIT concept.

<u>DM4 DEMETRA</u>

- ✓ Material procurement for the samples to be tested.
- ✓ Design, realization and post-irradiation examination of ASTIR experiments, installed in the BR2 reactor.
- ✓ Contributions to the thermal hydraulics task.

<u>DM5 NUDATRA</u>

- ✓ SCK・CEN was not involved in this domain.

The contributions of JAEA to each domain were as follows.

<u>DM1: DESIGN</u>

- ✓ JAEA presented the design activities on 800 MWth LBE cooled ADS for transmutation, and compared it with EFIT.

- ✓ Though the ADS design study under way, the design was discussed in terms of neutronic, thermal-hydraulics, structural mechanics, accelerator system, beam window, and safety.
- ✓ Information on the beam commissioning of LINAC in Japan Proton Accelerator Research Complex (J-PARC) and the development of superconducting proton LINAC were presented.

<u>DM2: ECATS</u>

- ✓ JAEA proposed to build the TEF under a framework of the J-PARC project.
- ✓ JAEA proposed the roadmap to realize ADS for the transmutation and to define the necessary experimental facilities on the roadmap, where the contribution of the expected outcomes by TEF to XT-ADS which is in reality the MYRRHA project presently and EFIT was discussed.
- ✓ The necessity and the possibility of integral experiments using MA fuel were investigated, aiming at the contribution of the facility to the transmutation technology by both ADS and FBR.

<u>DM3: AFTRA</u>

- ✓ JAEA mainly studied dedicated nitride fuel such as (MA, Pu)N+ZrN. JAEA presented the pre-design of nitride-fueled ADS to compare it with oxide one.
- ✓ Modeling study of MA fuel was made with focusing on the behavior of He produced mainly by the alpha decay of MA.
- ✓ Results of irradiation behavior of TRans-Uranium (TRU) nitride fuel carried out in JAEA have been reviewed, in order to facilitate the irradiation of MA nitride fuel pins in the FUTURIX-FTA program.
- ✓ Information on property measurements for MA nitrides and TRU oxides, and experimental data for pyrochemical process of nitride fuel were presented.

<u>DM4: DEMETRA</u>

- ✓ Static and loop corrosion test for the Si-added steels in LBE were carried out in order to compare with corrosion behavior of Al-coated steels prepared by European countries.
- ✓ Thermodynamic data obtained by equilibrium evaporation experiments for LBE, Po-210, etc. were summarized.
- ✓ Post-irradiation tests for specimens irradiated at the Swiss Spallation Neutron Source (SINQ) were performed.
- ✓ The thermal-hydraulic loop test with LBE was carried out to investigate the details of the frequency of temperature fluctuation around the beam window model flow.
- ✓ Flow velocity measurement technique for LBE by Ultrasonic Doppler Method (UDM) was developed.
- ✓ JAEA performed the benchmark calculations based on the thermal-hydraulic test

results obtained by KArlsruhe Lead LAboratory (KALLA) at Forschungszentrum Karlsruhe (FZK now KIT: Karlsruhe Institute of Technology).

DM5: NUDATRA

- ✓ JAEA suggested the importance of MA-loaded experiments to improve the uncertainty caused by the nuclear data based on the uncertainty evaluation of reactor physics parameters of ADS. The recommendations to improve the nuclear data were also presented.
- ✓ JAEA presented the latest measured cross sections of MA and LLFP, and the experimental techniques developed for the measurement for higher energy neutrons.
- ✓ The latest evaluation of nuclear data and covariance data of MA and FP nuclides and high-energy region were also reported.

At the time of EUROTRANS, there was not yet a direct collaboration between SCK・CEN and JAEA, but the EUROTRANS project allowed to prepare for an intensified bilateral collaboration between both institutes for the future.

4.2 Multilateral collaboration through FP7 MYRRHA Central Design Team

The FP7 Central Design team (CDT) was a dedicated FP project to progress the design of the XT-ADS version of the MYRRHA design. The CDT-project was coordinated by SCK・CEN with the participation in total of 20 European institutes and NUTRECK from South-Korea and JAEA from Japan. Two engineering researchers were dispatched from JAEA to SCK・CEN in 2008 and 2010 for a year for each. They joined to the MYRRHA team or the CDT established in a framework of the second FP7 as specialists of neutronic calculation.

The first researcher from the research group for nuclear transmutation system in JAEA updated the MYRRHA core parameters aiming at high neutron flux as the fast spectrum irradiation facility. The starting point was XT-ADS core that had been designed in EUROTRANS, whose neutron flux with energy above 0.75 MeV was about 7×10^{14} cm^{-2} sec^{-1} in the region of the hottest fuel rod. The purpose of this update was to achieve the neutron flux of 1×10^{15} cm^{-2} sec^{-1}.

