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## Standard procedures for Na loop operation and measurements treatment methodologies

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## Summary

Overview on operation of sodium facilities based on experiences of the partners on different facility sizes. Facility and test set up, status of instrumentation as well as sensor accuracy is added. Hints for hibernations are included to complete "cradle to grave" live cycle. Final version with contributions from IPUL, HZDR and KIT

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## Approval

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## CONTENTS

1	Purpose .....	9
2	General procedures for sodium facilities .....	13
2.1	Commissioning phase.....	13
2.1.1	Dry, without Sodium.....	13
2.1.2	Hot and Sodium filled .....	16
2.1.3	Sodium purification. ....	18
2.1.4	Hot trap.....	19
2.2	Test of safety installations and provisions .....	20
2.2.1	Qualification tests .....	20
2.2.2	Eddy current flow meters and its calibration in sodium flows.....	23
3	SENSOR interpretation.....	32
3.1	Signal analysis and interpretation .....	32
3.2	Signal to noise ratio .....	35
4	Integration of test sections into facility.....	35
4.1	Design and interface definition.....	35
4.2	Test section preparation.....	35
4.2.1	Commissioning phase.....	35
4.2.2	Qualification phase .....	36
4.2.3	Experimental phase .....	36
4.3	Shut down.....	36
4.3.1	Shut down steps .....	36
4.3.2	Emergency shut down steps.....	36
4.3.3	Short term shut down.....	36
4.3.4	Long term shut down .....	37
4.4	Dismantling of components.....	37
4.4.1	Safety provisions .....	37
4.4.2	Transport to cleaning station.....	37
4.4.3	Cleaning procedure.....	37
5	Hibernation .....	38
5.1	Conditions for preservation .....	38
5.2	Shut down to hibernation .....	39
5.3	Supervision of hibernation.....	39
6	Summary .....	39
7	Appendix.....	40



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7.1	List of reference documents.....	40
7.2	Example for KIT facility ramp-up procedures.....	41
7.3	Facilities inside KIT in LIMCKA .....	42
7.4	Facilities and procedures at HZDR .....	42



## List of Figures

Figure 1.1 A typical basic layout of alkali metal contour (installation).	10
Figure 1.2 TESLA (IPUL) layout of sodium metal contour with 2 electromagnetic pumps (EMP) and heating system.	11
Figure 1.3 Sodium and GaInSn fleet of experimental facilities dedicated to thermo-fluid-dynamics, material qualification and system verification (status indicated by colour).	12
Figure 1.4 Schematics of KASOLA with the planned CSP extension, the loop with the storage tank separated and a preliminary sketch of the basic look for TRACE simulation (left to right)	12
Figure 2.1 Operational stages stage of KASOLA PLC.	15
Figure 2.2 PLC operation window comprising all KASOLA systems.	15
Figure 2.3 Solubility of Oxygen in Sodium, theory and measurements	19
Figure 2.4 Cross-section of electromagnetic conduction flow meter having round pipe channel (from [9]).	20
Figure 2.5 Open magnetic system for easy installing and removal of CFM from the liquid metal piping.	21
Figure 2.6 Large scale CFM used at KASOLA	21
Figure 2.7 CFM calibration system	22
Figure 2.8 Results of CFM calibration on InGaSn loop.	22
Figure 2.9 Results of CFM calibration for Na.	23
Figure 2.10 Simplified scheme of the immersed ECFM	24
Figure 2.11 ECFM sensor that was used for the measurements at the NATAN loop	25
Figure 2.12 Test channel for simultaneous measurements with ECFM and UDV at the NATAN loop.	25
Figure 2.13 Frequency sweep to determine the optimal excitation frequency of the ECFM in sodium.	26
Figure 2.14 Measurement results for the voltage magnitude at sodium temperatures of 160 °C and 240 °C.	27
Figure 2.15 Measurement results for the phase shift at sodium temperatures of 160 °C and 240 °C.	27
Figure 2.16 Velocity profiles measured at slot 1 for different pump currents	29
Figure 2.17 Velocity profiles ( $I_{\text{pump}} = 5\text{A}$ ) measured from opposite sides (slot 1 and slot 3).	29
Figure 2.18 Simplified scheme of the TECFM sensor.	30
Figure 2.19 Numerical simulation results of the sensor output for the movement of the zero crossing point $x_0$ over 500 $\mu\text{s}$ at three different flow velocities $v$ .	30



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Figure 2.20 Measurement results for the flow velocity of the TECFM sensor in liquid sodium at 180 °C. The slope of the dashed red line is equal to the respective measured velocity.	31
Figure 3.1 The negative of the absolute thermoelectric power for Na and for Pt and values given by Cook and Fritsch for Na [11]. The thermoelectric power of Pt relative to Na ( $dE/dT$ ) is Included [12].	33
Figure 3.2 Honeywell SS490 Series Hall sensor signal dependence on temperature at zero magnetic field.	34
Figure 4.1 Lattice box for cleaning of small components (left) and partially blocked pipe (right)	38
Figure 7.1 Example for test rig and facility planning and design	41
Figure 7.2 Schematic view of the sodium loop ( <a href="https://www.hzdr.de/db/Cms?pOid=52201&amp;pNid=331">https://www.hzdr.de/db/Cms?pOid=52201&amp;pNid=331</a> )	43



## List of Tables

Table 3.1	Summary of the recommended correlations for main thermophysical properties of liquid sodium (Na) ( $p \sim 0.1$ Mpa, except critical parameters and the saturated vapour pressure) [10].	32
Table 7.1	List of liquid metal facilities operate within Liquid Metal Competence Center Karlsruhe	42





## Glossary

AC	Alternating current
ADRIANA	ADvanced Reactor Initiative And Network Arrangement
ALIP	Annular linear induction pump
ASR	Automatic sodium release (to storage tank)
CSP	Concentrating Solar Power (using sodium as HTF)
CFM	Electromagnetic Conduction Flow Meters
DC	Direct current
DuT	Device under Test
ECFM	Eddy Current Flow Meter, and Transient ECFM (TECFM)
EMP	Electromagnetic pump
HTF	Heat transfer Fluid
I&C	Instrumentation and Control
ISIR	In-Service Inspection & Repair
ISS	Interlock Safety System
LIMCKA	Liquid Metal Competence Center Karlsruhe
LM	Liquid metal
KISS	KIT Safety Information System
KIT	Karlsruhe Institute of Technology
Na	chemical symbol for sodium. It is used as an abbreviation
NADYNE	French acronym for dynamic sodium
NaK	the chemical eutectic system: sodium-potassium alloy
NI	National Instruments (Company supplying sensors and I&C)
PLC	Programmable Logic Controller
SWR	Sodium-water reactions
TC	Thermocouple
TUSHT	French name of a high-temperature ultrasonic transducer
UDV	Ultrasonic Doppler Velocimetry

*Priming chamber:* This tank is used to prime the pump used to fill the sodium system. It is filled with sodium from the storage tanks and is positioned above the level of the filling pump.



