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Structural Materials Data Management Survey

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Foreword

Under the guidance of the Nuclear Energy Agency (NEA) Nuclear Science Committee (NSC) and the mandate of the NEA Working Party on Scientific Issues of the Fuel Cycle (WPFC), the Expert Group on Liquid Metal Technology (EGLM) was established in 2015, after the publication of the *Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermalhydraulics and Technologies* by the NEA Expert Group on Heavy Liquid Metal Technology (EGHLM) (NEA, 2015). The scope of work of the EGLM includes activities on liquid Na and heavy liquid metal (HLM) and aims to assess the available data for application in design, construction and licensing issues on the one hand and operation, in-service inspection, handling and maintenance on the other.

To support this work, the members of the expert group conducted a survey to identify and establish common criteria and understanding on the complex issue of data selection and qualification based on standards relevant to construction code requirements. This report presents the results of the survey, its analysis and a set of recommendations for future data management processes.

Acknowledgements

The NEA would like to express its sincere gratitude to the members of the Expert Group on Liquid Metal Technology (EGLM) for contributing to the report. Special thanks go to T. Austin (JRC-Petten, European Union), who prepared and conducted the survey, analysed the results and wrote the report. The collaboration of P. Schuurmans, chair of the EGLM, and members of the group, are also gratefully acknowledged.

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List of abbreviations and acronyms

ADS	Accelerator-driven sub-critical system
AFA	Alumina-forming austenitic steels
ALFRED	Advanced Lead Fast Reactor European Demonstrator
ASTEC-Na	Accident Source Term Evaluation Code
ASTM	American Society for Testing Material
ASTRID	Advanced Sodium Technological Reactor for Industrial Demonstration (CEA, France)
CEA	Commissariat à l'énergie atomique et aux énergies renouvelables (Alternative Energies and Atomic Energy Commission, France)
CE	Code evolution
CEN	Comité Européen de Normalisation (European Committee for Standardization)
CERBERUS	Corrosion erosion behaviour of components in heavy-liquid metals
CFD	Computational fluid dynamics
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Center for Environmental and Technological Energy Research, Spain)
CNRS	Centre National pour la recherche scientifique (National Center for Scientific Research, France)
CODAP	Component Operational Experience, Degradation and Ageing Programme (NEA)
DCRC	Design and Construction Rules Committee
DEMETRA	Design of mechanical transmissions
DMP	Data management plan
DoE	Department of Energy (United States)
EB	Electron beam
EERA	European Energy Research Alliance
ESNII	European Sustainable Nuclear Industrial Initiative
EUROTRANS	EUROpean Research Programme for the TRANSmutation of High Level Nuclear Waste in an Accelerator Driven System
EDS	Energy dispersive X-ray spectroscopy

EGLM	Expert Group on Liquid Metal Technology (NEA)
ENEA	Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (National Agency for New Technologies, Energy and Sustainable Economic Development, Italy)
EPMA	Electron probe micro-analyser
FEA	Finite element analysis
FGC	Functionally Graded Composite
F/M	Ferritic/Martensitic
GEMMA	Generation IV materials maturity
GETMAT	Generation IV and transmutation materials
GIF	Generation-IV International Forum
HEA	High entropy alloy
HLM	Heavy liquid metal
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratory (United States)
IPPE	Institute of Physics and Power Engineering (Russia)
ISO	International Organisation for Standardisation
JAEA	Japan Atomic Energy Agency
JPNM	Joint Programme on Nuclear Materials (EU)
JRC	Joint Research Centre (EU)
JSME	Japan Society of Mechanical Engineers
KIT	Karlsruhe Institute of Technology (Germany)
LBE	Lead-bismuth eutectic
LCF	Low cycle fatigue
LEADER	Lead-cooled European Advanced DEmonstration Reactor
LFR	Lead-cooled fast reactor
LM	Liquid metal
LME	Liquid metal embrittlement
MatDB	Materials database
MATTER	Materials testing and rules
MATISSE	Materials innovation for safe and sustainable nuclear in Europe
MCNP	Monte-Carlo N-Particle transport code
MEGAPIE	Megawatt pilot experiment
MIT	Massachusetts Institute of Technology (United States)
MOLECOS	Modelling of heavy-liquid metal corrosion of steels

MOSEL	Modelling steel embrittlement by heavy liquid metals
MSS	Materials Strength Standard
MYRRHA	Multi-purpose hYbrid Research Reactor for High-tech Applications (SCK•CEN, Belgium)
NDE	Non-destructive examinations
NEA	Nuclear Energy Agency
NSC	Nuclear Science Committee (NEA)
NRC	Nuclear Regulatory Commission (United States)
ODS	Oxide-dispersion strengthened steels
PC	Personal computer
PID	Proportional–integral–derivative
RCC-MRx	Règles de conception et de construction des centrales électro-nucléaires: règles de conception et de construction des matériels mécaniques des installations nucléaires (Design and construction rules for mechanical components of high temperature, experimental and fusion nuclear installations)
RD&D	Research, development and demonstration
RDD&D	Research, development, demonstration and deployment
RD&I	Research development and innovation
RELAP	Reactor Excursion and Leak Analysis Program (US NRC)
SCCME	Service de la corrosion et du comportement des matériaux dans leur environnement (CEA Saclay Nuclear Research Centre, France)
SCK•CEN	Studiecentrum voor Kernenergie – Centre d'étude de l'énergie nucléaire (Nuclear Research Centre, Belgium)
SEM	Scanning electron microscopy
SFR:	Sodium-cooled fast reactor
SMR	Small modular reactor
SNU	Seoul National University
SSC	Structures, systems and components
SSRT	Slow strain rate testing
SSTT	Slow-strain tensile testing
STEM	Scanning transmission electron microscopy
TEF-T	Transmutation Experimental Facility
TEM	Transmission electron microscopy
TIG	Tungsten inert gas
TRAC	Transient Reactor Analysis **Code** (US NRC)

TRACE	TRAC/RELAP Advanced Computational Engine (US NRC)
TRL	Technology readiness level
WELLMET	Characterisation of liquid metal embrittlement of welded components in heavy-liquid metal
WS	Workshop
YSZ	Yttria-stabilised zirconia

Executive summary

The Nuclear Energy Agency (NEA) Expert Group on Liquid Metal Technology (EGLM) conducted a survey to identify and establish common criteria and understanding on the complex issue of materials data selection and qualification based on standards relevant to construction codes requirements for liquid metals (lead, lead bismuth eutectic and sodium).

The survey has been carried out on company profiles (domain of activity, activities related to liquid metal [LM] technologies, data requirements), material properties (mechanical testing activities, mechanical properties prioritisation, physical and thermal properties) and data management (availability, accessibility) (see Appendix 1).

Thirteen organisations took part in the survey: Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT, Spain), Commissariat à l'énergie atomique et aux énergies renouvelables (CEA, France), Centre National pour la recherche scientifique (CNRS, France), CV Řež, Czech Republic, Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (ENEA, Italy), Idaho National Laboratory (INL, United States), Institute of Physics and Power Engineering (IPPE, Russia), Japan Atomic Energy Agency (JAEA Oarai, JAEA Tokai, Japan), Joint Research Centre (JRC, European Union), Karlsruhe Institute of Technology (KIT, Germany), Centre d'étude de l'énergie nucléaire (SCK•CEN, Belgium) and Seoul National University (SNU, Korea). The results of this study were analysed thoroughly, discussed among participants and are detailed in Chapters 3, 4 and 5.

Business and liquid metal technology activities

Participating organisations are mainly research organisations and most respondents are active in heavy liquid metal (HLM) technology. Generation of data is performed through research projects (national and collaborative projects) and no large-scale materials qualification data were considered in this report. A list of material tested, test types, materials classes and data access levels was established.

Materials property data

Material property data is principally experimental data generated through research programmes dedicated to materials performance under operational conditions. Available data show major discrepancies in the different experiments performed due to the large variety of procedures used. However, efforts were made to establish criteria for correct use of the materials in relevant reactor applications. No large-scale LM testing programmes are undertaken at present; therefore, research centres are the only providers of data with potential use for construction codes. To use the codes, the pedigree and reliability of the data should be well documented. The need for developing representative physics models is highlighted. In terms of construction codes development, there is a need for normative procedures. Tests should be performed in accordance with emerging and agreed standards and procedures. Results of the survey also revealed an interest from participating organisations to develop a database of thermal and physical properties in order to facilitate structural modelling.

Data requirements

The survey showed a strong preference for primary data generated from experiments.

Risks and risk mitigations

The range of relevant structures, systems and components (SSC) is very broad and attempting to collect data without SSC prioritisation risks overburdening the EGLM. An inventory of the systems and components should be carried out in order to determine the materials properties requirements for the reactor systems of interest. In addition, a list of potential sources of materials data was established.

Recommendations

Finally, a set of recommendations was given in the form of concrete actions to support the scope of work established within the EGLM. More information is needed on operating conditions (temperature, loading conditions, environment, etc.) for construction codes to be developed.

Mainly experts in HLM completed the current survey. Hence, a second iteration of the survey is needed with a focus on sodium-cooled systems and associated projects in support of development of ASTRID, BN-1200, EBR-II or PGSFR.

Results of the survey revealed a strong desire to make data available, a precursor to which would be the formulation of a database arrangement. Thereafter, data sharing could be realised in the form of a database under the auspices of the NEA.

Within different European projects, extensive work has been done to perform literature reviews, generate experimental data and deliver guidelines on LM testing procedures. In this context, the following actions are recommended:

- promote prenormative research to normative status;
- collaborate with organisations active in the field;
- catalogue all past and on-going activities generating materials property data relevant to LM;
- establish an international data management plan.

1. Introduction

1.1. The Expert Group on Liquid Metal Technology (EGLM)

The Nuclear Energy Agency (NEA) Expert Group on Liquid Metal Technology (EGLM) was created in 2015 under the guidance of the NEA Nuclear Science Committee (NSC) to perform activities on coolant technologies (Na, Pb and Pb-Bi). The aim of the EGLM is to assess available data and bring it closer to application in design, construction and licensing issues on the one hand and operation, in-service inspection, handling and maintenance on the other hand. For this purpose, the members of the EGLM undertake activities with the goal to "translate" fundamental scientific understanding to application in order to:

- support the development of construction codes used for design;
- address key technical issues for licensing;
- give recommendations for operation, inspection and handling.

Activities carried out within the expert group focus in three main areas:

- Environmental conditions and factors that affect materials behaviour relevant for the structural integrity of confinement barriers and components. These include the impact on mechanical properties from the environment such as irradiation effects and liquid metal embrittlement as well as environmental assisted property effects like corrosion.
- Coolant and cover gas issues. The work focuses on issues relevant for radiological impact assessment, operation, including maintenance, inspection and handling, etc. In the field of chemistry, radiochemistry and physics of the coolant, its interaction with the cover gas, the impact of irradiation, the influence of corrosion, transport of radionuclides in the coolant, etc., are addressed.
- Thermal-hydraulics for liquid metals. Thermal-hydraulic behaviour of the coolant is a crucial factor in the sense that it essentially determines a large part of the environmental conditions for materials and the cooling such as the flow distribution and mixing, temperatures distribution, stratification and instabilities, pressure variations, coolant structure interactions, etc.

To support the abovementioned work, the expert group decided to conduct a survey to identify and establish common criteria and understanding on complex issues of data selection and qualification based on standards relevant to construction codes requirements.

1.2. Materials data management survey

To collect and disseminate materials data relevant to the EGLM, this report presents the findings of the survey (carried out among EGLM members) with a view to establishing a common understanding of the data management requirements of materials used in liquid metal systems. In this context, the survey extends to liquid metal environments such as Pb, LBE and Na.

After completing the first iteration of the survey, a second iteration was necessary for additional information. With 13 organisations (from the EGLM membership) participating in the first iteration, all but one participated in the second. This report summarises the results of the second iteration.

2. Method

The survey is provided in Appendix 1 and conducted research in the following areas:

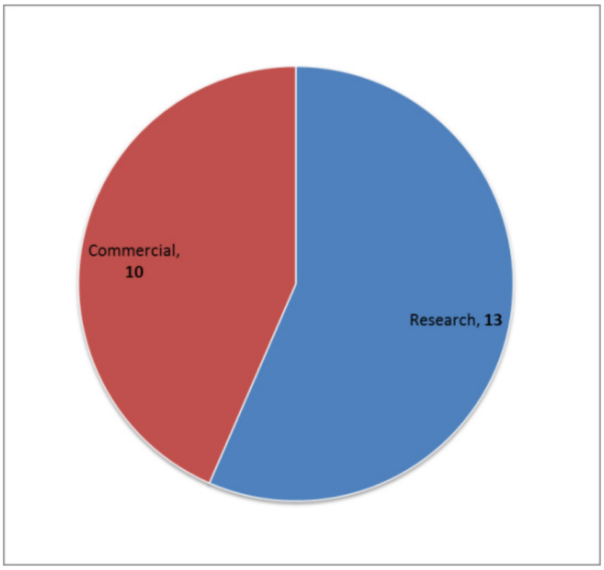
- company profiles:
  - domain(s) of activity;
  - activities related to liquid metal technologies;
  - data requirements.
- materials properties:
  - mechanical testing activities;
  - mechanical properties prioritisation;
  - relevant physical and thermal properties.
- data management:
  - availability;
  - accessibility.