The first step of the update was a multi-parametric neutronic analysis in terms of the number of fuel assemblies, fuel pin pitch, wrapper-less assembly design and active core height. After the analysis, it was proposed to keep the core configuration of the original XT-ADS except for the core power that should be increased up to 85 MWth (original value=57 MWth) and the coolant temperature increment that should be increased from 100 up to 130 °C.

Based on the updated core parameters, the researcher performed the analysis of the depletion modelling of the realistic fuel re-shuffling scheme and provided time evolutions of the total fuel assembly power, beam current, core power, neutron flux, fuel burn-up and irradiation damage on the fuel clad that was utilized in the following design for upgraded heat exchanger, thermomechanical behavior of the crucial fuel rods and the safety criteria in the accidental situation. Finally, the feasibility of the upgraded MYRRHA core with the maximum fast neutron flux was confirmed.

The second researcher from the same research group performed the uncertainty analysis by using the Standardized Computer Analyses for Licensing Evaluation (SCALE) code system to comprehend the reliability of the MYRRHA/XT-ADS criticality. The comparisons of the sensitivity coefficients and uncertainties with different calculation models, calculation codes and nuclear data libraries were also carried out. As the main result, it was confirmed the uncertainty deduced from the covariance data was about 1.0% for the MYRRHA/XT-ADS criticality with the 44-group covariance data prepared in the SCALE code system.

The second researcher also aimed to analyze the Unprotected Blockage Accident (UBA) in FAst Spectrum Transmutation Experimental Facility (FASTEF) by the SIMMER-III code. Through this analysis, the following flow was observed; Fuel assembly blockage --> Cladding tube failure --> Fuel particles discharged from the cladding tube --> Fuel particles touched LBE --> LBE evaporation. It was also observed that the time from the blockage (100% blockage in the fuel assembly) to the cladding tube failure was about 6 sec. It was also presented that there was a possibility of re-critical state by the UBA. In this analysis, the power peak reached to 100 times larger than the nominal one by inserting 1.2 $ reactivity.

4.3 Bilateral collaboration between SCK・CEN and JAEA on the validation of thermal-hydraulic characteristics for beam window

Validation of the thermal-hydraulic performance of ADS beam window was performed between Japan and Belgium. For this study, experimental data, which were generated by JAEA using JAEA Lead-Bismuth Loop-3 (JLBL-3), were applied. JLBL-3 (Fig. 4.3-1) has a test section with a beam window mock-up. A heater of 6 kW is installed inside the window simulation section to represent the heat deposition by the proton beam, and 24 thermocouples are located inside/outside surface of beam window to measure temperature profile for the experimental verification of heat-transfer behavior between beam window and flowing LBE alloy.

Figure 4.3-2 shows an example of the comparisons of experimental data and numerical analysis results done by JAEA. Although several experimental data were significantly different from numerical analysis, almost same temperature profiles were predicted. It is also observed that the several discrepancies appeared according to analytic parameters (solid and dashed line in Fig. 4.3-2).

Typical results from numerical analysis obtained by SCK・CEN are shown in Fig. 4.3-3. In the past year, the accuracy of the SCK・CEN data was greatly improved and a good correspondence between experimental and numerical data was obtained. The fit is not perfect. The reason is more likely to be linked to uncertainties on the experimental setup (namely power of the heater and precise position of the tip of the thermocouples) and to mesh/interpolation effects on the results within the solid domain, rather than being dependent on fluid modelling details (such as constant or variable heat transfer coefficient and turbulence description). Possible future developments must clarify these uncertainties.