## **Attention**

This report has been written based on document Nos. [1] and [2] and comprises information gathered at KIT during the ATEFA, SOLTEC and KASOLA programmes.

## **PREAMBLE**

The recommendations in this document take into account existing experiences at European laboratories operating liquid metal facilities, here focussed on sodium. In addition, experiences with sodium application in energy technology (concentrating solar power, CSP) are considered, for safety provisions during maintenance operations.

KIT has long experiences originating from sodium fast reactors leading to the SMR type: SNR-300. Also lead, SBE and PbLi as well as GaInSn are used in different experimental facilities. Nowadays, research fields are high temperature materials qualification, CSP, AMTEC and target medium for accelerator technologies. The wider range allows a broad spreading of the technology and the implications with respect to design and safety provisions.

HZDR operates different facility with lead alloys, GaInSn and the sodium loop NATAN (see section 7.4).

IPUL experience mainly is based on the sodium facilities AMPERE and TESLA.

## **1 PURPOSE**

The deliverable 2.3.2 comprises the experiences gained in the last 50 years in building and operation of liquid metal facilities at KIT, CEA, HZDR and IPUL.

Facilities using liquid metal high temperature heat carriers are labour-intensive and expensive equipment. Their operation is associated with a high level of safety and line-specific safety requirements. In such facilities, many systems, assemblies and hardware are original and their constructive performance is original.

The high chemical activity and other features of alkali metals raise the additional difficulties of operating liquid metals systems.

Such systems are different by:

- leak tightness;
- the use of high-purity inert gases in such systems and, in many cases, the equipment for the purification of gases;
- use of high purity alkali metals, as well as special equipment and methods for their treatment;
- use of special heaters in the loop;
- the presence of facilities for the selection and analysis of samples in order to determine the composition and purity of the heat carrier.

The nature of these premises and devices is determined in accordance with the instructions of the installation category: the amount of liquid-metal coolant contained therein, the danger, the heat carrier's activity, as well as, to some extent, the maximum temperature accepted for the contour. In

order to increase the reliability it is desirable to duplicate individual units of installations, as well as power supply and heat carriers. In many cases, it is also necessary to develop a remote control, a programmed automatic start and stop of the facility, as well as automatic emergency protection.

Despite of the widespread use of liquid-metal systems in laboratory and industrial installations, their elements, design and placement options are not systematized to this day. One of the reasons is that every facility might have different installation specifics in concepts using heat – transfer agent. Nevertheless, the basic concepts of liquid metal facilities and installations for different studies and exploitation are similar. The basic concept and main components of such an installation is shown in Figure 1.1.

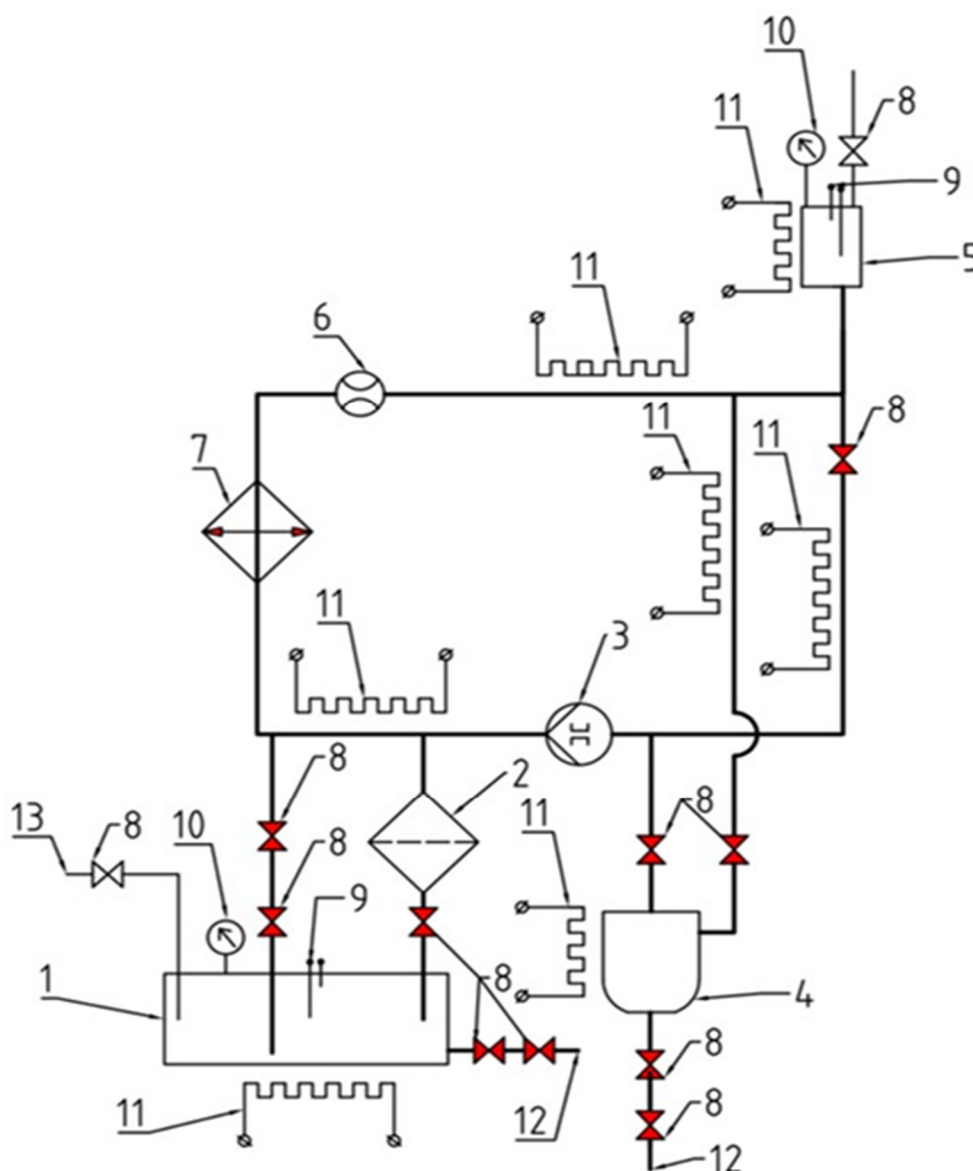


Figure 1.1 A typical basic layout of alkali metal contour (installation).