3. Results – Company/organisation profiles

3.1. Domain(s) of professional activity

Regarding the question on the nature of the organisations, most Nuclear Energy Agency (NEA) Expert Group on Liquid Metal Technology (EGLM) members replied that they are active in the research domain with their organisation conducting some commercial activities, as shown in Figure 1 and Table 1.

Figure 1. Domain(s) of professional activity of survey respondents



Source: OECD/NEA, 2020.

Table 1. Domain(s) of business activity of survey respondents

	EGLM member[1]	Research	Commercial activities
1	CV Řež, Czech Republic	X	X
2	Seoul National University, Korea	X	
3	CEA, France	X	X
4	CNRS, France	X	

1. The current EGLM participating institutions are all public organisations and partially supported through public funding.

	EGLM member[1]	Research	Commercial activities
5	JAEA, Tokai (ADS), Japan	X	X
6	JAEA, Oarai (FR), Japan	X	X
7	INL, United States	X	X
8	KIT, Germany	X	X
9	ENEA, Italy	X	x
10	IPPE, Russia	X	X
11	CIEMAT, Spain	X	
12	JRC-Petten, European Union	X	X
13	SCK•CEN, Belgium	X	X

Source: OECD/NEA, 2020.

3.2. Domain(s) of professional activity explanatory comments

1) CV Řež: Its activities mainly focus on research, but commercial services are also provided (in a limited amount).

2) Seoul National University: The main activities of SNU Nuclear Engineering Department in the College of Engineering focus on education and research activities that are led by six faculty members specialised in nuclear power technology, encompassing neutronics, thermal-hydraulics and materials engineering.

3) CEA[2]: CEA is a public organisation involved in research and development in four main areas, defence and security, nuclear and renewable energies, technological research for industry and fundamental research in the physical sciences and life sciences.

4) CNRS: CNRS is a French national research organisation and its activities focus on research.

5) JAEA Tokai: JAEA is a Japanese research and development institute for atomic energy in Japan. JAEA Tokai has research activities for accelerator-driven sub-critical system (ADS).

6) JAEA Orai: JAEA Oarai has research activities dedicated to fast reactors.

7) INL: INL is a US Department of Energy (DoE) National Laboratory whose primary mission is research, development, demonstration and deployment (RDD&D) of advanced nuclear energy technologies.

8) KIT: KIT is the German Research University in the Helmholtz Association.

9) ENEA: ENEA is a public agency strongly related to the industrial development. ENEA's activities are industry-oriented.

2. As CEA EGLM members participating in the survey are established in different locations in France, the survey reflects the responses of the two CEA respondents (CEA centres of Saclay and Cadarache).

10) IPPE: IPPE is a world leader in the use of liquid metals as coolants in nuclear power plants with fast reactors, marine and space nuclear power plants.

11) CIEMAT: CIEMAT is a public research centre. Its activity is structured around projects, which form a bridge between research development and innovation (RD&I) and social interest goals. CIEMAT carries out some commercial activities but not in the field of LM technology.

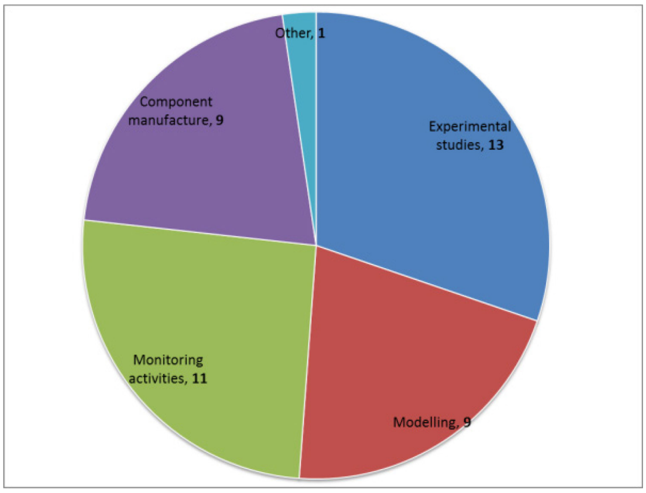
12) JRC: JRC is the European Commission's in-house science and knowledge service.

13) SCK•CEN: SCK•CEN is mainly a research institute including a small activity with (partial) commercial motivation such as production of medical isotopes, Si doping, reactor surveillance programmes.

3.3. Liquid metal technology activities

Regarding the question on the activities related to liquid metal technologies undertaken at the organisations and, as depicted in Figure 2 and Table 2, it is apparent that all EGLM members are concerned with experimental studies and most with modelling, monitoring activities and component manufacture.

Figure 2. Liquid metal technology activities of survey respondents



Source: OECD/NEA, 2020.

Table 2. Liquid metal technology activities of survey respondents

	EGLM member	Experimental studies	Modelling[3]	Monitoring and/or inspection of liquid metal facilities including fast reactors	Component manufacture within the organisation	Other
1	CV Řež, Czech Republic	X			X	
2	Seoul National University, Korea	X	X	X		
3	CEA, France	X	X	X	X	
4	CNRS, France	X	X			
5	JAEA, Tokai (ADS)	X		X	X	
6	JAEA, Oarai (FR)	X		X		
7	INL, United States	X	X	X	X	
8	KIT, Germany	X	X	X	X	
9	ENEA, Italy	X	X	X	X	
10	IPPE, Russia	X	X	X	X	
11	CIEMAT, Spain	X		X		
12	JRC- Petten, European Union	X	X	X	X	X
13	SCK•CEN, Belgium	X	X	X	X	

Source: OECD/NEA, 2020.

3.4. Liquid metal technologies explanatory comments

1) CV Řež: CVR activities are mainly focused on materials (corrosion and mechanical properties), chemistry of HLM and instrumentation. Development of technology is also included in terms of design and manufacturing of experimental loops as well as components such as pumps for HLM application. Moreover, there is a large effort in the field of thermal-hydraulics (modelling and validation).

2) Seoul National University: SNU activities are principally dedicated to the development of corrosion-resistant material, the study of corrosion behaviour in high temperature, thermal-hydraulic loop testing, pool-type small modular reactor (SMR) scaled test bed, seismic isolation studies, system safety modelling.

3) CEA: Liquid metal technology activities are performed mainly to support the Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID) project for: i) experimental studies in liquid metals (lead alloys and sodium, fretting, thermodynamic capabilities) in relation with the corrosion of materials in order to model long-term damage

3. In this context, modelling refers to modelling of materials under irradiation.

(CEA Saclay); ii) experimental studies on liquid sodium technology (components and instrumentation, in-service inspection, processes, etc.) together with the required modelling studies (e.g. ultrasounds imaging) (CEA Cadarache); and iii) codification for AFCEN RCC-MRx (CEA-Saclay). Experimental devices and set-up components are manufactured in-house or by sub-contractors.

4) CNRS: The laboratories of CNRS study the mechanical properties of materials in contact with liquid metal (LBE, lead, sodium) such as liquid metal embrittlement and liquid metal accelerated damage.

5) JAEA Tokai: At JAEA, some types of oxygen sensors and flow meters have been developed for the LBE loops. Transmutation experimental facility (TEF-T) target window mock-up was manufactured and connected to the TEF-T mock-up loop.

6) JAEA Oarai: Liquid metal technology activities such as thermal hydraulics, core/plant safety and sodium compatibility for sodium-cooled fast reactors are carried out at Oarai and Tsuruga.

7) INL: INL maintains a robust nuclear capability for the US DoE with significant resources dedicated to fuels and materials development activities including design, fabrication, and irradiation and post-irradiation examination capabilities and multi-physics modelling capabilities including characterisation of irradiated materials. Nuclear reactor and system design capabilities are performed as integrated programmatic activities for both the DoE and a worldwide base of university and industry customers, such as characterisation of elevated temperature properties of advanced structural alloys.

8) KIT: Activities of KIT include numerical modelling and experimental studies on thermal-hydraulics and material properties as well as the development of components and sensor techniques. KIT also provides equipment for material tests in liquid metal to other research organisations.

9) ENEA: ENEA activities are related to structural materials and coating qualification in harsh environments, coolant chemistry, component design, construction and qualification. Large experimental programmes are coupled with numerical investigations and modelling.

10) IPPE: SSC RF-IPPE activities are dedicated to the support of BN-1200 and BREST projects. In sodium technology, IPPE is performing analysis of the features of the implementation of technological processes in non-isothermal circuits for advanced nuclear power plant projects at elevated parameters of coolant such as impurities analysis, sodium purification, impurities monitoring and control in sodium, thermal-hydraulics, corrosion and mass transfer, leak monitoring, components of sodium circuits, decommissioning.

11) CIEMAT: Activities are mainly focused on corrosion and mechanical properties of structural materials in lead-bismuth eutectic.

12) JRC: Activities conducted at JRC include: i) safety assessment modelling (including severe accident modelling); ii) experimental studies on fuel and materials in support to safety assessments, emergency preparedness, waste management, and licensing; and iii) nuclear security (proliferation resistance) assessments. JRC acts as implementing agent of Euratom in Generation IV International Forum (GIF) and, as such, it takes part in the work of GIF methodology working groups (Risk and Safety Working Group and Proliferation Resistance and Physical Protection Working Group), sodium-cooled fast reactor (SFR) and lead-cooled fast reactor (LFR) System Steering Committees as well as several SFR Project Management Boards. Among others, JRC is also member of the IAEA Technical Working Group on Fast Reactors, European Sustainable Nuclear Industrial

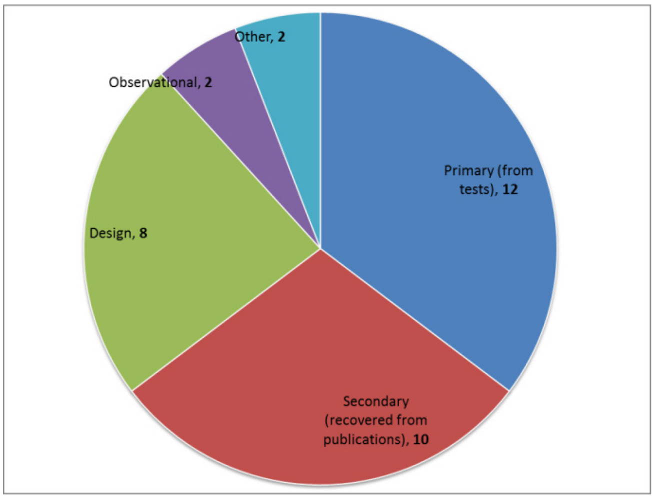
Initiative (ESNII) Task Force, NEA EGLM and participates as scientific supervisor in co-operation meetings between the Euratom collaborative project LEADER and BREST LFR project in Russia. Heavy liquid metal experimental facility for mechanical testing of candidate structural materials for heavy liquid metal cooled reactors is currently under development at JRC Petten.

13) SCK•CEN: Activities at SCK•CEN regarding heavy liquid metal technology are mainly in support of the MYRRHA project. They include corrosion and mechanical properties research on materials, thermal-hydraulics experiments, coolant chemistry control including radiological release and component testing. Modelling activities focus on materials modelling, thermal-hydraulics modelling using computational fluid dynamics (CFD) and system codes and mass transport modelling using coupled chemistry-CFD codes. Components manufacturing refers to manufacturing of experimental devices and set-up components.

3.5. Data requirements

Regarding the question on data requirements and as depicted in Figure 3 and Table 3, most organisations are interested in primary and secondary data, with a strong preference for experimental data and data recovered from publications[4]. While a significant interest (~25%) in design data is identified, the much stronger preference for primary and secondary data is perhaps suggestive of a present focus on research rather than the development of construction codes.

Figure 3. Data requirements of survey respondents



Source: OECD/NEA, 2020.

4. It should be noted that the total number of requirements exceeds the number of respondents because all but one of the respondents indicated a requirement for multiple data types.

Table 3. Data requirements of survey respondents

	EGLM member	Primary (from tests)	Secondary (recovered from publications)	Design	Observational	Other
1	CV Řež, Czech Republic	X		X		
2	Seoul National University, Korea	X	X	X	X	
3	CEA, France	X	X			
4	CNRS, France	X	X			
5	JAEA, Tokai (ADS), Japan	X	X	X		
6	JAEA, Oarai (FR), Japan			X		
7	INL, United States	X	X	X		
8	KIT, Germany	X	X			
9	ENEA, Italy	X	X	X		
10	IPPE, Russia	X	X	X	X	X
11	CIEMAT, Spain	X	X			
12	JRC-PettenEuropean Union	X	X			
13	SCK•CEN, Belgium	X	X	X		X

Source: OECD/NEA, 2020.

3.6. Data requirements explanatory comments

1) CV Řež: The activities are focused on primary generation of data from CV Řež experimental facility. Design data are a fundamental part of the work, due to commitment to support the development of ALFRED.

2) Seoul National University: The activities are dedicated to cladding materials corrosion database, environmental fatigue, creep rupture, degradation of functionally graded composite.

3) CEA: The main activity is related to sodium technology systems, which are designed and tested for qualification for ASTRID project. Thus, performances, operation in nominal conditions, endurance tests are performed.

4) CNRS: No information was provided by the organisation.

5) JAEA Tokai: Pre-design of TEF-T target window has been done for low irradiation temperature under conditioning operation of TEF-T by using SUS316L steel. At higher temperature after the normal operation around 500°C, material irradiation data under flowing LBE is needed for T91 steel by using LBE loops and TEF-T target itself. Experimental activities have been carried out following this design step.

6) JAEA Oarai: Design and its related research for demonstrated fast reactor have been performed.