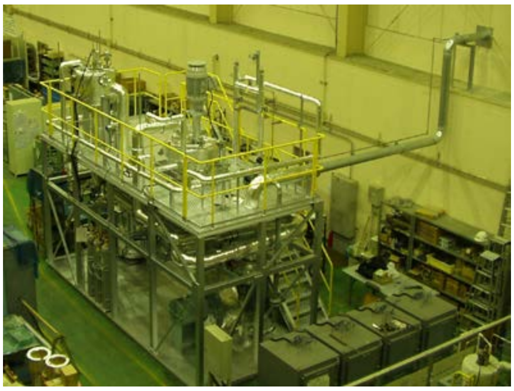

Fig. 4.3-1 JAEA Lead-Bismuth Loop-3

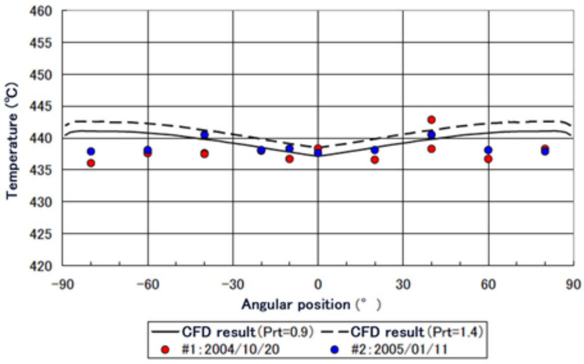

Fig. 4.3-2 Thermal-hydraulic Analysis results from JAEA

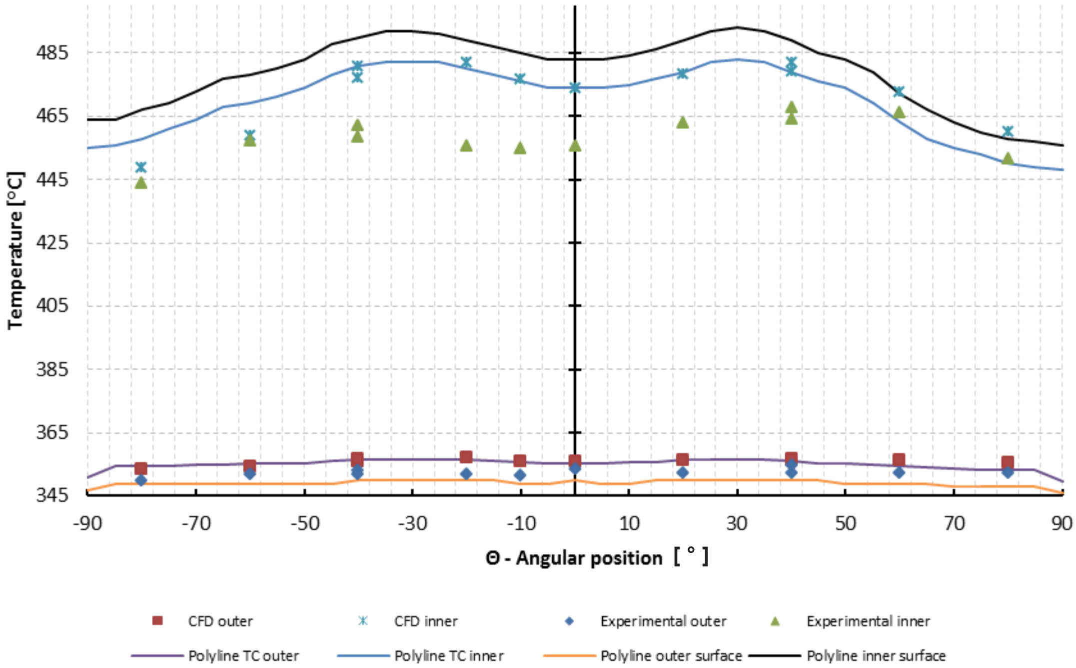

Fig 4.3-3 Thermal-hydraulic analysis results from SCK・CEN (corresponding to the experiment done by JAEA on 27/10/2004)

4.4 Bilateral collaboration between SCK・CEN and JAEA on FREYA experiments

SCK・CEN has conducted research and development activities on the MYRRHA facility, and has continued the design studies on the technical feasibility of the transmutation in the framework of the Integrated Project EUROpean research program for the TRANSmutation of high level nuclear waste in an ADS project (IP-EUROTRANS). Under the framework of the Generator of Uninterrupted Intense NEutron at the lead VEnus REactor (GUINEVERE) project (2006–2011), as a part of IP-EUROTRANS project, the VENUS reactor at the SCK・CEN Mol site has been revised to a zero-power fast lead-based reactor (VENUS-F) coupled with a deuteron accelerator (GEnérateur de NEutrons Pulsé Intense (GENEPI-3C)), and now the experimental activities have been proceeded under the framework of the Fast Reactor Experiments for hYbrid Applications (FREYA) project.

For the neutronic design of such nuclear systems, it is important to determine the safety margin in the criticality calculations. Among various possible sources of uncertainty in the criticality calculations, the uncertainty in nuclear data is considered to have a significant impact on the total uncertainty value. To quantify the nuclear-data uncertainties, much effort has been devoted to evaluating the covariance data of the nuclear data parameters. Thanks to the recent evaluation of covariance data for lead isotopes in JENDL-4.0[24)], the uncertainties induced by nuclear data can be comprehensively estimated for lead-based fast reactors.

As a part of collaborative work for the FREYA project, JAEA focused on a critical configuration of the VENUS-F core as a representative reactor of lead- or lead-bismuth-based fast reactors such as MYRRHA and future ADS, and estimated its k_{eff} using existing nuclear data libraries: JENDL-4.0, ENDF/B-VII.1, and JEFF-3.1.2. The variation in k_{eff} for typical deterministic methodologies (the diffusion and transport theories) and geometric modeling (three-dimensional XYZ and two-dimensional RZ models) was also investigated. Furthermore, JAEA investigated the cause of the differences in k_{eff} between the nuclear data libraries using sensitivity coefficients. Finally, the uncertainty induced by the nuclear data was evaluated using the JENDL-4.0 covariance data. Details are provided in Reference[25)].