1 - supply tank; 2 - filter; 3- electromagnetic pump; 4 – cold trap; 5 – expansion tank; 6 – flow meter; 7 – heat exchanger; 8 – valves; 9 – level meters; 10 – pressure sensors; 11 – heaters, 12 – drainage, 13 – gas supply

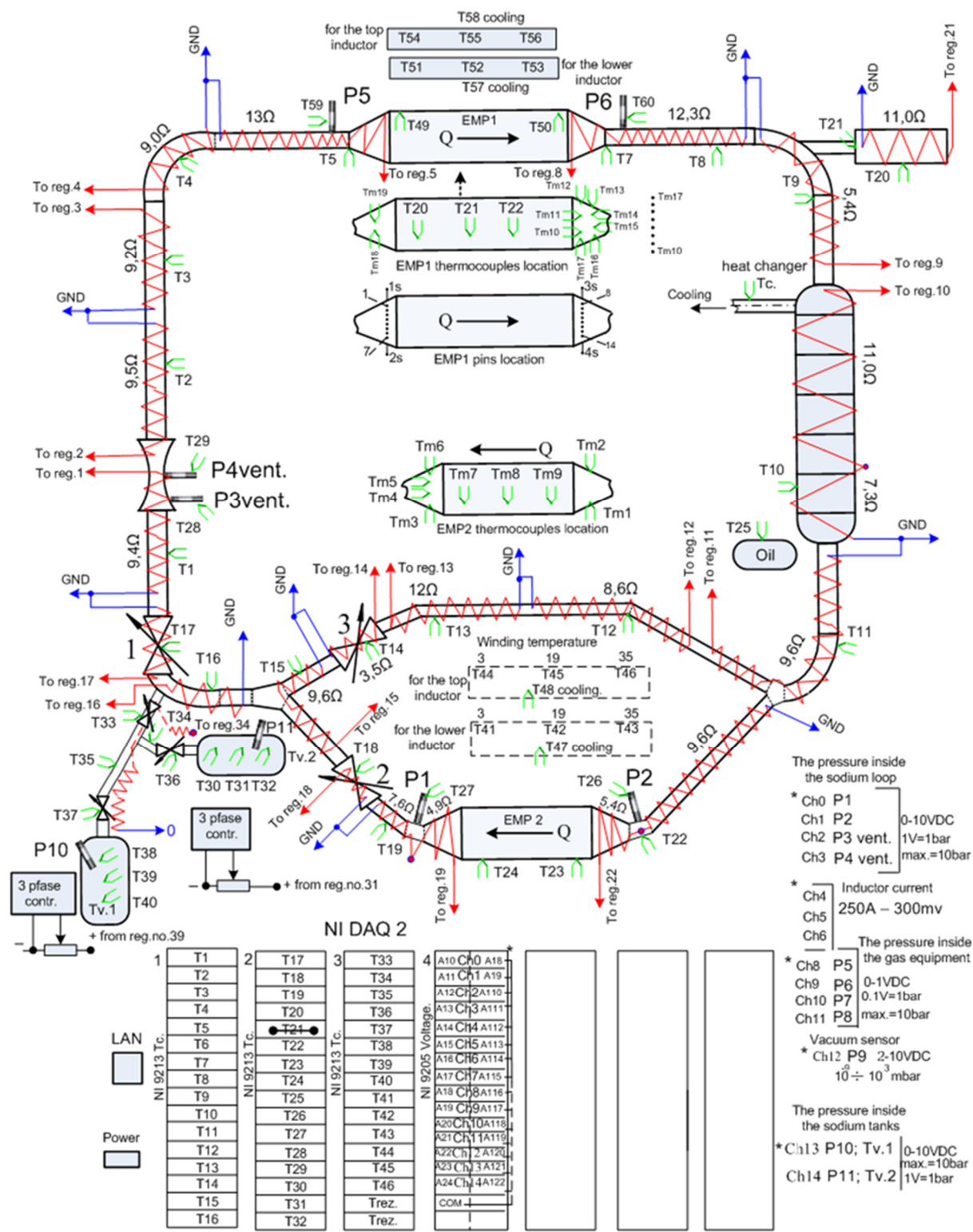


Figure 1.2 TESLA (IPUL) layout of sodium metal contour with 2 electromagnetic pumps (EMP) and heating system.

A specific layout of TESLA sodium facility at IPUL is presented in Figure 1.2. Thermocouple locations and the heating elements on the loop are identified.

At KIT sodium facilities were designed and built starting in 2013 and ending in 2020 with the set into operation of KASOLA. As a novelty, the SOLTEC [5] facilities were designed to provide a mobile high temperature facility for operation in standard laboratory environments.

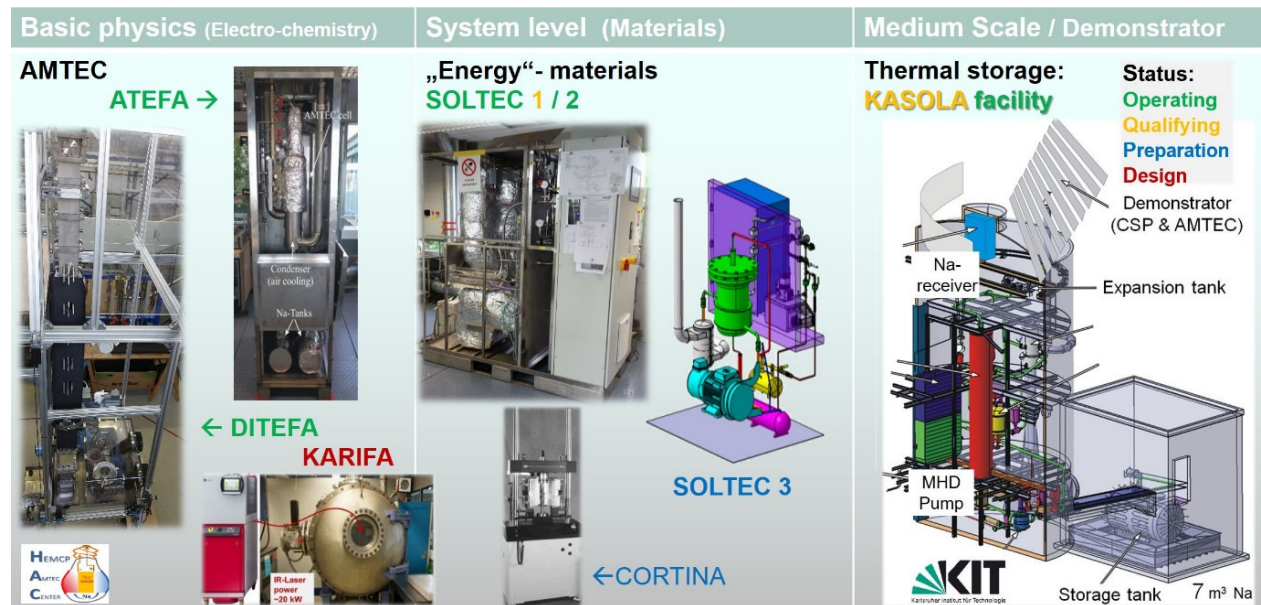


Figure 1.3 Sodium and GaInSn fleet of experimental facilities dedicated to thermo-fluid-dynamics, material qualification and system verification (status indicated by colour).