7) INL: Sodium systems and component design tasks are being considered but without large-scale testing capability necessary for feedback.

8) KIT: No information was provided by the organisation.

9) ENEA: The main activities are related to lead compatibility with structural material and coating for (LFR) application at relevant environmental operative conditions and operational modes**.**

10) IPPE: New data will be incorporated into future projects. The main task of technology for installations with heavy coolant is a resource of the reactor.

11) CIEMAT: No information was provided by the organisation.

12) JRC: No information was provided by the organisation.

13) SCK•CEN: The data requirement under "other" refers to the need to collect and analyse the return of experience information that is obtained from operation of experimental facilities as a contribution to the qualification of components.

4. Results – Materials properties

4.1. Environmental, corrosion and mechanical testing activities

Regarding the question on mechanical testing activities and as depicted in Figure 4, all respondent organisations have experience in mechanical testing. With the survey extending to 31 mechanical test types in ten groups (corrosion, creep, small punch, relaxation, fatigue, fracture, tensile, irradiation, crack growth, and hardness) and three categories (LM, reference, and irradiation), reference tests have been performed for all but one of the listed test types, namely fretting corrosion. Further, tests have been performed in a LM environment for all but eight of the listed test types, namely torsional creep, small punch creep, uniaxial relaxation, multiaxial relaxation, thermo-mechanical fatigue, creep crack growth, creep-fatigue crack growth and Brinell hardness.

Of the various test types undertaken in a LM environment, ~60% of respondents indicated experience with each of general corrosion testing and high-temperature corrosion testing[5], with ~30% having experience with each of uniaxial creep, load-controlled low cycle fatigue (LCF) and uniaxial tensile tests.

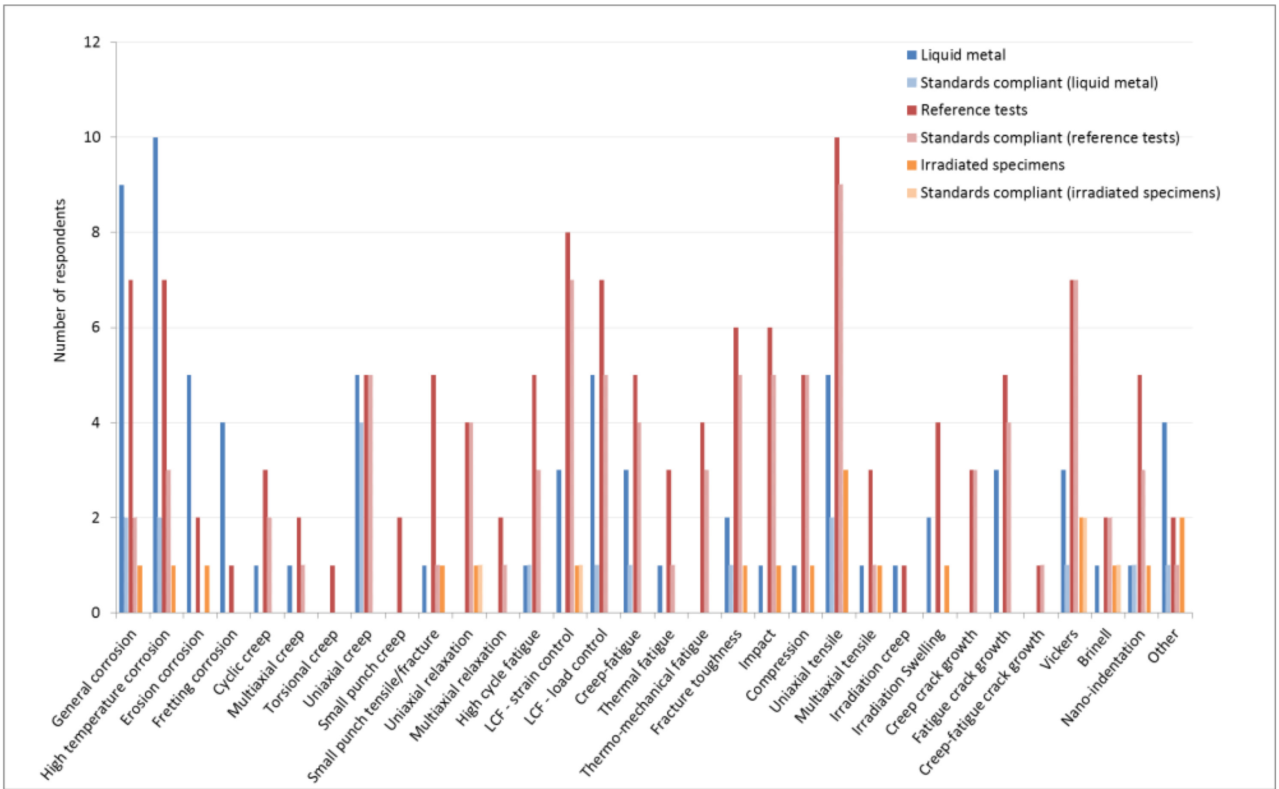
Along with the reference and LM testing categories, the survey sought to establish the extent of test types undertaken on irradiated materials. Not unexpectedly, there is significantly less capability among survey respondents to undertake such tests, with just the CEA, JAEA, KIT and SCK•CEN indicating such a capability.

As depicted in Figures 5, 6 and 7, when considering the reference, LM and irradiated testing activities separately, it is clear from the results that the larger proportion of respondents performs their reference tests according to normative procedures. Of the general corrosion testing and high-temperature corrosion tests performed in an LM environment, approximately 25% of respondents indicated compliance with a normative procedure (i.e. international standards). However, given that there are no normative procedures specific to mechanical tests and corrosion testing in an LM environment and taking into consideration the explanatory comments in Section 4.2, with the CEA making reference to company standards, while CV Řež, KIT, SCK•CEN, CIEMAT and the ENEA refer to guidelines developed in the FP7 materials testing and rules (MATTER) project, it seems likely that LM embrittlement and corrosion tests can only be claimed to be performed according to best practices rather than normative procedures. That said, for each LM, the existing normative procedures for LM corrosion testing need to be adapted and new normative procedures for LM mechanical testing should be developed considering all factors of importance (such as sample preparation, temperature, solution composition, concentration of dissolved gases, flowrate and flow pattern).

5. Given that "high-temperature corrosion" is specific to corrosion that takes place in gas turbines and furnaces i.e. at temperatures considerably higher than those of an LM environment, where respondents selected this test type is understood they meant general corrosion at an elevated temperature.

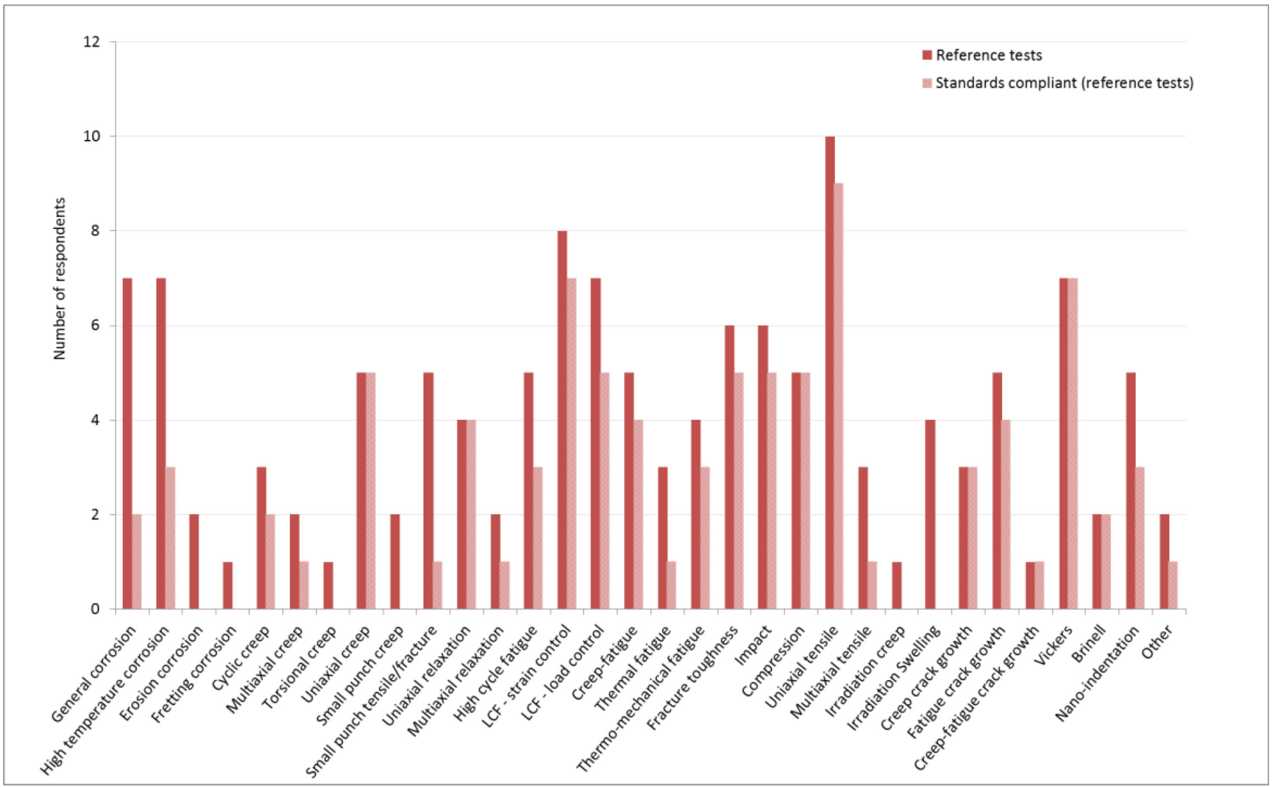
Although identification of the relevant physical and thermal properties is described in Sections 4.5 and 4.7, as explanatory comments from CEA highlighted in Section 4.2, the survey does not extend to establishing the extent of thermodynamic testing activities. Whether this should be considered, an oversight depends on the relevance of physical and thermal properties data to construction codes. If such data are only relevant to modelling, their relevance to the objectives of the EGLM is limited because modelling is not sufficiently mature for results to contribute directly to the properties data required for construction codes. In this respect, development of representative physics models is needed to attain high-level understanding and predictive capability to underpin the development of design rules.

Figure 4. Environmental, corrosion and mechanical testing competencies of respondents



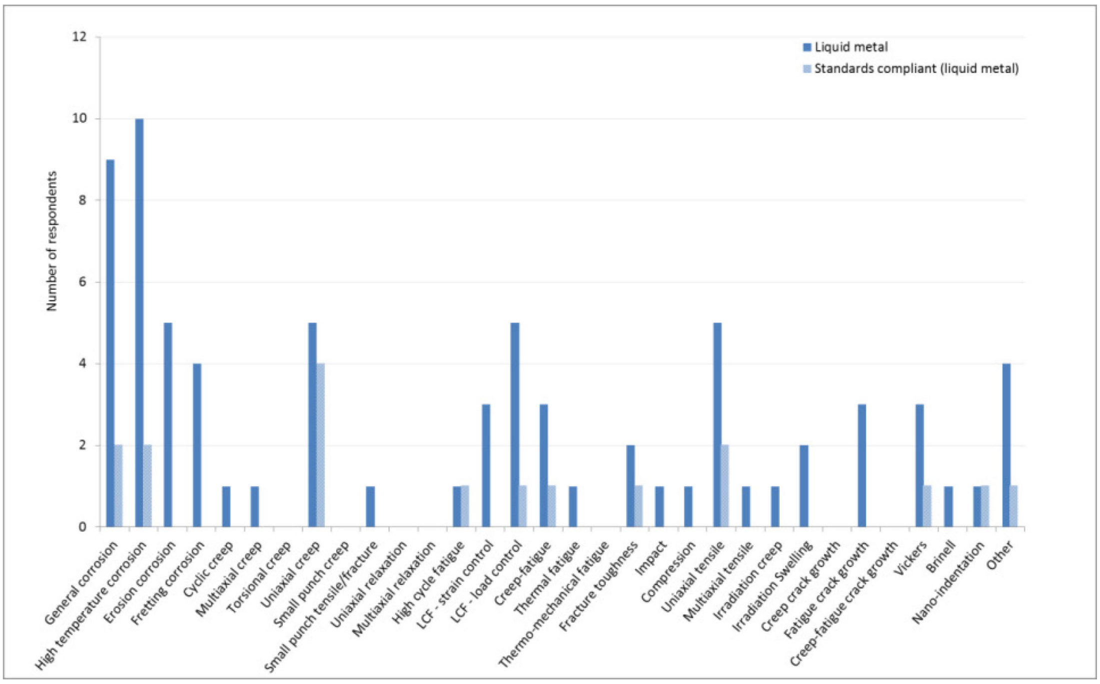
Source: OECD/NEA, 2020.