As a result, it was found that there were considerable differences in k_{eff} among nuclear data libraries and geometrical models. Moreover, it was found that lead isotopes have a large impact on the uncertainty of criticality. Future collaborative works with SCK・CEN are expected to reduce the evaluated uncertainty by mixing our analytical experiences (*e.g.* nuclear data, calculation code, methodology) and SCK・CEN experimental ones (*e.g.* subcritical and critical experiments with VENUS-F).

4.5 Bilateral collaboration between SCK・CEN and JAEA on oxygen potential sensor for lead-bismuth alloy

JAEA bought two oxygen sensors from SCK・CEN to measure the oxygen concentration in LBE. The oxygen sensor was the Bi/Bi_2O_3 type sensor which has had a good record in SCK・CEN.

The oxygen concentration in LBE was measured in the static and saturated oxygen conditions by both sensors. The LBE temperature range was 350-450 °C. As the result, the measured values were almost same as the theoretical value.

After the performance check of the oxygen sensors, one of the sensors was installed to JAEA Lead-Bismuth Loop-4 (JLBL-4) to measure the oxygen concentration in the LBE flow condition. The LBE temperature was 350 °C and the LBE flowrate was about 26 L/min. It was confirmed that the oxygen concentration decreased during the operation of JLBL-4 due to the consumption of the oxygen by pipes. After that, an injection of oxygen gas to LBE has been performed to control the oxygen concentration.

5. Possible collaborations in the future

5.1 Nuclear data improvement via code benchmarking

The accuracy of neutronic design codes is crucial for core design, safety analysis, operation, and so on for the ADS. SCK･CEN and JAEA have respectively developed the different codes and nuclear data libraries that is different to each other. They can be benchmarked using MYRRHA calculation model in this task. The double check of the MYRRHA neutronic design by JAEA' code is also valuable for solidification of design and estimation of uncertainty included in the design codes.

SCK･CEN can provide the benchmark calculation model and results for the same core parameters as JAEA with MCNPX on MYRRHA design. Therefore a code-to-code benchmark can be of mutual interest. SCK･CEN also tried to use the JENDL-HE library (High Energy library) for particle transport in MCNP. But the file contains particle data that cannot be handled by NJOY, so it would be useful to have JAEA support on this.

JAEA can provide the calculation results for core parameters, which are k_{eff}, source effectiveness, power distribution and burn-up behavior, of MYRRHA by JAEA's calculation codes (PHITS, MARBLE and MVP) with the JENDL-4.0 or the later version of JENDL. PHITS is the main code for designing ADS regarding high energy particle in JAEA, which incorporates sophisticated physical models different from those in MCNPX that is the main code in SCK･CEN. MARBLE, the main code for ADS design in JAEA, is designed as a software development framework for reactor analysis including 3-D diffusion and transport theory for neutron calculation with burn-up function. MVP code is a continuous-energy Monte Carlo code developed by JAEA, which is used for detailed (pin-wise) ADS analysis as a supplemental code to MARBLE. JAEA can also provide information relating to NJOY code to process the JENDLE-HE library.

5.2 Oxygen sensor and control techniques

Development of oxygen sensors and control techniques has been one of the main topics of LBE chemistry R&D at SCK･CEN since 2010. SCK･CEN can provide following items. As for the oxygen addition/reduction devices development, PbO mass exchanger technology and electrochemical oxygen pumping system were developed. For the oxygen sensors development, SCK･CEN performed the design, construction, over 200,000 sensor-hours of operation in small LBE setups and large loops, signal measurement and transmission, were done with high accuracy. SCK･CEN developed three types of sensors. First one is the sensors with air reference electrode, capable of measuring as low as 200 °C, and passive systems to avoid LBE leakage/air ingress in case of ceramic rupture. Second option is the sensors with liquid metal/metal oxide reference electrode including Bi/Bi_2O_3 with specific experience feedback on avoiding ceramic rupture during use. The third option is the sensors with solid metal/metal oxide reference electrode such as Cu/Cu_2O. SCK・CEN can provide the information and operation experiences for these sensors. Information on experimental measurement of Sievert's constant for oxygen dissolution in LBE down to 300 °C and the oxygen partial pressure in oxygen saturated LBE down to 200°C – to calculate PbO solubility and oxygen concentration from oxygen sensor output at low end of operation temperatures of MYRRHA can also be provided from SCK・CEN. SCK・CEN can also provide information about CFD simulations of oxygen transport in LBE including detailed simulations of oxygen consumption by surfaces of complex geometry such as a fuel bundle, revealing local oxygen depleted zones important for corrosion prediction and development of corrosion mitigation strategies.