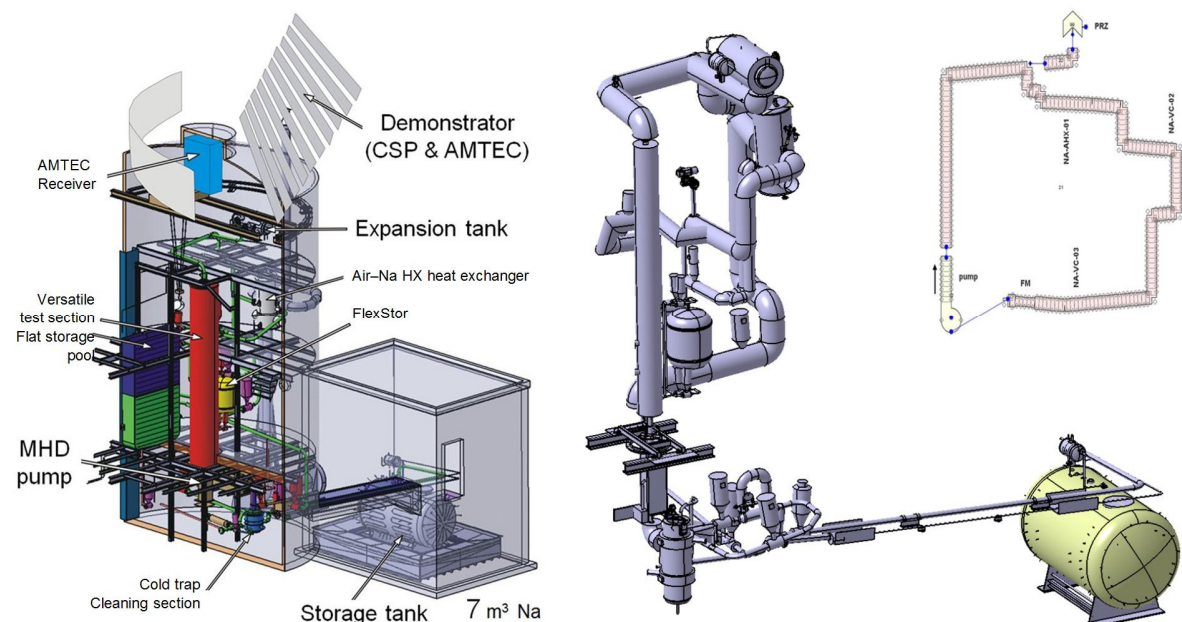


Figure 1.4 Schematics of KASOLA with the planned CSP extension, the loop with the storage tank separated and a preliminary sketch of the basic look for TRACE simulation (left to right)





## 2 GENERAL PROCEDURES FOR SODIUM FACILITIES

Before ramping up a sodium facility several steps of qualification are necessary to check, reviewed and analyze all sensitive elements of sodium technology, in particular:

### **Commissioning phase:**

- procedures used for testing prototypical components at large facilities
- structures heating (baking, wetting) and out-gassing (several times),
- filling and draining, sodium purification;

### **Qualification phase:**

- procedures for calibration of sensors and signal treatment for measuring systems such as flowmeters, electrochemical sensors for oxygen, hydrogen, carbon meters, electrodes;
- methodologies for treatment of the measurements for subsequent use as input data for codes, *i.e.* data “reconciliation”, characterization of uncertainties.
- Qualification of whole system incl. test sections, max. temperatures and flow rates as well as safety systems (e.g. Interlock Safety System)

Due to the non-permanent use of facilities, it is often required to keep the facility in appropriate conditions, in order to be able to restart it in safe conditions. A review of current uses in various institutions will be done, than in the section hibernation a “cocooning” procedure is described.

In the appendix, section 7.2 some flow maps and tables are listed for facility concept, design, and construction. A section to hazard estimations are added for information.

### 2.1 Commissioning phase

Set into operation or commissioning test are separated into two phases: commissioning and qualification. The first phase is necessary for licensing and safety, the latter important for assessment of facility and instrumentation quality.

It has to be mentioned here, that most of the valves are stem type valves where the stem is isolated to the atmosphere by a thin walled bellow, which is folded. To avoid cracking of the thin material, a minimum temperature for valve operation has to be maintained, once the valve was wetted with sodium!

This was the reason for a large accident in the Almeria Solar plant in 1986 – a simple crack in a bellow.

Therefore, it is recommended to perform as most as possible test without sodium, and later assure by trace heating that the bellow exceeds at least 100°C.

#### 2.1.1 Dry, without Sodium

Dry test are very important to identify unforeseen or unexpected deviations. They have a high importance for later successful experimental campaigns. As long as the valves are not covered with sodium (especially the bellows) all possible operations can be checked at any temperature. This allows to get precise opening and closure timed for valves.

The trace heating is tested under such harsh conditions, since the lack of sodium means lack of heat spreading. Consequently, more time is required to achieve equilibrium. If all desired temperature levels are reached, the trace heating is qualified. Interplay between ISS (interlock and safety systems) and PLC (Programmable Logic Controller) is checked under all conditions including failure of the energy



supply. For the latter case, an uninterruptable power supply is installed. If a facility is operated semi- or full automatic, this is the best way to identify bugs and wrong implementation of process steps. Furthermore, fast emergency draining is tested.

#### *2.1.1.1 Component test procedures*

Component test procedure are in both parts, in dry and filled mode. They are oriented to the special purposes of the components such as pump, heat exchanger, valve, cooler, cold trap, plugging meter, etc.

#### *2.1.1.2 Heating equipment tests*

Heating equipment has a base function to preserve freezing of sodium or other liquid metals. Therefore, the minimum requirement is to reach temperature necessary for the wetting process. Furthermore, the heating system shall allow for adiabatic boundary conditions using electrical heating.

If necessary the heating system can be used to perform cleaning e.g. wetting procedures, if not feasible by a heating system in a test section.

#### *2.1.1.3 Loop baking and out-gassing*

The drying is carried out after the installation and check for tightness to completely remove traces of air and moisture.

The unit is heated to a temperature of 150-200°C and blown by a gas stream, preferentially of Argon. This provides some heat balancing especially at large pipes where trace heating is feasible only at some sides. Outgassing is preformed keeping the facility at vacuum at temperatures 150-200°C to a system pressure determined by the working conditions, not exceeding a lower limit of 3 Pa. Tgis value is important not to initiate sodium boiling.

After receiving the necessary vacuum system is at least two times washed by purified inert gas (argon). The installation is filled with argon to the pressure of 0.1-0.3 bar and again vacuum to the pressure of no more than 3 Pa.

Before filling the installation with liquid alkaline metal, the argon is located at an excess pressure of 0.1-0.3 bar to avoid air ingress when circuit opened unintentionally. For filling, the facility is evacuated to remove all gases, which could be dissolved in sodium.

#### *2.1.1.4 Safety installations*

Main safety limits are overpressure, overfilling and detection of leakages. Today two protection systems enhance safety. The operational limits, which are indicated by the design and purpose, are controlled by the PLC. The safety limits are supervised by the hard-wired ISS, with acts fast and efficient to protect facility and staff. A detailed safety strategy was developed for KASOLA, sicne this was the first large facility licenced in Germany since ages.