Figure 5. Environmental, corrosion and mechanical testing competencies of respondents for reference tests alone



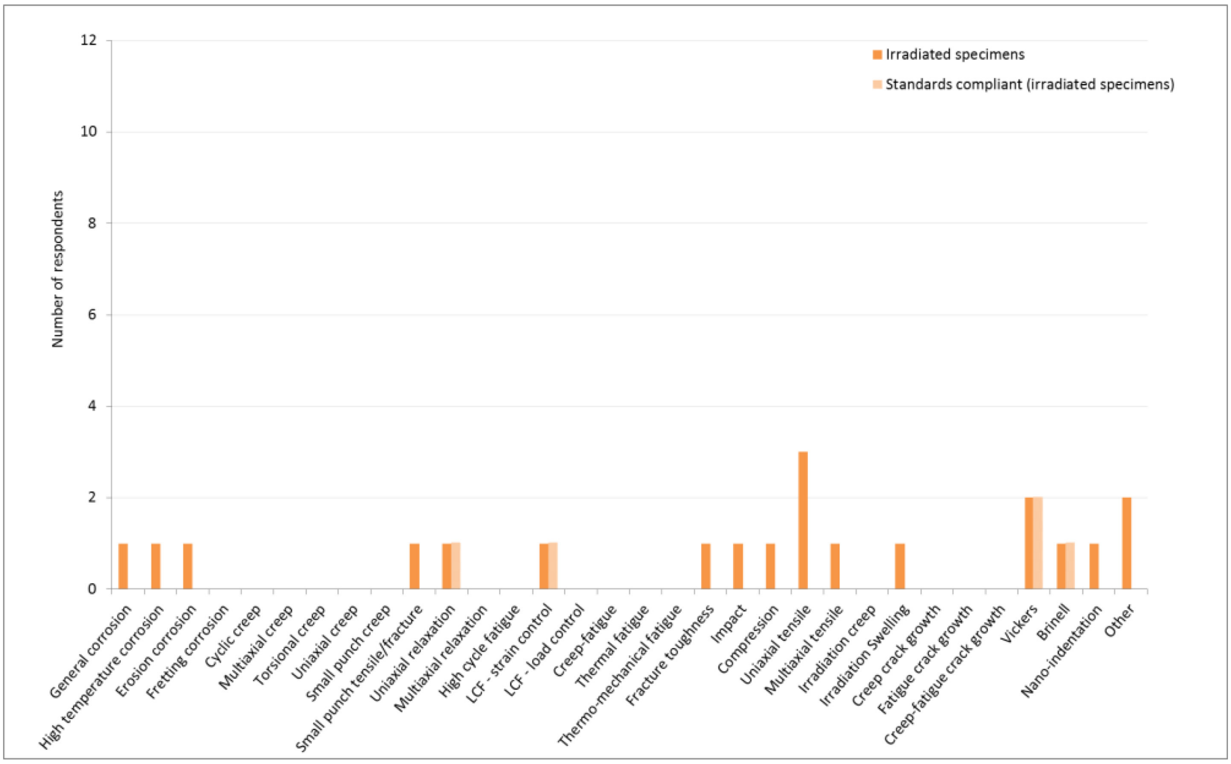
Source: OECD/NEA, 2020.

Figure 6. Environmental, corrosion and mechanical testing competencies of respondents for liquid metal tests alone



Source: OECD/NEA, 2020.

Figure 7. Environmental, corrosion and mechanical testing competencies of respondents for irradiated specimen tests alone



Source: OECD/NEA, 2020.

4.2. Environmental, corrosion and mechanical testing explanatory comments

1) CV Řež: For tests in liquid metals, oxygen sensors (Bi/Bi_2O_3) are present to measure the oxygen content (in loop or static cell) together with gas dosing control. Thermocouples measuring temperatures in various locations are placed in the outer surfaces of the pipes. The materials tested are the ferritic/martensitic T91, austenitic 316L, oxide-dispersion strengthened steel (ODS) (12-14Cr) steels, coated steels. Several tests in Pb were performed at a temperature of 650°C.

Standards such as American Society for Testing Material (ASTM) and International Organisation for Standardisation (ISO) are normally used for all the tests in air and in parallel adapted to the tests in HLM, since there are no specific standards for this technology. Where relevant, the guidelines developed in the frame of the EU MATTER project were implemented and are used.

2) Seoul National University: For materials development, alloys development processing, corrosion tests and slow strain rate tensile tests with static corrosion cell are performed. New alumina-forming ferritic stainless steels have been developed and tested to demonstrate their outstanding corrosion resistance over existing austenitic stainless steels as well as advanced silicate-forming steels. Corrosion tests have been carried out in static cells with YSZ oxygen sensor based on Bi/Bi_2O_3 reference by controlling oxygen concentration by flowing H_2/H_2O gas with regulated composition and flow rates.

Microstructural examinations of tested materials showed that selective chromium leaching depletion leaving Cr-depleted zone is one of the most important responsible corrosion mechanisms. Aluminum oxide can effectively retard Cr-leaching, and thus subsequent corrosion. Slow strain rate tests showed no embrittlement in austenitic stainless steels.

Thermomechanical processes have recently been developed to produce tubes of functionally graded composite (FGC). In collaboration with the Massachusetts Institute of Technology (MIT), a hot-extruded pipe of 2.5 Si steels overlayed on T91 has been used to apply cold pilgering process. An elastic-plastic finite element analysis (FEA) has been used to design processes and tooling.

3) CEA: The materials tested range from steels to ceramic materials including pure metal and mono-crystal when available: 316L(N), 316L, 304L, T91, Alloy800, 253MA, ODS steels, alumina, zirconia, hafnia, ceramic composites, coated steels, etc.

Concerning the test, defining materials strength standard on structural materials for French sodium-cooled fast reactors, a database has been established at CEA and has been used to define the design data on the RCC-MRx code (design and construction rules for mechanical components of high temperature, experimental and fusion nuclear installations.

For the liquid metal test, the environmental conditions could be as follows:

- 100°C < T < 675°C;
- 100 h < t < 5 000 h;
- 0.1 ppm wt. < [0] < 200 ppm wt. for the liquid sodium in static conditions;
- 10^{-8} wt.% < [0] < saturation for the liquid lead alloys.

Rotating cylinders allow determining the hydrodynamic effects on corrosion rates for liquid lead alloys (developed for sodium as well but not validated yet).

Instrumentation is based on electrochemical sensor for dissolved oxygen in lead alloys melt (zirconia – indium reference). For liquid sodium, such sensors are under development, so that the chemistry control is made differently by purification (Zr getter), followed by oxide addition at the beginning of the corrosion test. Final oxygen content is checked by a final purification at the end of the test.

Fretting is studied in a specific test bench immersed in static sodium.

The effect of carburisation on the mechanical properties of steels is achieved in collaboration with Nuclear Materials Department after pre-exposure to liquid sodium in various conditions and removal of sodium residue.

Liquid metal embrittlement is studied in collaboration with the CNRS, where a tensile test is performed in pure argon and liquid metal being trapped within the notch. Specimens are first immersed in specific liquid sodium condition in CEA Saclay to achieve wetting of the specimen.

Liquid sodium corrosion under irradiation is studied through the expertise of specimens coming from operating reactors (Phénix).

At present, no under-sodium mechanical test is performed at CEA, but studies for the implementation on tensile machine started. Some standardisation tests are conducted for providing/confirming RCC-MRx material data: progressive deformation is studied for ASTRID stainless steel material.

There were also some tests in the 1980s devoted to thermal stripping and thermal fatigue of stainless steel material into sodium (thermal shocks between 280 and 620°C).

4) CNRS: The following materials are being investigated: T91 martensitic steel, T91 with different coatings, 304L and 316L austenitic steel, 316L(N), T91/316L welds (electron beam /EB/ and Tungsten inert gas /TIG/), 15-15Ti steel, different ODS steels.

Tests are carried out both in liquid metal and atmosphere (reference tests): tensile test, LCF test, fatigue crack growth test, fracture toughness, small punch test, bending standards-compliant test. The cover gas of experimental facilities sets the chemistry of the liquid metal (oxygen saturated LBE for example or reductive condition).

5) JAEA Tokai: Corrosion tests in stagnant and flowing LBE for ferritic and austenitic standard steels, tensile, fatigue and creep test in LBE have been performed under saturated oxygen concentration and reduction conditions. Dynamic mechanical testing machine has been set up in high-temperature LBE corrosion loop. All mechanical tests indicated are performed by using small size specimen, which size is comparable to the thickness of TEF-T target windows. Compliance of test methods for slow-strain tensile testing (SSTT) will be necessary as a next step.

6) JAEA Oarai: Material strength standard (MSS) of the structural materials for Japanese sodium-cooled fast reactor (type-304SS, -316SS, -321SS, 316FR, 2.25Cr-1Mo and Mod.9Cr-1Mo) has been registered to Japan Society of Mechanical Engineers (JSME) code (codes for nuclear power generation facilities − rules on design and construction for nuclear power plants). Such standard for the core materials will be required in the future.

7) INL: Presently, no under-sodium mechanical testing is being performed at INL, but some creep-fatigue testing in compliance with ASTM standards is being performed.

8) KIT: Experiments are equipped with the appropriate instrumentation including coolant chemistry control using oxygen supply and oxygen sinks, sensors and vacuum lock system allowing samples to be loaded in pre-conditioned liquid metal; as standards do not exist for tests in liquid metals, KIT is applying best-practice guidelines derived from MATTER and other projects.

Corrosion tests are performed on oxygen controlled flowing and stagnant conditions for a variety of different materials. Beside the design relevant steels like 316L, in-house developments like alumina-forming austenitic steels (AFA), surface alloys and high entropy alloys (HEAs) are tested and further optimised. In addition to standard corrosion tests, combined loads like fretting, pressurised tubes, creep and erosion corrosion are concerned. The before mentioned testing procedures focus on Pb or PbBi. Tests in Na covering corrosion, thermal fatigue and others started in 2018.

9) ENEA: ENEA participates in several international committees and working groups of Euratom, NEA and IAEA to develop strategies and carrying out studies in the field of dependence of liquid metal corrosion on various factors. Underlying mechanisms were investigated for the selected steels (316L and 15-15Ti) in the framework of several European projects (EUROTRANS, GETMAT, MATTER, MATISSE, GEMMA) and also of national programmes. In the frame of the MATTER project (European project), standards for liquid metals test type were developed and implemented in collaboration with European partners. In addition, best practices or preliminary guidelines for corrosion tests in stagnant LM were established.

The materials tested in ENEA are ferritic/martensitic (F/M) steels and austenitic steels. The corrosion tests are performed in stagnant and flowing lead alloys, with temperature and oxygen monitoring and control in the liquid metal using specific oxygen sensors (for the monitoring of the oxygen concentration in the melt) and using a dedicated gas system providing Ar-H_2 deoxygenating gas mixture (to control the oxygen concentration in the melt). For this purpose, ENEA laboratories are equipped with several experimental steel capsules (small and large) for the containment of small amounts of liquid lead alloys (from 750 to 10 000 g) heated up to 550°C. Tests in flowing conditions are performed in a loop working with liquid lead fluid in the temperature range 420-550°C with oxygen control. The activities of the facility focus on corrosion tests in flowing lead, in relevant fluid-dynamic and temperature conditions for lead fast reactors.

The mechanical tests performed with inert gas or in atmosphere are creep, creep fatigue, fatigue tests, indentation tests at high temperature, which are performed in compliance with ASTM standards.

Creep and SSRT tests are performed on AISI 316L and 15-15Ti in lead with chemistry control up to 650°C.

10) IPPE: Currently, materials tests are not being performed.

11) CIEMAT: Material is tested in lead-bismuth included different types of martensitic and austenitic stainless steels.

12) JRC: Reference tests are conducted in air and water (corrosion and stress corrosion cracking). For small punch tests, a code of practice exists. Multiaxial tensile tests have been conducted in the past. The materials tested include austenitic steels, such as Grades 316L and 15/15Ti, ferritic/martensitic steels, such as T91, and ODS alloys.

Irradiation tests are performed in collaboration with organisations with the required testing facilities.

The heavy liquid metal experimental facility allows studying stress corrosion cracking/liquid metal embrittlement phenomena under tensile and compressive stress and performing slow strain-rate tensile, fatigue, fracture toughness, and creep tests with well-controllable parameters, in particular temperature (up to 650°C), oxygen content in HLM, load, and fluid flow conditions.

13) SCK•CEN: The materials commonly tested at SCK•CEN include T91, AISI316L type steels and DIN 1.4970.

SCK•CEN has the capability of performing various types of materials tests. These include general corrosion, impact tests, multiaxial tensile tests and irradiation tests in the BR2 materials test reactor. For the latter two, there are no active research programmes involving these techniques. It should be noted that the impact tests are performed on liquid metal exposed samples although the tests are not carried out under liquid metal.

As for many of these types of tests, no formal standards exist. This is, for example the case for general corrosion tests in liquid metals, swelling or irradiation creep tests. In general, SCK•CEN uses ASTM standards when applicable. In some circumstances, however, using the standards does not lead to representative (conservative) results. In this case, best practices guidelines are followed, for example, which are developed within the MATTER project.