JAEA has developed the oxygen sensor to measure the oxygen concentration in LBE. Previously, JAEA purchased the oxygen sensors through international cooperation with Europe and used to measure the oxygen concentration in LBE. In 2014, JAEA fabricated two-types of oxygen sensors (platinum type and bismuth type) with referring the European ones. As the result of performance test, it was confirmed that output signal of the platinum type sensors was adequate in a wide temperature range. JAEA can provide the original oxygen sensor (platinum type) referring to air as reference electrode. JAEA can also provide results of performance test (trend of output signal) using the same kind of sensor under 350 °C to 450 °C of LBE temperature and 10^{-4} to 10^{-7} weight percent of oxygen concentration.

Calibration of oxygen sensor of both institutes is valuable as well as information exchange of technologies relating to oxygen control. Furthermore, to set up reference method to measure and control oxygen concentration in LBE, the technological exchange between JAEA and SCK・CEN is effective.

5.3 Development of dissolved impurity monitoring system

Corrosion products (Fe, Cr, Ni) released from stainless steels into LBE can have important consequences on safety and operation of an ADS, through formation of solids which may cause deposits and blockages. Despite the importance of corrosion products, there is yet no fast method available to monitor their concentration in LBE. R&D on corrosion product detection methods could therefore be a valuable topic for a collaboration between SCK・CEN and JAEA.

In 2016, SCK・CEN will start a feasibility study on the online monitoring of dissolved Ni in LBE based on two principles. The first principle is determination of the dissolved Ni concentration by monitoring the oxygen concentration transient during a thermal cycle. In theory, it is feasible to estimate the dissolved Ni concentration by monitoring the evolution of oxygen concentration during a thermal cycle based on the Ni-NiO equilibrium. In order to detect ppm levels of dissolved Ni in LBE, it is required to monitor the dissolved oxygen concentration below 200°C. SCK・CEN developed an oxygen sensor which can measure the oxygen concentration reliably at these low temperatures. The second one is direct electrochemical measurement of the dissolved Ni concentration by using molten salt electrolyte. A galvanic cell with Ni ion conducting electrolyte such as NiCl2-KCl-LiCl will allow to detect dissolved Ni concentration in LBE. SCK・CEN will construct a galvanic cell (Ni(LBE) | NiCl2-KCl-LiCl | Ni(S)) and we will evaluate the detection limit of the cell.

JAEA performs the development and improvement of oxygen sensor for LBE. The influence of impurity in LBE, which is mainly caused from corrosion of structural material, will be evaluated experimentally.

Information exchange on this topic is needed to further identify the detailed areas of joint collaboration.

5.4 R&D for polonium behavior in LBE

One of the main issues to use LBE is the production of highly radiotoxic polonium (Po) isotopes and their potential release to the environment. Because the Po emits alpha particle at decay phase and is volatile, produced Po in LBE should be carefully managed and controlled. There are limited experimental data for Po release from LBE and also the data to collect the Po evaporated from LBE. It is important to establish the method to satisfy the safety requirements for Po.

Since 2010, SCK・CEN has performed extensive R&D on Po chemistry in LBE in support of MYRRHA licensing. Po chemistry is complex and safety-relevant phenomena such as release and volatility strongly depend on conditions such as temperature, the oxygen concentration in LBE and the presence of impurities in the cover gas. Concurrent with the R&D on Po, the chemistry of mercury in LBE was studied at SCK・CEN and more recently, the chemistry of fission products such as iodine. On Po chemistry, SCK・CEN can provide following items. The detailed results of experiments of Po evaporation from LBE in various atmosphere including air from room temperature to 1000 °C, the results of transient in the release of Po from LBE, and our current understanding of the role of the oxygen content in LBE in these transient effects, can be provided. Information can be provided about the methodology to extract thermodynamic data on Po compounds (pure condensed, gas, dissolved in LBE) from experimental results and from theoretical calculations (extrapolations, semi-empirical models and quantum-chemical calculations) and the implementation of these thermodynamic data in software to calculate Po vapor pressure and Po vapor molecule speciation as well as prediction of Po compound precipitation from LBE as function of Po concentration in LBE, cover gas composition, oxygen concentration in LBE, and the results on the deposition of volatile Po vapor molecules on surfaces and filter materials (steel, activated carbon) in humidified cover gas. SCK・CEN also be able to make the advice on the use of these results and of thermodynamical data on Po vapor molecule adsorption on surfaces (most importantly steel) in different gas atmospheres, to calculate transport of Po vapors through steel-walled pipes. Furthermore, SCK・CEN can provide detailed, quantitative study on mercury evaporation from liquid LBE (up to 350 °C) and solid LBE in Ar. The results of preliminary studies on iodine evaporation from LBE and design and construction of setups to measure fission product evaporation from LBE can also be provided.