In KASOLA the facility is operated based on the stage approach as can be seen in Figure 2.1. It shows the whole process from system standby up to operational and experimental activities. This is advantageous, since with such an approach, the transitions from one state to another can be defined clearly with respect of valve and pump operation. Furthermore, behind such a schema the safety



provisions such as access control or pump stop is realized. It also shows that between Cold standby and operation, two other states have to be reached and checked for further performance.

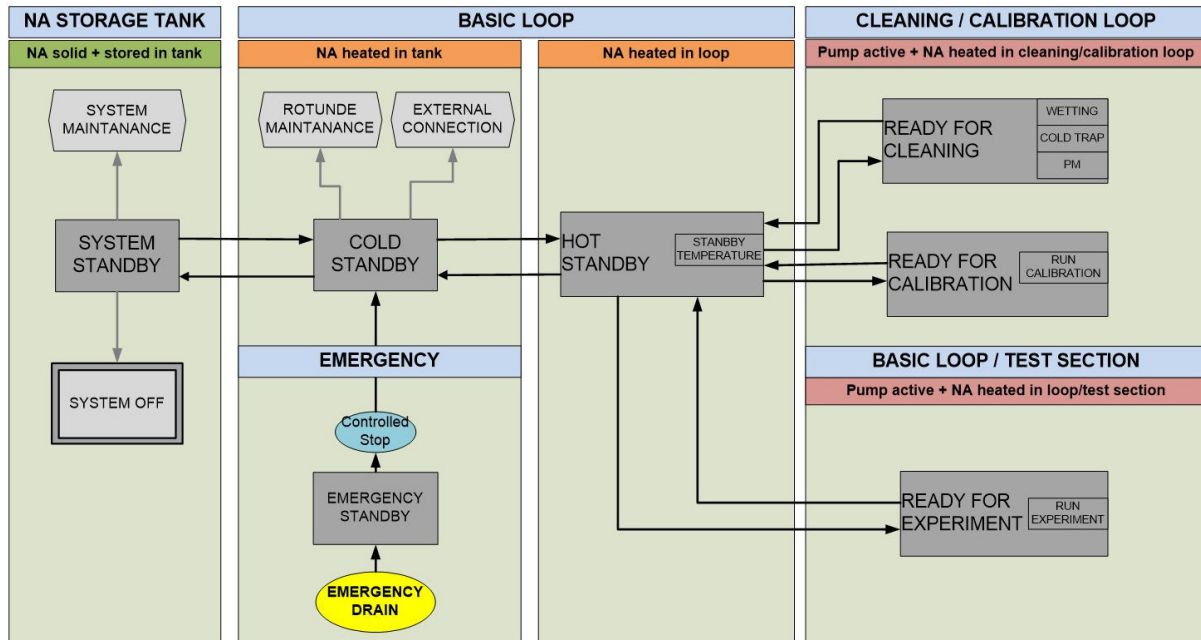


Figure 2.1 Operational stages stage of KASOLA PLC.

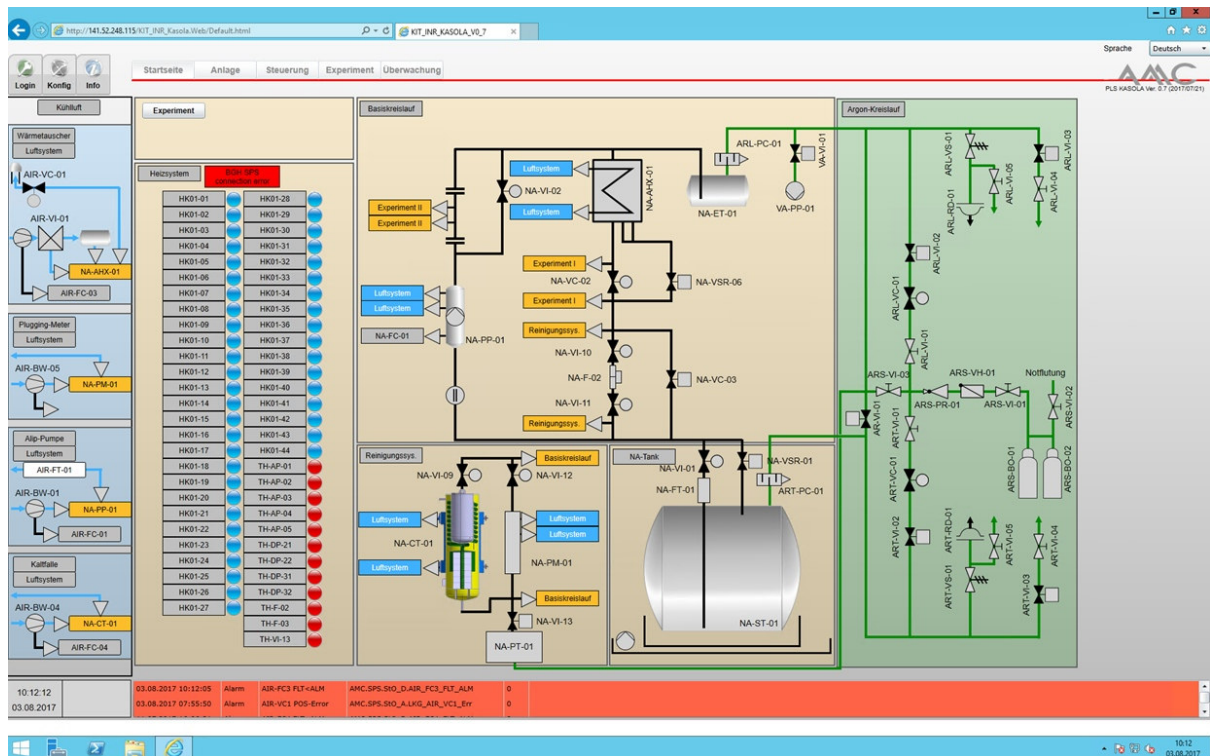


Figure 2.2 PLC operation window comprising all KASOLA systems.





More details are shown in the PLC operation window as shown in Figure 2.2, comprising all systems, sodium, Argon and pressurized gas, required for valve operation.

## 2.1.2 Hot and Sodium filled

### 2.1.2.1 Filling and draining procedures

The greatest danger when filling the circuit with a liquid alkali metal is the ejection of liquid metal into the atmosphere or into an adjacent system and the formation in the cavity of the loop excess pressure above the rated pressure. The release of metal from the circuit occurs as a result of depressurization of the circuit before filling or during the filling with liquid metal. The causes of depressurization are as follows:

1. Mechanical damage to thin-walled units (bellows, flow meter sections, channels of electromagnetic pumps).
2. High thermal stresses resulting from uneven heating, at the junctions - the transition of thin-walled parts to thick ones.
3. High thermal stresses occurring in pipelines during preheating and when filling the circuit with liquid metal in the absence of temperature compensators.
4. Unacceptably high loads on certain sections of pipelines, especially thin-walled ones, as a result of an irregular suspension of the contour.
5. Formation of excessive pressures in the cavities of the circuit that is higher than the calculated ones due to the interaction of liquid alkali metal when filled with the washing liquid remaining after washing.