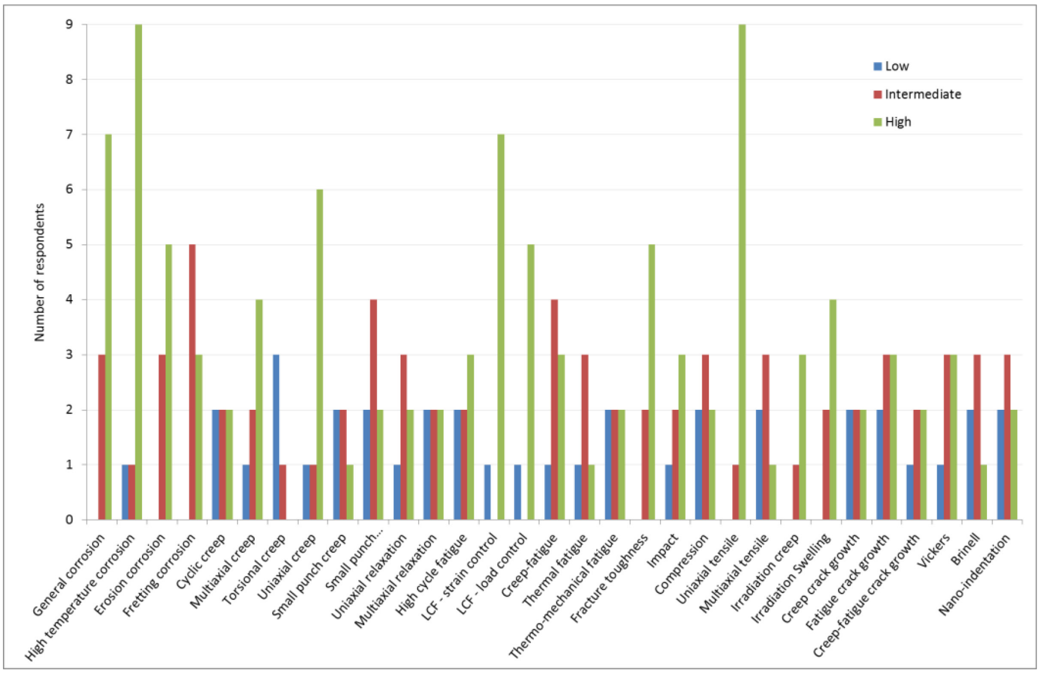
Experiments are equipped with the appropriate instrumentation including coolant chemistry control using electrochemical pumps, sensors and a vacuum lock system allowing samples to be loaded in pre-conditioned liquid metal.

4.3. Environmental, corrosion and mechanical properties prioritisation

Regarding the questions on the relative importance of individual test types to liquid metal technology activities at their organisations and as depicted in Figure 8, while respondents identified corrosion, uniaxial creep, and uniaxial tensile properties as being important, practically every test type was identified as being of intermediate or high importance by at least one organisation. Further, where one organisation indicates a test type to be of high importance, it is often the case that another organisation has identified the test type as being of low or no importance. This circumstance likely reflects organisation-specific system preferences.

As seen in Section 4.1 and as per the Section 4.4 explanatory comments, it appears that respondents have understood "high-temperature corrosion" as general corrosion in a liquid metal environment at an elevated temperature. While high-temperature corrosion is generally associated with the temperatures at which gas turbines operate, for liquid metal technologies a temperature of 550°C is mentioned by SCK•CEN on the basis that the commonly used (uncoated) steels show serious corrosion problems around (above) 500-550°C. In this report, high-temperature corrosion is defined as corrosion taking place at above 550°C in a liquid metal environment.

Figure 8. Mechanical properties priorities of survey respondents



Source: OECD/NEA, 2020.

4.4. Environmental, corrosion and mechanical properties prioritisation explanatory comments

1) CV Řež: The values were assigned and limited to the experiments that CV Řež carried out due to limited experience with the other type of tests. Mechanical testing in HLM was a direct translation from the mechanical testing in water, adapted to the media requirements. High-temperature corrosion is above 500°C.

2) Seoul National University: There is a need to add testing on liquid metal embrittlement, environmental fatigue, recommends identifying tests specified in ASME (see Section III of the ASME code – liquid metal reactor and RCC-MR).

3) CEA: Priorities are made based on the needs for the Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID) R&D programme and the current state of knowledge. All mechanical and irradiation tests are performed by the Nuclear Material Division at Saclay (DMN/SEMI and DMN/SRMA).

The tests performed at Saclay and Grenoble Centres are normalised (performed along existing standards). For irradiated materials, the same tests as for non-irradiated materials can be performed at CEA Saclay (except for fatigue).

Validation of codes and modelling by means of large scale tests are performed on welded mock-ups made of stainless steel.

The following two categories (the two entries for which each had adjacent check boxes) were listed in Table 6 of the survey:

- inspection (ultrasonic telemetry and vision, in liquid Na, non-destructive examination in liquid Na);
- repair (laser repair, in Na ambiance, tightness in liquid Na).

4) CNRS: Priorities are made on the basis of the programmes in which the CNRS is involved. Furthermore, relevant mechanical experiments in liquid metal are defined for a better understanding of the behaviour and damage of the material in contact with liquid metal embrittlement (LME).

5) JAEA Tokai: No information was provided by the organisation.

6) JAEA Oarai: Priorities are made on the basis of the needs for design of sodium-cooled fast reactors.

7) INL: No information was provided by the organisation.

8) KIT: No information was provided by the organisation.

9) ENEA: Priorities are made on the basis of the needs for advanced lead fast reactor European demonstrator (ALFRED) R&D programme. Relevant corrosion experimental data are defined as corrosion at 450°C, 480°C, 550°C and 600°C. Mechanical tests likes creep-fatigues, tensile, creep and slow-strain tensile testing (SSRT) in inert atmosphere and LM are made at relevant ALFRED conditions, 450°C, 480, 550°C and 650°C.

10) IPPE: No information was provided by the organisation.

11) CIEMAT: CIEMAT evaluation has been performed based on the basic information needed to design a new reactor.

12) JRC: Low cycle fatigue and strain control tests are used as screen tests for liquid metal embrittlement (LME) effect. Irradiation creep and swelling are used to screen the cladding materials.

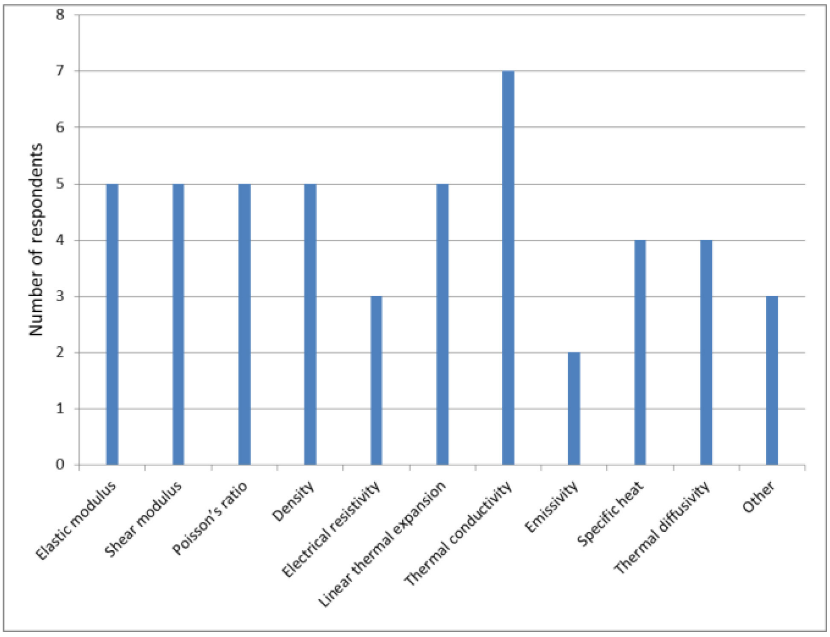
The tests are ranked in order of importance for safety assessment and licensing of liquid metal technologies.

13) SCK•CEN: Priorities are made on the basis of the needs for MYRRHA and the current state of knowledge. High-temperature corrosion is defined as corrosion above 550°C.

4.5. Relevant materials physical and thermal properties

Regarding the question on the nature of their organisation and as depicted in Figure 9, EGLM members are primarily active in the research domain. It should be noted that the total number of properties exceeds the number of respondents because most respondents indicated a requirement for multiple physical and thermal properties.

Figure 9. Physical and thermal properties requirements of survey respondents



Source: OECD/NEA, 2020.

4.6. Relevant materials physical and thermal properties explanatory comments

1) CV Řež: No information was provided by the organisation.

2) Seoul National University: Other diffusion coefficient of passivating element in alloy, parabolic rate constant (in parabolic oxidation law).

3) CEA: Most of the physico-chemical, thermodynamics and kinetics rates data are unknown in liquid metals and their identification requires strong effort. In particular, solubility limits and diffusion coefficients in metallic (Fe, Cr, Ni…) and non-metallic impurities (O, C, N, H) should to be measured.

In addition, corrosion products as a function of temperature and oxygen potential for various solid alloys are relevant data, in order to limit the impact of corrosion and determine working areas

Interactions of these impurities (even present in traces), within the liquid metal or with the structural materials represent a topic that should be addressed (oxide solubility, mixed oxides, etc.).

4) CNRS: No information was provided by the organisation.

5) JAEA Tokai: No information was provided by the organisation.

6) JAEA Oarai: Young's modulus, Poisson's ratio and linear thermal expansion are required as the materials strength standard. These values of the structural materials for Japanese sodium-cooled fast reactors were registered to the JSME code.

7) INL: No information was provided by the organisation.

8) KIT: All properties are relevant; thermal diffusivity and other relevant data will be evaluated for the new developed materials like AFA-steel, HEA, surface alloys.

9) ENEA: All properties are relevant.

10) IPPE: There are numerous experimental data on the steel corrosion in the liquid metal coolants. Data on corrosion in the radiation conditions are extremely limited.

11) CIEMAT: No information was provided by the organisation.

12) JRC: The other properties of interest include: i) solidus and liquidus melt temperatures, ii) heat of melting, iii) crystallographic phase transition, and iv) burst stress or rupture strain.

The modelling tools include: (i) MCNPX neutronic code, (ii) COBRA thermal-hydraulic sub-channel code, (iii) TRACE/RELAP system codes, (iv) ASTEC-Na and SIMMER severe accident analysis codes, (v) ABAQUS & ANSYS structure mechanics codes, (vi) TRANSURANUS fuel pin mechanics code, and (vi) CFX computational fluid dynamics code.

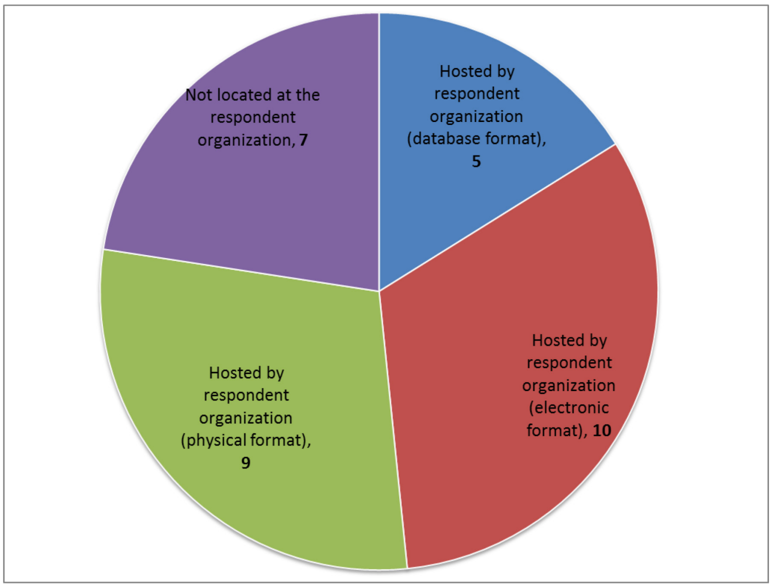
13) SCK•CEN: All properties mentioned here are relevant. However, regarding thermal conductivity, better data are needed.

5. Results – Data management

5.1. Data availability

Regarding questions on data availability and as shown in Figure 10 and Table 4, the larger proportion (~75%) of respondents indicated that the data are hosted at their organisation in either physical or electronic format[6]. Where data are not located at the respondent organisation, explanatory comments in Sections 5.2 and 5.4 suggest that the organisation preserves data or owns data.

Figure 1. Data availability of survey respondents



Source: OECD/NEA, 2020.

6. It should be noted that the majority of respondents indicated multiple categories of availability.

Table 4. Data availability of survey respondents

	EGLM member	Hosted by respondent organisation (database format)	Hosted by respondent organisation (electronic format)	Hosted by respondent organisation (physical format)	Not located at the respondent organisation
1	CV Řež, Czech Republic		X		
2	Seoul National University, Korea		X	X	
3	CEA, France	X	X	X	X
4	CNRS, France		X		
5	JAEA, Tokai (ADS), Japan			X	X
6	JAEA, Oarai (FR), Japan				X
7	INL, United States	X	X	X	
8	KIT, Germany		X	X	
9	ENEA, Italy	X (database developed by JRC and EERA JPNM database)	X	X	X
10	IPPE, Russia			X	X
11	CIEMAT, Spain		X	X	X
12	JRC-Petten, European Union	X	X		
13	SCK•CEN, Belgium	X	X	X	X

Sourxe: OECD/NEA, 2020.

5.2. Data availability explanatory comments

1) CV Řež: All the data are stored in PCs. They are not collected in databases.

2) Seoul National University: Materials corrosion data in LBE, processing-microstructure relationship for Al-containing ferritic stainless steels.

3) CEA: A thermodynamic database has been developed at SCCME CEA Saclay. Publications have been prepared on various items (thermodynamic database on Fe, Cr, Ni solubilities, corrosion, etc.) and deliverables from projects such as EUROTRANS, DEMETRA, TECLA, MEGAPIE are publicly available. However, some results (corrosion and thermodynamic data) are not gathered in any deliverables or publications.

For sodium, most of the references are available in physical format (from 1960-1980) from which, the identified numbered references have been scanned, but with restricted access. Others are not available at all, except in some organisations where the data were produced, archived or scanned. For recent studies, most of the results (e.g. acoustic data) are not gathered in deliverables or publications but only in CEA technical documents with restricted access.