JAEA performed the filtering tests of Po released from neutron irradiated LBE and obtained decontamination factor of stainless mesh filter. JAEA can provide the results of the experiment on evaporation rate of Po from LBE and decontamination factor of stainless mesh for several temperature points of LBE below 600 °C. Using vacuum vessel prepared by JAEA, small amount of lead-bismuth which was irradiated at JRR-4 reactor was heated up to 600 °C and evaporated Po were transferred to the exhaust line with stainless mesh filter. Two kinds of stainless steel mesh with different fineness were used with 1 to 6 layers. The observed transmission of Po was provided by a form of decontamination factor as a function of lead-bismuth pot temperature, filter temperature, and filter configuration (mesh size and number of layer).

It is useful to exchange the information of Po management done by each research institute to overcome the safety issues caused by Po.

5.5 Development of flow meter

Calibration of all instrumentation in LBE and flow/velocity meters in particular is of importance in LBE technology. From the current experimental loops SCK・CEN has good operational experience with industrial flow meters of various types (Vortex, Coriolis, Dp) covering a wide range of flow rates. At the same time, high-temperature ultrasonic sensors have been successfully developed for visualization purposes. SCK・CEN has the ambition to apply the same sensors for velocity measurements in the near future and explore the possibilities of ultrasonic flow measurement. SCK・CEN can exchange its experience with the industrial flow meters and the results of the future comparison of the ultrasonic measurements with these flow meters with JAEA.

The ElectroMagnetic Flow meter (EMF) is one of the major flow meters for liquid metal and then, JAEA used EMF for the earlier experimental LBE loops in JAEA. However, the accuracy of the EMF deeply depends on the wettability of the electrode and sometimes gave incorrect flow rates. Moreover, the calibration method for EMF is not simple manner. On the other hand, JAEA has developed the flow meter using Doppler effect of ultrasonic wave as a technology for fast reactor application. JAEA tried to apply the Ultrasonic Flow Meter (UsFM) using existing test loop for instruments development. Intercomparison between

EMF and UsFM were performed and it gives quite adequate results. The latest large experimental loops for material corrosion tests and spallation target mockup adopt the UsFM as a flow meter. Throughout these experiences, JAEA can provide the experimental results for flow rate measurement and intercomparison data with EMF.

The information exchange of flow meter development will be effective collaboration.

5.6 Establishment of cleaning method

The cleaning method of LBE attached on structural materials or test materials is one of key technologies to treat heavy liquid metals. SCK・CEN routinely uses cleaning solutions based on hydrogen peroxide/acetic acid to remove LBE from steel and ceramic components. In a dedicated study, the performance of such solutions has been analyzed and an optimal composition was determined. SCK・CEN is interested in exchanging experience and results on cleaning methods with JAEA.

JAEA is developing the cleaning method to perform the material tests for irradiated samples in flowing LBE environment that should be cleaned up for observation of the surface. Moreover, the cleaning of remaining LBE should be necessary to replace the spallation target head, which are heavily irradiated. JAEA tried to perform various method to clean up the sticking LBE. In the case of irradiation sample, cleaning using heated silicon oil is desirable to keep the sample surface in good condition. Another method using acid or hydrogen peroxide is usable for target maintenance. Additional tests using non-radioactive LBE can be done to construct the spallation target replacement sequence. The information on former experiments and additional experimental results can be provided.

The information exchange of cleaning method will be effective collaboration.

5.7 Accelerator technology

SC-LINAC in JAEA's design of ADS and the MYRRHA Linac obviously share several features. Although the choice of the RF frequency is different (hampering the exchange of physical objects), a collaboration at the level of the applied technologies may bear great interest. Especially the development of the superconducting high beta elliptical cavities and of their associated cryomodule may generate essential information regarding both the design and the fabrication process of the equivalent MYRRHA objects. The operational experience with a fully equipped cryomodule, including the RF power source(s), the power coupler(s) and the Low Level RF control, will create highly valuable feedback for future realizations.

SCK・CEN and JAEA exchange information of accelerator design and fabrication of prototype RF cavity.

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Appendix A Members of working group for collaboration between SCK・CEN and JAEA for partitioning and transmutation through accelerator-driven system

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国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 組立単位	
	名称	記号
面積	平方メートル	m^2
体積	立方メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m^{-1}
密度，質量密度	キログラム毎立方メートル	kg/m^3
面積密度	キログラム毎平方メートル	kg/m^2
比体積	立方メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
量濃度(a)，濃度	モル毎立方メートル	mol/m^3
質量濃度	キログラム毎立方メートル	kg/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率(b)	（数字の）1	1
比透磁率(b)	（数字の）1	1

(a) 量濃度（amount concentration）は臨床化学の分野では物質濃度（substance concentration）ともよばれる。
(b) これらは無次元量あるいは次元１をもつ量であるが、そのことを表す単位記号である数字の１は通常は表記しない。