Considering the danger of depressurization of the circuits, it is necessary to take measures that preclude the possibility of leakage of liquid alkali metal when the contour is filled.

Such measures include:

1. Removal from the cavity of the contour of the remaining washing liquid in the pockets, in case the contour has been washed before filling.
2. Tightness control before filling by pumping the equipment to the specified pressure and checking all welds, flange connections and inputs with a leak seeker;
3. Uniform heating of pipelines before filling;
4. Keeping the temperature difference between the liquid metal and the filled circuit as small as possible;
5. Having all contour systems operable during the filling.

To prevent the emergency position of the circuits and to ensure safe working conditions for maintenance personnel before filling the circuits with liquid metal, the following requirements must be fulfilled:

- checking the operation of the circuit heating system in accordance with the operating instructions;
- ensuring the tightness of the liquid-metal circuit;
- checking the condition and performance of auxiliary circuits (gas - vacuum, water and sewer, etc.);
- checking the operation of automatic control systems, interlocks, alarms;



- checking the position of the valve in accordance with the operating instructions, the condition of pipelines and supports, as well as remote control devices for valves:
- checking the inscriptions under the devices, knobs and control buttons on the boards.

During filling process of the circuit with a liquid metal, it is recommended to conduct a visual observation of its condition, but the heat control system should provide control over the flow of metal into the circuit throughout the filling period.

Liquid metal filling of the circuit can be carried out both in vacuum and in the inert gas environment, depending on the tightness of the circuit, the filling speed and the requirements for the purity of the metal in the circuit. In most cases it is preferable to fill in the medium of inert gas, thus eliminating the leakage of air into the cavity of the circuit, and the filling process is more relaxed than when filled into vacuum.

Before filling the circuit, ensure that the circuit is tight and that all systems are operable. It is necessary to include and set the levels of the loading and expansion tanks in the designated positions; The level gauges shall inform the start and end of filling the circuit by means of a signal. Some types of level meters can give information during the entire filling period (i.e., to show the position of the level of liquid metal in the charging and expansion tanks). Filling of the sections and devices of the circuit can be controlled by flow meters and thermocouples in these sections too.

In the presence of parallel sections in the contour, cases of overlapping of individual sections with liquid metal from the reverse side are possible. To avoid this, it is necessary to reduce the fill rate of the circuit.

When filling the circuit, it is also necessary to take into account the hydraulic resistance of the parallel sections. In some cases, it is advisable to artificially increase the hydraulic resistance of individual parallel sections having a minimum hydraulic resistance, covering the valve in this section. It is recommended to switch off the pumps and special heating furnaces of the circuit during the filling of the liquid metal circuit. The doors and hatches of the guards during the entire period of filling the circuit, as well as in the course of the circuit, must be in the closed position. Monitoring of the contour and all systems inside the protective enclosures during filling and during the operation of the contour should be carried out through the inspection windows of the protective enclosures.

Category I-III installations must have drainage tanks placed in the pit or in a separate room. The volume from the bottom of the drain pit to the lowest point of the drain tank must be at least the volume of the drain tank. The liquid metal coolants introduce specificity into the plant layouts.

From the point of view of draining the contour, the scheme with the upper expansion tank is the most acceptable. It is convenient and to the greatest extent meets safety requirements. The metal is drained from the system by gravity when the pressure of the inert gas in the drain tank is equalized and in the expansion tank mounted at the top point. By feeding an inert gas under pressure into the expansion tank, it is possible to accelerate the discharge of liquid metal from the circuit. The main drain line should be provided with two valves, one of which is reserved. If the system has a number of low points, they are all drained into the drain tank. Drainage lines should have a diameter of at least 12 - 15 mm. It is finally determined taking into account the size of the system and the required drainage time.



### **2.1.3 Sodium purification.**

#### **2.1.3.1 Background**

Liquid sodium has a high reactivity and hence solubility for water and oxygen forming sodium oxides and hydroxides. In technical facilities, the sodium volumes are evacuated and baked to remove as far as possible the surface bound humidity. So the surface is considered as technically cleaned. However, the metals are alloyed by different species and the surfaces are oxidized during storage and manufacturing. Compared to sodium, these oxides have a higher melting temperature compared to sodium. This fact is used to separate and clean sodium in the so called “cold trap”.

Each sodium installation or laboratory requires a solution to provide experiments with purified sodium. For small experiments, the sodium can be replaced after wetting process by fresh sodium, so that the oxides are removed manually. For larger experiments of basic research installation (basic loops) this procedure becomes expensive.

Since the beginning of sodium research as heat transfer fluid, cold traps were developed and improved to address the special needs of each facility. Two concepts have been established so far: 1. cleanable and 2. permanent cold traps.

#### **2.1.3.2 Cleanable cold trap**

The cleanable systems have a valve at the lower end and the wire mesh can be cleaned by heating up the cold trap without circulation so that nearly all impurities are soluble and can be washed out with the sodium. So the cold trap becomes smaller, however, the size of the heat exchanger is not changed, since the temperature levels have to be maintained. In addition, the pressure drop is not reduced, since the wire mesh packs are oriented in parallel. Such a design is chosen if the oxygen concentration and internal surface is large to avoid big cold-traps. In that case the cold-trap is operated during commissioning and qualification phase, where often transients and maintenance operation are necessary. After that period, a second cleaning phase provides clean sodium for plant or power operation. Having achieved that level the cold-trap can be removed and cleaned. The loss of sodium comprises the whole inventory of the wire mesh pack (void is reduced due to growing oxide scales). This volume can be reduced by separating wire mesh packs and economizer (IHX). The wire mesh packs can be cleaned by steam or water to produce sodium hydroxide, which can be released with a buffer or neutralizer acid.

#### **2.1.3.3 Permanent cold trap**

To avoid the costly maintenance in replacement of sodium oxide coated wire mesh packs, permanent cold traps have been developed, to operate during the whole lifetime of a base loop facility comprising several experimental campaigns and modification of the facility. If the frequency of modification and the additional inner surfaces of the experimental test sections are small compared to the base loop surface and expected lifetime of the facility this design offers several advantages. Presently available wire mesh packs offer a very high inner surface, so that the additional costs are only on the investment side attributed to a larger vessel and wire mesh packs. Taking into account the difficulties of a frequently disposal of “dirty” sodium-oxide, the design of a permanent cold trap is favourable.

#### **2.1.3.4 Cold trap operation**

The cold trap operation, cleaning or purging, starts after the wetting phase, initiated preferentially after each modification of the facility. This assures that all oxygen is dissolved in the liquid sodium and



can be transported to the cold trap. Before or inside the cold trap the sodium temperature is reduced by a recuperator and a cooler (air, oil) to a temperature range below  $\sim 160^{\circ}\text{C}$ . Following the solubility curve as shown in Figure 2.3 this means an oxygen concentration of 10 ppm. For a reasonable sodium purification, the temperature is further reduced by cooling the sodium inventory to achieve  $120^{\circ}\text{C}$  in the cold trap. This allows crystallization of the sodium oxides on the metal surfaces of the stainless steel mesh.