4) CNRS: All the data are stored electronically in the laboratory and can be retrieved or distributed. They are not collected in databases.

5) JAEA Tokai: Data obtained at JAEA cannot be distributed without any agreement, except for the data published in the scientific papers. Technical design report on J-PARC Transmutation Experimental Facility – ADS Target Test Facility (TEF-T) – can be distributed.

6) JAEA Oarai: Data obtained at JAEA cannot be distributed, except for the data published in the scientific papers.

7) INL: Data gathered at the behest of the US DoE are published in a number of deliverables. The ability to release this information is subject to a case-by-case review. Non-government funded data is very unlikely to be available.

8) KIT: Data stored in electronic form but not organised in a database. Public available data distributed as publication or internal report via KIT library.

9) ENEA: All data generated in GETMAT and MATTER projects are made available in the materials database hosted by JRC Petten at https://odin.jrc.ec.europa.eu, according to the confidential level identified in the project.

10) IPPE: No information was provided by the organisation.

11) CIEMAT: Most of the data are included in deliverables of EU projects.

12) JRC: All public data are made available in the materials database hosted by JRC Petten at https://odin.jrc.ec.europa.eu.

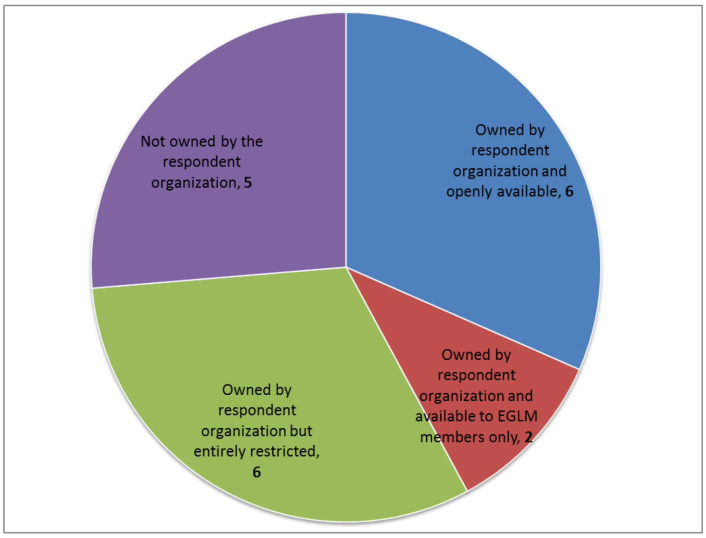
13) SCK•CEN: All public data are made available in the materials database hosted by JRC Petten at https://odin.jrc.ec.europa.eu.

5.3. Data accessibility

Regarding questions on data accessibility and as shown in Figure 11 and Table 5, approximately 33% of the respondents indicated the data are openly accessible[7], with the same proportion indicating the data are entirely restricted. Although a small proportion indicated a willingness to share restricted data with EGLM members, the explanatory comments indicate that this sharing will be selective. Where EGLM members have indicated their data are openly available, access is usually on-demand rather than open, meaning that named individuals will process data access requests. In such circumstances, it has to be determined how details of the available data will be made known.

7. It should be noted that the majority of respondents indicated multiple categories of accessibility.

Figure 11. Data accessibility of survey respondents



Source: OECD/NEA, 2020.

Table 5. Data accessibility of survey respondents

	EGLM member	Owned by respondent organisation and openly available	Owned by respondent organisation and available to EGLM members only	Owned by respondent organisation but entirely restricted	Not owned by the respondent organisation
1	CV Řež, Czech Republic	X			
2	Seoul National University, Korea	X			
3	CEA, France	X		X	
4	CNRS, France			X	
5	JAEA, Tokai (ADS), Japan				X
6	JAEA, Oarai (FR), Japan				X
7	INL, United States			X	X
8	KIT, Germany	X			
9	ENEA, Italy		X		X
10	IPPE, Russia			X	
11	CIEMAT, Spain	X			
12	JRC-Petten, European Union	X		X	X
13	SCK•CEN, Belgium		X	X	

Source: OECD/NEA, 2020.

5.4. Data accessibility explanatory comments

1) CV Řež: Data are available on request. There is no open access from the website.

2) Seoul National University: Data available on request.

3) CEA: CEA data are not publicly available, unless published in scientific articles

4) CNRS: Data could be available on request − no open access from website or databases.

5) JAEA Tokai: Data obtained in JAEA cannot be distributed without any agreement, except for the data published in the scientific papers.

6) JAEA Oarai: Data obtained at JAEA are not publicly available and cannot be distributed, except for the data published by the scientific papers.

7) INL: Data published in the open literature is clearly available. Otherwise, data are considered restricted until reviewed for release, unless the data are obtained under an agreement of ownership with an industrial partner.

8) KIT: Details about the data could be available on request.

9) ENEA: The accessibility will be confirmed from the top management after that the present survey will be completed and other members of the EGLM will confirm the intention to share the data.

10) IPPE: Earlier results are published.

11) CIEMAT: Details about the data could be available on request.

12) JRC: Access details for the structural/cladding materials of interest, as follows:

- 316L-361 data sets from fission research (128) and from fusion research (232);
- fission: general corrosion (1-open access); low cycle fatigue – strain control (11-restricted access, 22 registered access); uniaxial creep (2-cited restricted access, 30-registered access); uniaxial tensile (54 registered access, and 3-cited restricted access); electrical resistivity (1-registered access); linear thermal expansion (1-registered access); thermal conductivity (1-registered access); and Young's modulus (2-registered access);
- fusion: uniaxial tensile (20-open access); remainder temporarily unavailable;
- 316L(N)-1 339 data sets from fission research (48) and from fusion research (1 291);
- fission: thermo-mechanical fatigue (45-restricted access) and uniaxial creep (3-restricted access);
- fusion: 1 291 (temporarily unavailable);
- X10CrNiMoTiB15-15-523 data sets from fission research;
- fission-multi-axial creep (365-restricted access) and uniaxial tension (148-restricted access);
- fusion: none.

The data are stored in and accessible data available through the JRC hosted web-based database and evaluation system MatDB (https://odin.jrc.ec.europa.eu).

13) SCK•CEN: At present, there is not openly accessible data at SCK•CEN. For restricted data owned by SCK•CEN, access is presently not granted but can be decided on a case-by-case basis.

6. Discussion

As the eight specific questions raised in the survey yielded quantitative and unstructured results (see the comments fields), closed examination was performed and is discussed below.

6.1. Business and liquid metal technology activities

The preliminary questions in the survey intend to establish the activities and interests related to liquid metal (LM) technology of Nuclear Energy Agency (NEA) Expert Group on Liquid Metal Technology (EGLM) members. Since the current scope of the EGLM aims to support the development of construction codes used for design, the fact that all EGLM members are research organisations offered the first indication that relevant data would mostly be generated by research projects rather than any large-scale LM materials qualification programme. Industrial feedback is considered through interactions with industrial partners of various liquid metal cooled reactor projects.

Comments in Sections 3.2 and 3.4 demonstrate the varied technical interests of the respondent organisations, making reference to LBE-cooled ADS, lead-cooled fast reactors and Na-cooled fast reactors; corrosion behaviour in both static and flowing LM environments and component manufacture. As the explanatory comments are shown in Chapter 5, these wide-range activities related to liquid metal technologies change into varied materials properties requirements.

6.2. Materials property data

The results of the materials property parts of the survey are summarised in Table 6 (where the test types, material classes, and data access levels are listed for each respondent) and Table 7 (which lists the materials in each class). Both tables provide, in the scope of the survey, a convenient way to locate data corresponding to the properties and materials of interest.

6.2.1. Origins of design data

Design data are derived from experimental data and thus there is an inherently close relation between the two. Typically, design data are represented by an equation describing a conservative relationship between the dependent variable (the property of interest) and the independent variable (such as temperature, stress, etc.). The conservatism in the relationship represents a built-in safety factor that accommodates experimental scatter, potential excursions outside standard operating conditions, etc.

Design data will often be derived from test data generated in research programmes designed specifically to establish the performance of materials under the conditions in which components will operate i.e. materials qualification tests.

6.2.2. Prior evaluations of data availability

The materials selection and qualification are critical issues for the successful development of nuclear systems. Safe operation of nuclear components relies on a number of physical and thermo-mechanical properties of the structural materials used for their fabrication. These properties are usually determined in testing laboratories on laboratory-scale specimens according to prevailing standards. Such standardised testing procedures are available for a number of (but not all) properties but their application to the specific conditions of the advanced nuclear systems is not straightforward. Indeed, the specimen size used nowadays is usually smaller than the standard one. Because of the space limitations inherent to materials irradiation, most of the samples, including for example tensile, fatigue and fracture toughness specimens are smaller and often adapted to the available space. Consequently, the data that are generated worldwide exhibit major discrepancies because of the variety of testing procedures and evaluation methodologies. Several efforts were dedicated to investigate materials behaviours in Generation IV operational conditions, to find out criteria for the correct use of these materials in relevant reactor applications and complement the materials researches, within the frame of the European Energy Research Alliance (EERA) guidelines.

In this framework, the MATTER project performed research studies on the materials behaviour in Generation IV operational conditions and established criteria for the correct use of these materials in reactor applications.

In the scope of the FP7 MATTER project and the actual version of the NEA HLM handbook [1], an intensive literature survey was performed to assess the available data. The scatter of the data could be related either to inadequate testing procedures applied by some researchers and more generally by the lack of accepted testing procedures for corrosion tests in LM. On the other hand, the phenomena of localised corrosion phenomena that could not be linked with clear experimental conditions (like temperature, oxygen content or flow velocity) provides another source of uncertainty. Although some general rules can be established at which conditions corrosion becomes an issue, the data existing today are still due to the above described uncertainties unsuitable for implementation in a construction code.

Concerning the data in a sodium fast reactor environment, numerous studies were performed in the 1980s to establish the limited impact of sodium on mechanical properties used for design [work of Design and Construction Rules Committee (DCRC) for European fast reactor]. Nevertheless, only a few documents on this work are available and the work on the standardisation of test in liquid metal is relevant for tests in sodium as well.

However, based on the experimental activities performed in the framework of the MATTER project, a common protocol was agreed among the involved research centres as a first step for standardisation of tests in heavy liquid metals.

6.2.3. Reliability of experimental data

In order to develop construction codes, the extent to which tests are performed according to normative procedures (meaning recognised international standards), codes of practice and protocols, is of particular interest. Thus, the test types listed in Table 6 are colour coded according to whether they are compliant with international standards (black) or recognised guidelines (orange); or, are instead performed according to an ad-hoc procedure (red). As indicated to the EGLM [2], for data to be included in a construction code, such as RCC-MRx, it will perhaps be sufficient to perform the tests according to guidelines issued by competent organisations (such as the guidelines for LM testing developed in the scope of the EC-funded MATTER project). However, given that the FP7 MatISSE [3] (Materials innovation for safe and sustainable nuclear in Europe) project; the WELLMET and CERBERUS pilot projects taking place within the framework of EERA joint programme on nuclear materials (JPNM) sub-programme I[4]; and other H2020 project proposals, which all anticipate further refinement of testing procedures, the MATTER guidelines will likely be subject to revision. In any case, it should be expected that for data to be accepted as sufficiently reliable, the MATTER guidelines and those of any other project would need to be formally accepted by the organisation responsible for codification, for example AFCEN for RCC-MRx.

Given that no large-scale LM testing programmes have taken place, at the present time it is likely that research centres are the sole source of data for construction codes. Within the EU Horizon 2020 programme, the GEMMA project was established with the objective to resolve important remaining materials qualification issues for European fast reactors systems. In the circumstance that guidelines from research projects are formally accepted, where EGLM members have indicated having performed tests in a LM environment according to those guidelines, the data are potentially suitable for construction codes. In any case and irrespective of whether guidelines are formally accepted, where data are used for constructions codes their pedigree and reliability should be documented, otherwise there is no possibility to use the data.

6.2.4. Materials modelling

The EERA JPNM project highlights the need for the development of representative physics models to attain high-level understanding and predictive capability to underpin the development of design rules, e.g. in view of a 60-year life design.

Experimental data (primary data and its translation into design curves) is the main part for design, but modelling will help to interpret data and is needed to extrapolate from laboratory conditions to long-term operational conditions. Modelling will also be needed to derive "degradation factors". There are two JPNM pilot projects addressing HLM degradations and their modelling: modelling steel embrittlement by heavy liquid metals (MOSEL) LME and modelling of heavy-liquid metal corrosion of steels (MOLECOS).

With a view to establishing a European construction code for new reactor concepts, Comité Européen de Normalisation (CEN) CEN/WS 64 Phase II [5] has produced recommendations for 1) code evolution (CE) for the design of HLM reactors and 2) associated R&D proposals to derive the supporting data to be used in design. The CEN proposal suggests two approaches based on investigating the resistance to HLM degradation in terms of degradation of the mechanical properties, rather than in terms of corrosion. In this case, mechanical tests (creep, fatigue, tensile, etc.) undertaken in compliance with normative procedures are performed in HLM environment. If the mechanical properties in HLM are equal to air or better, the material is considered immune to HLM degradation. In this case, no further considerations are needed. Otherwise, the design needs to take into account degradation e.g. by environmental factors.