表３．固有の名称と記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン(b)	rad	1(b)	m/m
立体角	ステラジアン(b)	sr(c)	1(b)	m^2/m^2
周波数	ヘルツ(d)	Hz		s^{-1}
力	ニュートン	N		$m\ kg\ s^{-2}$
圧力，応力	パスカル	Pa	N/m^2	$m^{-1}\ kg\ s^{-2}$
エネルギー，仕事，熱量	ジュール	J	N m	$m^2\ kg\ s^{-2}$
仕事率，工率，放射束	ワット	W	J/s	$m^2\ kg\ s^{-3}$
電荷，電気量	クーロン	C		s A
電位差（電圧），起電力	ボルト	V	W/A	$m^2\ kg\ s^{-3}\ A^{-1}$
静電容量	ファラド	F	C/V	$m^{-2}\ kg^{-1}\ s^4\ A^2$
電気抵抗	オーム	Ω	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
コンダクタンス	ジーメンス	S	A/V	$m^{-2}\ kg^{-1}\ s^3\ A^2$
磁束	ウエーバ	Wb	Vs	$m^2\ kg\ s^{-2}\ A^{-1}$
磁束密度	テスラ	T	Wb/m^2	$kg\ s^{-2}\ A^{-1}$
インダクタンス	ヘンリー	H	Wb/A	$m^2\ kg\ s^{-2}\ A^{-2}$
セルシウス温度	セルシウス度(e)	℃		K
光束	ルーメン	lm	cd sr(c)	cd
照度	ルクス	lx	lm/m^2	m^{-2} cd
放射性核種の放射能(f)	ベクレル(d)	Bq		s^{-1}
吸収線量, 比エネルギー分与, カーマ	グレイ	Gy	J/kg	$m^2\ s^{-2}$
線量当量, 周辺線量当量, 方向性線量当量, 個人線量当量	シーベルト(g)	Sv	J/kg	$m^2\ s^{-2}$
酸素活性	カタール	kat		s^{-1} mol

(a)SI接頭語は固有の名称と記号を持つ組立単位と組み合わせても使用できる。しかし接頭語を付した単位はもはやコヒーレントではない。
(b)ラジアンとステラジアンは数字の１に対する単位の特別な名称で、量についての情報をつたえるために使われる。実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号である数字の１は明示されない。
(c)測光学ではステラジアンという名称と記号srを単位の表し方の中に、そのまま維持している。
(d)ヘルツは周期現象についてのみ、ベクレルは放射性核種の統計的過程についてのみ使用される。
(e)セルシウス度はケルビンの特別な名称で、セルシウス温度を表すために使用される。セルシウス度とケルビンの単位の大きさは同一である。したがって、温度差や温度間隔を表す数値はどちらの単位で表しても同じである。
(f)放射性核種の放射能（activity referred to a radionuclide）は、しばしば誤った用語で"radioactivity"と記される。
(g)単位シーベルト（PV,2002,70,205）についてはCIPM勧告2（CI-2002）を参照。

表４．単位の中に固有の名称と記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa s	$m^{-1}\ kg\ s^{-1}$
力のモーメント	ニュートンメートル	N m	$m^2\ kg\ s^{-2}$
表面張力	ニュートン毎メートル	N/m	$kg\ s^{-2}$
角速度	ラジアン毎秒	rad/s	$m\ m^{-1}\ s^{-1}=s^{-1}$
角加速度	ラジアン毎秒毎秒	rad/s^2	$m\ m^{-1}\ s^{-2}=s^{-2}$
熱流密度，放射照度	ワット毎平方メートル	W/m^2	$kg\ s^{-3}$
熱容量，エントロピー	ジュール毎ケルビン	J/K	$m^2\ kg\ s^{-2}\ K^{-1}$
比熱容量，比エントロピー	ジュール毎キログラム毎ケルビン	J/(kg K)	$m^2\ s^{-2}\ K^{-1}$
比エネルギー	ジュール毎キログラム	J/kg	$m^2\ s^{-2}$
熱伝導率	ワット毎メートル毎ケルビン	W/(m K)	$m\ kg\ s^{-3}\ K^{-1}$
体積エネルギー	ジュール毎立方メートル	J/m^3	$m^{-1}\ kg\ s^{-2}$
電界の強さ	ボルト毎メートル	V/m	$m\ kg\ s^{-3}\ A^{-1}$
電荷密度	クーロン毎立方メートル	C/m^3	m^{-3} s A
表面電荷	クーロン毎平方メートル	C/m^2	m^{-2} s A
電束密度，電気変位	クーロン毎平方メートル	C/m^2	m^{-2} s A
誘電率	ファラド毎メートル	F/m	$m^{-3}\ kg^{-1}\ s^4\ A^2$
透磁率	ヘンリー毎メートル	H/m	$m\ kg\ s^{-2}\ A^{-2}$
モルエネルギー	ジュール毎モル	J/mol	$m^2\ kg\ s^{-2}\ mol^{-1}$
モルエントロピー, モル熱容量	ジュール毎モル毎ケルビン	J/(mol K)	$m^2\ kg\ s^{-2}\ K^{-1}\ mol^{-1}$
照射線量（Ｘ線及びγ線）	クーロン毎キログラム	C/kg	kg^{-1} s A
吸収線量率	グレイ毎秒	Gy/s	$m^2\ s^{-3}$
放射強度	ワット毎ステラジアン	W/sr	$m^4\ m^{-2}\ kg\ s^{-3}=m^2\ kg\ s^{-3}$
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2\ sr)$	$m^2\ m^{-2}\ kg\ s^{-3}=kg\ s^{-3}$
酵素活性濃度	カタール毎立方メートル	kat/m^3	$m^{-3}\ s^{-1}$ mol