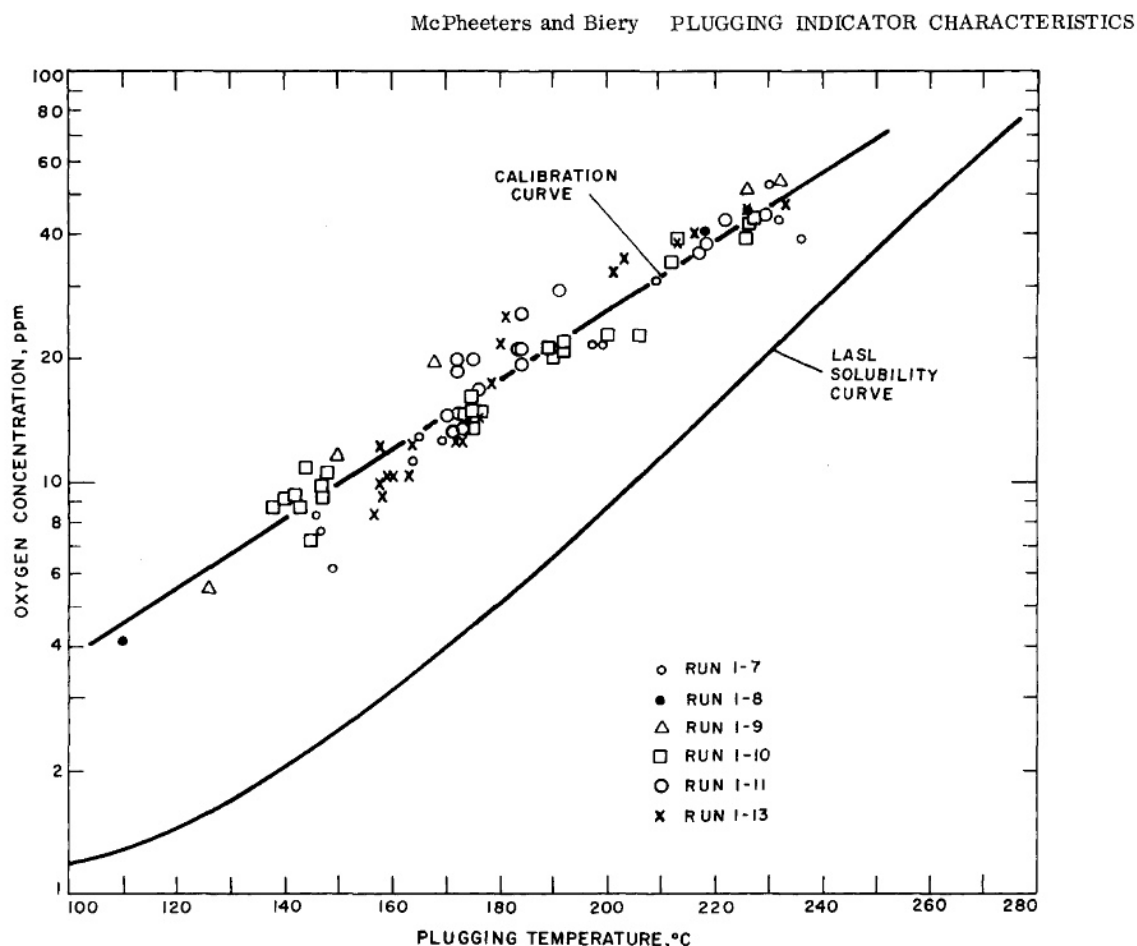


Figure 2.3 Solubility of Oxygen in Sodium, theory and measurements

### 2.1.4 Hot trap

A hot trap is based on additional materials working as getter to attract and keep the impurities. It is normally not used in sodium systems, since the solubility limits for O and H can be easily reached with an cold trap. For other liquid metals or alloys this is not so easy, they require a hot trap.

## 2.2 Test of safety installations and provisions

### 2.2.1 Qualification tests

At the end of the commissioning phase, the licensing authority has released the facility to operability so that now the experimental programme can start. If a new facility reached that state, a second phase called qualification phase is added. Here all passive and active components were tested.

#### 2.2.1.1 Test of sensors and data management

#### 2.2.1.2 CFM calibration

Electromagnetic Conduction Flow Meters are very reliable for measuring flow rates of liquid metals. The main advantages of CFM are following:

- simple construction,
- easy measurable even rather small its direct current (DC) voltage output signal which is not submitted to alternating current (AC) noises [contrary to induction flow meters]
- voltage output signal is linear with measured flow rate and practically does not depend on the liquid metal velocity profile in the channel of flow meter [9].

The construction of CFM is very simple, just on the pipe with liquid metal the constant magnetic field [it can be electromagnet or assembled from permanent magnets] is applied perpendicular to pipe and two electrodes for measuring induced DC output signal. There are two main design concepts of CFMs: round pipe and rectangular cross-section of the channel of flow meter, or close to rectangular cross-section which is made by flattening of the part of round on which constant magnetic field is applied (Figure 2.1).

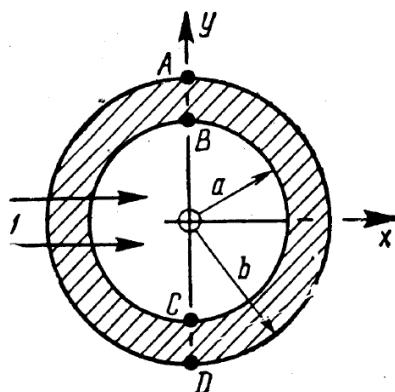


Figure 2.4 Cross-section of electromagnetic conduction flow meter having round pipe channel (from [9]).

The sensitivity of such CFM at uniform magnetic field and good wetting of electrically conducting channel walls by liquid metal (then measuring electrodes may be just welded from outside to the channel) can be calculated according to formula from Shercliff's book [9]:

$$S = \frac{U_{AD}}{2b \cdot B \cdot V} = \frac{2a^2}{(a^2 + b^2) + (\sigma_w / \sigma) \cdot (b^2 - a^2)}.$$

For the constructions of magnetic systems there are several possibilities. For example, mostly used is not closed magnetic system for easy installing and removal of CFM from the liquid metal piping (Figure 2.2) or magnetic system with closed ferrous yoke at which stronger magnetic field can be gained.