The R&D proposals give recommendations on how the resistance to HLM degradation can be demonstrated. To investigate immunity, test programmes are formulated to generate data that will help determine the immunity of the relevant material(s) to HLM degradation. To ensure reliability of the data, the tests should be performed in accordance with agreed standards and procedures. In this respect, where needed, the R&D work extends to the development of the standards and procedures. When immunity to environmental degradation can be demonstrated, no further considerations are needed and reference can be made to existing design curves. Otherwise, when immunity cannot be determined, the influence of environmental factors will need to be investigated and more extensive R&D undertaken.

As an example, T91 has demonstrated susceptibility to LME and is thus, ruled-out for structural components. While AISI 316 is not strongly sensitive to LME (where instead dissolution is the critical degradation mode), the resistance of weld joints to HLM degradation is largely unknown. In this context, the EERA JPNM WELLMET pilot project incorporates a mechanical test programme on welded components of AISI 316. Importantly, the test programme is based on the design requirements. If the results are as good as for AISI 316 base material, then AISI 316 satisfies the immunity requirement and is a candidate design material. On the basis of the results of its test programme, the final deliverables of WELLMET will include design rules.

Similarly, the EERA JPNM CERBERUS pilot project has been investigating the corrosion resistance of several materials to deliver design rules.

In the case of both WELLMET and CERBERUS, tests will be in accordance with best practices given that there are no normative procedures i.e. international mechanical testing standards for HLM reactor environments. Therefore, it is expected that WELLMET and CERBERUS will refine existing procedures for their eventual promotion to normative status. Concerning sodium coolant, several construction codes dedicated to the design of sodium reactors are available (ASME div 5, JSME, RCC-MRx, etc.), but these standards are not opened for the moment to other kind HLM reactors.

Table 6. Matrix of the findings of the mechanical testing activities*[8]

	EGLM member	Access	Materials				Corrosion				Creep				Small Punch		Relaxation		Fatigue						Fracture			Tensile		Irradiation		Crack Growth			Hardness			
			Ferritic + F/M	Austenitic	Low Alloy	Weldments	General	High T	Erosion	Fretting	Cyclic	Multiaxial	Torsional	Uniaxial	Creep	Tensile	Uniaxial	Multiaxial	High cycle	LCF - strain control	LCF - load control	Creep-fatigue	Thermal	Thermo-mechanical	Fracture toughness	Impact	Compression	Uniaxial	Multiaxial	Creep	Swelling	CCG	FCG	CFCG	Vickers	Brinell	Nano indentation	Other
1	CV Rez, Czech Republic		X	X			LM	LM						LM	Ref	Ref			LM Ref	Ref	LM Ref	LM Ref			LM Ref	Ref	Ref	LM Ref	Ref				LM		LM Ref		LM Ref	
2	Seoul National University, Korea		X	X			LM	LM																				LM										
3	CEA Saclay, France		X	X			LM Ref	LM Ref		LM		Ref						Ref						Ref				Ref										
4	CEA Cadarache, France		X	X		X										LM Ref				LM Ref	LM Ref	LM Ref						LM Ref					LM Ref		Ref		Ref	
5	University of Lille, CNRS, France		X	X			LM	LM	LM							Ref Irr					LM Ref				Ref			LM Ref Irr			Ref						Ref	
6	JAEA, Tokai (ADS), Japan		X	X	X			LM						LM																								
7	JAEA, Oarai (FR), Japan										Ref			Ref			Ref			Ref								Ref										
8	INL, United States		X	X		X	LM Ref	LM Ref	LM	LM		LM Ref	Ref	LM Ref			Ref Irr	Irr	Ref	LM Ref Irr	LM Ref	LM Ref	LM Ref	Ref	Ref	Ref	Ref	Ref Irr	Ref			Ref	Ref		Ref Irr	Ref Irr	Ref Irr	
9	KIT, Germany		X	X		X	LM Ref	LM Ref	LM	LM				LM Ref			Ref		Ref	Ref	Ref	Ref	Ref	Ref		Ref	Ref	Ref										
10	ENEA, Italy						LM Ref	LM Ref	LM Ref	LM Ref																					Ref				LM	LM		
11	IPPE, Russia		X	X			LM Ref	LM Ref						LM Ref		Ref			Ref	Ref	Ref				Ref	Ref		Ref					Ref		Ref	Ref	Ref	
12	CIEMAT, Spain		X	X			Ref	Ref			Ref				Ref	Ref	Ref		Ref	Ref		Ref	Ref	Ref	Ref	Ref	Ref	Ref		LM Ref	LM Ref	Ref	Ref	Ref	Ref		Ref	
13	JRC-Petten, European Union		X	X			LM Ref Irr	LM Ref Irr	LM Ref Irr		LM Ref									LM Ref	LM Ref				LM Ref Irr	LM Ref Irr	LM Ref Irr	LM Ref Irr	LM Ref Irr		LM Ref Irr		LM Ref		LM Ref Irr			

*Color coding: green: open; red completely restricted; abrupt green-red; open or restricted; and gradual green-red; nominally open to the EGLM members but with conditions

Source: OECD/NEA, 2020.

8. Access colour-coding-green: open; red completely restricted; abrupt green-red; open or restricted; and gradual green-red; nominally open to the EGLM but with conditions.

Test category acronyms-LM: liquid metal environment.

Test category colour-coding-black: testing compliant with International Standard; orange: testing compliant with guidelines; and red: ad-hoc procedure.

Table 7. Matrix of materials tested by respondent organisations

			Ferritic + Ferritic/Martenstitic						Austenitic											Low Alloy	Weld	Coated		
	EGLM member	Access	T91	HT9	ODS	FeCrAl	Modified 9Cr-1Mo	316	316L	316LN	316L(N)	316FR	304	304L	321	15-15Ti	HTUPS-4	Alloy 800	253 MA	2.25Cr 1Mo	T91/316L	$T91_{coated}$	$316L_{coated}$	$15\text{-}15Ti_{coated}$
1	CV Řež, Czech Republic		X		X				X															
2	Seoul National University, Korea		X	X		X			X				X				X							
3	CEA, France		X		X				X		X			X				X	X					
4	CNRS, France		X		X				X	X						X					X	X		
5	JAEA, Tokai (ADS), Japan		X						X															
6	JAEA, Oarai (FR), Japan						X	X				X	X		X					X				
7	INL, United States																							
8	KIT, Germany																							
9	ENEA, Italy		X						X				X			X					X	X	X	X
10	IPPE, Russia																							
11	CIEMAT, Spain																							
12	JRC-Petten, European Union		X		X				X							X								
13	SCK•CEN, Belgium		X						X							X								

Source: OECD/NEA, 2020.

Where the candidate materials and operating conditions are known for given systems and components, data of potential interest can be located among the EGLM members. For example, referring to the candidate materials for different designs examined in the scope of MATTER, presented in Table 8 and cross-referencing with Table 7, six organisations have experience testing AISI 316L stainless steel.[9] While the data at two of these organisations has restricted access, two other organisations make their data openly available, and two others have a mixed data access policy.

9. It should be noted that the Table 7 reference is to 316L, which might in fact mean 316L grade (of which there are variants) rather than AISI 316L /EN 1.4404 specifically.

Table 8. Candidate materials for different reactor designs

	GFR (ALLEGRO) [6]		LFR (ALFRED)[16]		SFR (ASTRID)[16]		SFR (JSFR)[10]		MYRRHA	
Components	Candidate material(s)	Replaceability	Candidate material(s)	Replaceability	Candidate material(s)	Replaceability	Candidate material(s)	Replaceability	Candidate material(s)	Replaceability
Fuel claddings	ODS SiC_{fiber}/SiC	Yes	ODS $T91_{coated}$ 15-15Ti	Yes	ODS 15-15Ti	Yes	ODS PNC316 (Mod.316SS)	Yes	T91 15-15Ti	Yes
In-core applications	T91 SS316L(N) SiC_{fiber}/SiC TiC, NbC Zr_3Si_2 Cermet	Yes	T91 SS316L	Yes	EM10 316L(N) AIM1 15-15Ti OSD steels	Yes	PNC-FMS SUS316	Yes	T91	Yes
In-reactor components	T91 S316 Ni Fe/Cr/Ni based alloys	Yes/No	SS316L	Yes/No	SS316LN	Yes/No	316FR	No	T91	Yes/No[11]
Reactor vessel	T91	No	SS316L	No	SS316LN	No	316FR	No	SS316L	No
Primary pump	SS316L(N)	No	SS316L Ti_3SiC_2	Yes	SS316LN T91	No	Mod.9Cr-1Mo	No	-	No
Steam generator, heat exchanger systems	SS316L(N) Ni-base alloys	No	T91	Yes	SS316LN T91	No	Mod.9Cr-1Mo	No	T91	No

Source: OECD/NEA, 2020.

10. This project FaCT (Fast Reactor Cycle Technology Development Project) was suspended in 2011 due to the TEPCO Fukushima #1 NPP Accident.

11. One of the design principles of MYRRHA is that everything is replaceable except for the vessel itself.

Table 9. Candidate materials for the BN-1200 reactor design [7] and CLEAR I

Components	SFR (BN-1200)		LFR (CLEAR-I)	
	Candidate material(s)	Replaceable	Candidate material(s)	Replaceable
Fuel claddings	Cr16Ni15Mo2MnTiSi(CW)	Yes	15-15Ti(CW)	Yes
In-core applications	Cr13MnNb (wrapper material)	Yes	15-15Ti (wrapper material)	Yes
In-reactor components	Cr 18 Ni 9	Yes	AISI316L	Yes
Reactor vessel	Cr 18 Ni 9	No	AISI316L	No
Primary pump	SS stellite	No	AISI316L	Yes
Steam generator, heat exchanger systems	10Cr 2 Mo VNB	No	AISI316L	Yes
Intermediate heat exchangers	Cr 16 Ni 11 M 3 (shell) Cr 18 Ni 9 M 3 (tube)	No	AISI316L	Yes

Source: OECD/NEA, 2020.

For the specific test types and properties, the information presented in Tables 8 and 9 is too high level and more details on the operating conditions of individual components are needed. Although the survey has not yielded information in this respect, the respondents of the survey have indicated a broad range of activities in the domain of LM technology. As these activities are aligned with the required components and systems, relevant data can be expected in the future. For example, where respondents of the survey make reference to MATTER (Section 4.2 explanatory comments), the data are either relevant to develop common testing and evaluation procedures for LM corrosion; fracture toughness testing in LBE; or creep testing of thin-walled components (as per MATTER deliverables D3.4 and D3.6; D3.2 and D3.5; and D3.1, D3.3, and D3.7, respectively); or intend to verify or adapt design rules for T91 components in respect of ratcheting, creep and creep-fatigue resistance (as per MATTER deliverables D4.4, D4.5, D4.6, and D4.7).

The survey of materials properties also identified an interest to develop a database of thermal and physical properties. Before investing effort in this respect, it should be determined to what extent such a database is relevant to the expert group. Some thermal and physical properties will facilitate structural modelling and hence an understanding of the stress distributions, which is relevant to the mandate of the EGLM. However, while materials modelling may yield interesting insights into materials behaviour, this is not necessarily relevant to the mandate of the EGLM.

6.3. Data requirements

The preference of EGLM members for primary data generated from experiments rather than secondary data recovered from publications is suggestive either of a lack of confidence in secondary data or, more likely, given the prior assessment of data availability performed in the scope of the MATTER project, a lack of primary data. Typically, a lack of confidence in data would be attributed to a lack of metadata limiting the opportunities to reuse the reported data. For mechanical properties data, it could be improved by confirming that the tests have been performed according to international standards or recognised procedures. Where there is a lack of data, the EGLM will need to identify the gaps and make their requirements known in anticipation of future testing programmes being planned accordingly.

6.4. Risks and risk mitigation

6.4.1. Data collection

Due to the EGLM scope extending to all LM environments, the range of relevant structures, systems and components is very broad and attempting to collect data without SSC prioritisation risks overburdening the EGLM. With a view to mitigating this risk, SSC prioritisation will in turn prioritise the materials and conditions for which data are required. Data collection can progress as priority needs are addressed even if (due to limitations on resources and time) the exercise is not fully comprehensive.

6.4.2. Gap analysis

To determine the EGLM materials properties requirements, inventories of the systems and components for the designs of interest should be carried out. Where gaps in the database are identified, the required materials property data will then need to be prioritised. Given that interest in LM technology is not limited to the NEA EGLM, it can be expected that other membership organisations will have similar requirements and have perhaps already performed work relevant to EGLM interests. Duplication of effort, redundancy and possible contradictory outcomes are potential risks that can be mitigated through close co-operation with such organisations.

6.5. Data sources

With a view to establishing a materials properties database of relevance to LM technology, Table 10 lists potential sources of materials property data.

Table 10. Potential sources of materials property data

Source	Owner	Source type	Data type	Comments
EGLM	Individual EGLM members	Databases, electronic reports and physical reports	Primary and secondary	See Chapter 4 for details.
NEA Data Bank	OECD	Database	Unknown	While the NEA Data Bank does not extend to materials property data, in the scope of CSNI [8] other WGs operate databases independently of the NEA Data Bank, with third-party 'clearinghouses' managing data. CODAP [9] is one example.
NEA Handbook of HLM	OECD	Electronic report		www.oecd-nea.org/science/pubs/2015/7268-lead-bismuth-2015.pdf
Fusion Materials Database	EUROfusion, IO, F4E	Database	Secondary	Presently decommissioned but with the possibility of migration to MatDB.
Generation IV Materials Handbook	US DoE	Database	Secondary	Hosted by ORNL at https://gen4www.ornl.gov.
MatDB	European Commission	Database	Primary	Hosted by JRC at https://odin.jrc.ec.europa.eu.
MATTER	MATTER consortium	Electronic reports	Secondary	Public deliverables available from http://www.eera-jpnm.eu.
Materials Science and Engineering: A	Elsevier	Journal	Secondary	See for example DOI: 10.1016/j.msea.2014.09.003.
Nuclear Engineering and Design	Elsevier	Journal	Secondary	See for example DOI: 10.1016/j.nucengdes.2010.08.005
Journal of Nuclear Materials	Elsevier	Journal	Secondary	See for example DOI: 10.1016/j.jnucmat.2015.06.021, DOI: 10.1016/0022-3115(80)90136-1.
Corrosion Science	Elsevier	Journal	Secondary	See for example DOI: 10.1016/j.corsci.2015.10.003.