表５．SI 接頭語

乗数	名称	記号	乗数	名称	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	µ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^{9}	ギガ	G	10^{-12}	ピコ	p
10^{6}	メガ	M	10^{-15}	フェムト	f
10^{3}	キロ	k	10^{-18}	アト	a
10^{2}	ヘクト	h	10^{-21}	ゼプト	z
10^{1}	デカ	da	10^{-24}	ヨクト	y

表６．SIに属さないが、SIと併用される単位

名称	記号	SI 単位による値
分	min	1 min=60 s
時	h	1 h =60 min=3600 s
日	d	1 d=24 h=86 400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10 800) rad
秒	”	1”=(1/60)’=(π/648 000) rad
ヘクタール	ha	1 ha=1 $hm^2=10^4m^2$
リットル	L，l	1 L=1 l=1 $dm^3=10^3cm^3=10^{-3}m^3$
トン	t	1 t=10^3 kg

表７．SIに属さないが、SIと併用される単位で、SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位で表される数値
電子ボルト	eV	1 eV=1.602 176 53(14)$\times10^{-19}$J
ダルトン	Da	1 Da=1.660 538 86(28)$\times10^{-27}$kg
統一原子質量単位	u	1 u=1 Da
天文単位	ua	1 ua=1.495 978 706 91(6)$\times10^{11}$m

表８．SIに属さないが、SIと併用されるその他の単位

名称	記号	SI 単位で表される数値
バール	bar	1 bar=0.1MPa=100 kPa=10^5Pa
水銀柱ミリメートル	mmHg	1 mmHg≈133.322Pa
オングストローム	Å	1 Å=0.1nm=100pm=10^{-10}m
海里	M	1 M=1852m
バーン	b	1 b=100$fm^2=(10^{-12}cm)^2=10^{-28}m^2$
ノット	kn	1 kn=(1852/3600)m/s
ネーパ	Np	SI単位との数値的な関係は、対数量の定義に依存。
ベル	B	
デシベル	dB	

表９．固有の名称をもつCGS組立単位

名称	記号	SI 単位で表される数値
エルグ	erg	1 erg=10^{-7} J
ダイン	dyn	1 dyn=10^{-5}N
ポアズ	P	1 P=1 dyn s cm^{-2}=0.1Pa s
ストークス	St	1 St =1$cm^2\ s^{-1}=10^{-4}m^2\ s^{-1}$
スチルブ	sb	1 sb =1cd $cm^{-2}=10^4$cd m^{-2}
フォト	ph	1 ph=1cd sr cm^{-2} =10^4lx
ガル	Gal	1 Gal =1cm $s^{-2}=10^{-2}ms^{-2}$
マクスウエル	Mx	1 Mx = 1G $cm^2=10^{-8}$Wb
ガウス	G	1 G =1Mx cm^{-2} =10^{-4}T
エルステッド(a)	Oe	1 Oe ≙ $(10^3/4\pi)$A m^{-1}

(a) ３元系のCGS単位系とSIでは直接比較できないため、等号「 ≙ 」は対応関係を示すものである。

表10．SIに属さないその他の単位の例

名称	記号	SI 単位で表される数値
キュリー	Ci	1 Ci=3.7$\times10^{10}$Bq
レントゲン	R	1 R = 2.58$\times10^{-4}$C/kg
ラド	rad	1 rad=1cGy=10^{-2}Gy
レム	rem	1 rem=1 cSv=10^{-2}Sv
ガンマ	γ	1 γ=1 nT=10^{-9}T
フェルミ		1 フェルミ=1 fm=10^{-15}m
メートル系カラット		1 メートル系カラット= 0.2 g = 2$\times10^{-4}$kg
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	1 cal=4.1858J（「15℃」カロリー），4.1868J（「IT」カロリー），4.184J（「熱化学」カロリー）
ミクロン	µ	1 µ =1µm=10^{-6}m

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