Source: OECD/NEA, 2020.

6.6. Recommendations

Recommendations for concrete actions in support of the objectives of EGLM in the context of materials properties, are given as follows:

1. Survey: several shortcomings remain to be addressed for this report to provide sufficient information for the development of constructions codes for LM technologies:

- 1.1 Operating conditions: although the report provides a comprehensive overview of the activities of EGLM members generating materials property data relevant to LM technologies, it is not sufficiently advanced to allow construction codes to be developed. For this to be feasible, operating conditions should be documented, such as temperature, loading conditions, environment, etc. of the relevant components. In parallel, conditions under which the tests detailed in Table 6 were performed should be indicated. With this information available, the relevant data can be identified and used for the development of construction codes.

The codes used by the different organisations are:

- RRC-MRx;
- ASME;
- JSME;
- KEPIC (Korea Electric Power Industry Code) [10]

- 1.2 Sodium-cooled systems: with its focus on MATTER and JPNM activities and the specific example of T91 and 316, it is acknowledged that the present report is somewhat biased towards HLM and that there is a requirement to better consider sodium-related activities of EGLM members. A further iteration of this report should thus consider new projects undertaken in support to BN-1200, EBR-II, PGSFR and ASTRID, etc.

2. Databases: with several EGLM members having indicated a willingness to make their data available, an effective data sharing infrastructure is required:

- 2.1 Materials property database(s): with a view to creating a database of materials properties of relevance to the EGLM, it can reasonably be expected that primary data [11] could be provided by EGLM members, with secondary data [12] coming from a close examination of the data sources listed in Table 10. This circumstance will likely necessitate the use of two different database applications.
- 2.2 Database agreement: similarly to the practice in other NEA expert groups (such as the CSNI EGs), a database agreement should be formulated to define the terms and conditions under which data (primary and secondary) will be made available amongst EGLM members.

3. Engagement: the EU projects MATTER [13] and GETMAT [14,15] undertook extensive literature reviews, generated experimental data relevant to the EGLM mandate and delivered guidelines on LM testing procedures, all of which provide a starting point for EGLM activities on materials selection and database development. In this context, the following actions are recommended:

- 3.1 Test procedures: irrespective of the volume of data collected, data reliability will determine the extent of reuse in construction codes. In the absence of any normative procedure for mechanical or corrosion testing in LM environments but with prenormative research having been performed in MATTER, the EGLM can help promote the prenormative research to normative status.
- 3.2 Liaisons: with a view to avoiding redundancy, active dialogue with organisations in the domain of LM technology is recommended, including H2020 GEMMA, CEN/WS 64-II and EERA JPNM [16].
- 3.3. Cataloguing: given that various projects continue to assess and prioritise materials for reactor components operating in an LM environment, EGLM activities should be aligned accordingly, making sure to contribute to rather than duplicate or worse contradict their findings. With this in mind, beyond establishing database(s) or primary and secondary data, the EGLM could usefully undertake to catalogue all past

and on-going activities generating materials property data relevant to LM, thereby allowing informed planning of future activities.

4. Data management plan (DMP): to facilitate the development of database(s) and the cataloguing of activities generating materials property data relevant to LM, the present report could evolve into a data management plan with an international scope.

7. Conclusions

This survey was carried out by the Nuclear Energy Agency (NEA) Expert Group on Liquid Metal Technology (EGLM) on materials data management requirements. The findings indicate that EGLM membership consists entirely of research organisations and as such research data are available for the materials properties of relevance to LM technologies. Whether these data have relevance for construction codes depends in large part on two factors. Firstly, the data need to correspond to the operating conditions (stress, temperature, fluence, LM environment, etc.) that components are expected to experience. Given that materials research undertaken by EGLM members will correspond to present research imperatives, it is reasonable to assume that data available are relevant. Where there is less certainty with regard to the reliability of data and whether the testing procedures are compliant with the guidelines under development in the scope of research projects (and that, at present, still need formal acceptance). Further, it is acknowledged that the report is biased to heavy liquid metal (HLM) systems and that future work should aim to give equal consideration to sodium-cooled systems. In any event, with a view to contributing to the existing database of relevance to LM technology, concrete actions could include collating an inventory of components and their operating conditions; assessing the extent of available data and hence gaps in the database and promoting guidelines on LM testing to normative status. To facilitate these objectives, it is recommended that the present report evolve into a data management plan (DMP) that is revised regularly over the term of the EGLM.

References

[1] NEA (2015), Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-hydraulics and Technologies, OECD-NEA, NEA No. 7268, OECD, Paris.

[2] NEA (2016), "Summary Record of the third meeting of the Expert Group in Liquid Metal Technology", OECD Publishing, Paris, NEA/NSC/WPFC/DOC(2016)22.

[3] FP7-EURATOM-FISSION , Materials' Innovations for a Safe and Sustainable nuclear in Europe (MATISSE), http://cordis.europa.eu/project/rcn/110016_en.html, retrieved 2 December 2016.

[4] EERA JPNM , Sub-programme 1, Materials for ESNII demonstrators and prototypes, www.eera-jpnm.eu/?q=jpnm&sq=sub1, retrieved 2 December 2016.

[5] European Committee for Standardization (2016), CEN/WS 64 – Phase 2 (2016), Design and Construction Code for mechanical and civil engineering for Gen II to IV nuclear facilities; www.cen.eu/news/workshops/Pages/WS-2014-006.aspx, retrieved 22 November 2016.

[6] FP7-EURATOM-FISSION, MATerials TEsting and Rules (MATTER); "Structural Materials – Main Candidate Materials"; www.matterfp7.it/Layout/matter/index.asp?page=/upload/moduli/pagine/public/MainCandidateMaterials.html&target=&tit=MainCandidateMaterials, retrieved 6 May 2017.

[7] IAEA (2006), *Fast Reactor Database* , Update, IAEA-TECDOC-1531, IAEA, Vienna.

[8] CSNI, Committee on the Safety of Nuclear Installations (2017), www.oecd-nea.org/nsd/csni, retrieved 8 May, 2017.

[9] NEA Joint Project , Component Operational Experience, Degradation and Ageing Programme (CODAP) Project; www.oecd-nea.org/jointproj/codap.html, retrieved 8 May 2017.

[10] KEPIC, derived primarily from ASME (SI version), IEEE, AISC (American Institute of Steel Construction). RCC-M has been used for French units only when there were discrepancies from KEPIC; www.kepic.org/en/main/main.php

[11] Kitchin, Rob (2014), *The Data Revolution: Big Data, Open Data, Infrastructures & their Consequences*. United States: Sage Publications Ltd., DOI: 10.4135/9781473909472, p. 6.

[12] Boslaugh, Sarah (2007), *Secondary Data Sources for Public Health: A Practical Guide*, Cambridge University Press, DOI: 10.1017/CBO9780511618802, pp. 1-3.

[13] FP7-EURATOM-FISSION, MATerials TEsting and Rules (MATTER) project;http://cordis.europa.eu/project/rcn/97428_en.html, retrieved 2 December 2016.

[14] GEn IV and Transmutation MATerialsfrom; http://cordis.europa.eu/project/rcn/85745_en.html.

[15] H2020 MatISSE project, https://cordis.europa.eu/project/id/648779/fr

[16] EERA JPNM Joint Programme on Nuclear Materials of the European Energy Research Alliance; www.eera-jpnm.eu, retrieved 22 November, 2016.

Appendix 1 – Survey template

1. What is the nature of your organisation?

Research	
Industry	
Public authority	
Other	

Comments:

2. What are the activities related to liquid metal technologies undertaken at your organisation?

Experimental studies	☐
Modelling	☐
Monitoring activities	☐
Component manufacture	☐
Other	☐

Comments:

3. What are the types of data used at your organisation in the context of its liquid metal activities?

Primary (from tests)	☐
Primary (recovered from publications)	☐
Design	☐
Observational	☐
Other	☐

Comments:

4. If your organisation undertakes materials testing (either in a liquid metal environment or reference tests in air, vacuum, etc.), please indicate the test types; whether tests extend to irradiated specimens; and whether the tests were performed in compliance with a recognised international standard.

TEST TYPE	LIQUID METAL	REFERENCE TESTS	IRRADIATED SPECIMENS	STANDARDS COMPLIANT
Corrosion				
General	☐	☐	☐	☐ ☐ ☐
High temperature	☐	☐	☐	☐ ☐ ☐
Erosion	☐	☐	☐	☐ ☐ ☐
Fretting	☐	☐	☐	☐ ☐ ☐
Creep tests				
Cyclic creep	☐	☐	☐	☐ ☐ ☐
Multiaxial creep	☐	☐	☐	☐ ☐ ☐
Torsional creep	☐	☐	☐	☐ ☐ ☐
Uniaxial creep	☐	☐	☐	☐ ☐ ☐
Small punch tests				
Creep	☐	☐	☐	☐ ☐ ☐
Tensile/Fracture	☐	☐	☐	☐ ☐ ☐
Relaxation tests				
Uniaxial	☐	☐	☐	☐ ☐ ☐
Multiaxial	☐	☐	☐	☐ ☐ ☐
Fatigue tests				
High cycle fatigue	☐	☐	☐	☐ ☐ ☐
Low cycle fatigue -	☐	☐	☐	☐ ☐ ☐
Low cycle fatigue - load	☐	☐	☐	☐ ☐ ☐
Creep-fatigue	☐	☐	☐	☐ ☐ ☐
Thermal fatigue	☐	☐	☐	☐ ☐ ☐
Thermo-mechanical	☐	☐	☐	☐ ☐ ☐
Fracture tests				
Fracture toughness	☐	☐	☐	☐ ☐ ☐
Impact	☐	☐	☐	☐ ☐ ☐
Tensile tests				
Compression	☐	☐	☐	☐ ☐ ☐
Uniaxial tensile	☐	☐	☐	☐ ☐ ☐
Multiaxial tensile	☐	☐	☐	☐ ☐ ☐
Irradiation tests	☐	☐	☐	☐ ☐ ☐
Irradiation creep	☐	☐	☐	☐ ☐ ☐
Swelling	☐	☐	☐	☐ ☐ ☐
Crack growth tests				
Creep crack growth	☐	☐	☐	☐ ☐ ☐
Fatigue crack growth	☐	☐	☐	☐ ☐ ☐
Creep-fatigue crack	☐	☐	☐	☐ ☐ ☐
Hardness				
Vickers	☐	☐	☐	☐ ☐ ☐

Brinell	☐	☐	☐	☐ ☐ ☐
Nano indentation	☐	☐	☐	☐ ☐ ☐
Other				
Other	☐	☐	☐	☐ ☐ ☐

Comments (including details of materials tested):

5. From the perspective of your organisation, please indicate the relative relevance of individual test types to liquid metal technologies on a scale of 1 to 3 (blank-none; 1-low; 2-intermediate; 3-high).

Corrosion	
General	
High temperature	
Erosion	
Fretting	
Creep tests	
Cyclic creep	
Multiaxial creep	
Torsional creep	
Uniaxial creep	
Small punch tests	
Creep	
Tensile/Fracture	
Relaxation tests	
Uniaxial	
Multiaxial	
Fatigue tests	
High cycle fatigue	
Low cycle fatigue - strain control	
Low cycle fatigue - load control	
Creep-fatigue	
Thermal fatigue	
Thermo-mechanical fatigue	
Fracture tests	
Fracture toughness	
Impact	
Tensile tests	
Compression	
Uniaxial tensile	
Multiaxial tensile	
Irradiation tests	
Irradiation creep	
Swelling	
Crack growth tests	
Creep crack growth	
Fatigue crack growth	

Creep-fatigue crack growth	
Hardness	
Vickers	
Brinell	
Nano-indentation	
Other	
Other	

Comments:

6. Besides the already considered mechanical properties, please indicate which physical and thermal properties if any are relevant, either directly or in the context of modelling.

Young’s modulus	☐
Shear Modulus	☐
Poisson’s ratio	☐
Density	☐
Electrical resistivity	☐
Linear thermal expansion	☐
Thermal conductivity	☐
Emissivity	☐
Specific heat	☐
Thermal diffusivity	☐
Other	☐

Comments:

7. Availability of the data referenced in this survey.

Located at the respondent organisation and available from a database	☐
Located at the respondent organisation and available in an electronic format	☐
Located at the respondent organisation and available in a physical format	☐
Not located at the respondent organisation	☐

Comments:

8. Accessibility of the data referenced in this survey.

Owned by the respondent organisation and openly available	☐
Owned by the respondent organisation and available to EGLM members only	☐
Owned by the respondent organisation but entirely restricted	☐
Not owned by the respondent organisation	☐

Comments (including details for obtaining any openly accessible data):