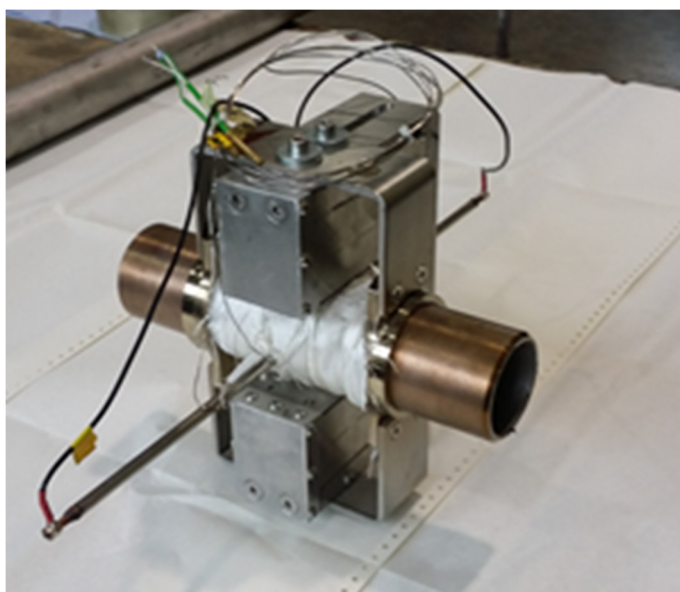


Figure 2.5 Open magnetic system for easy installing and removal of CFM from the liquid metal piping.



Figure 2.6 Large scale CFM used at KASOLA



### Assembly scheme of conduction Flow meters

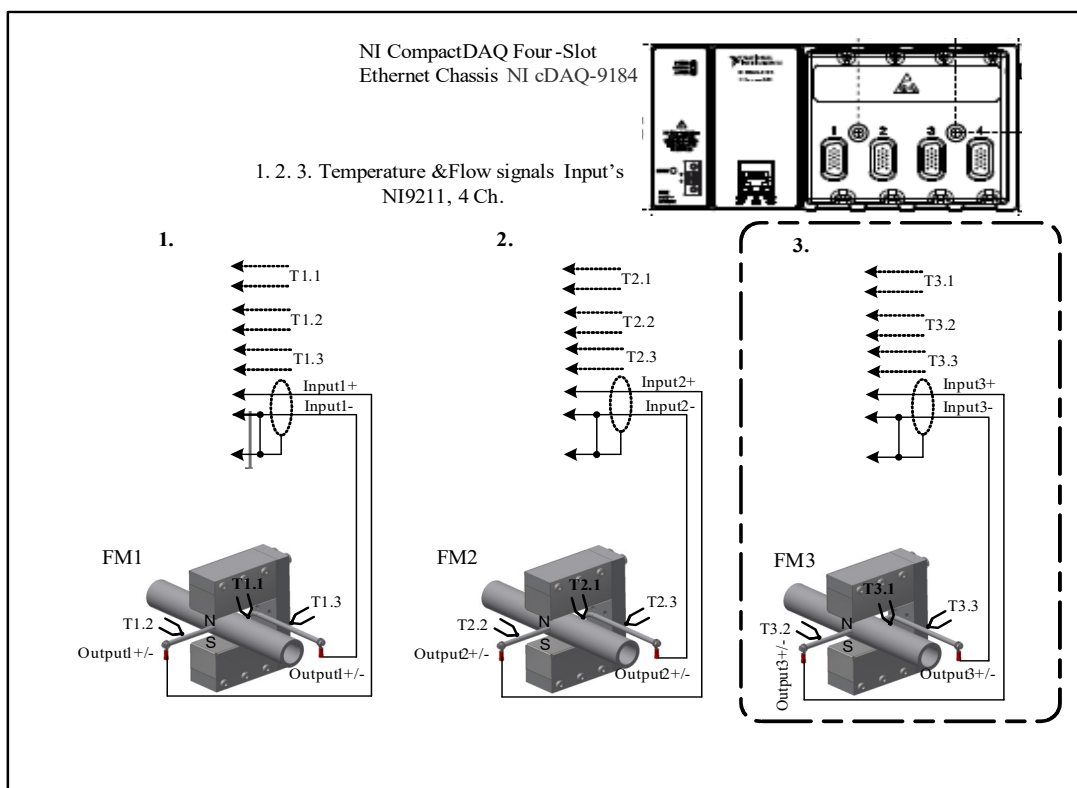


Figure 2.7 CFM calibration system

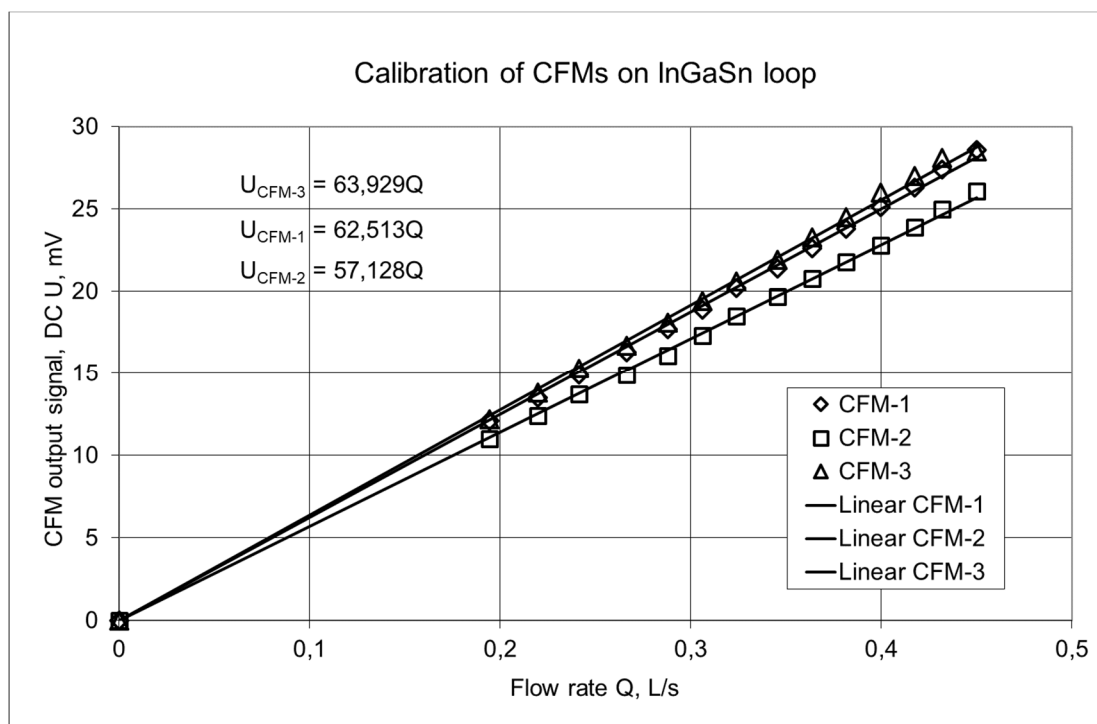


Figure 2.8 Results of CFM calibration on InGaSn loop.

At Institute of Physics of University of Latvia (IPUL) different liquid metal circulation loops are used for CFM calibration, including low temperature InGaSn loops, using reference Venturi flow meters. For measurements data acquisition and their visualization NI measurement system and LabView software is used (Figure 2.3).

For the stainless steel round piping (also the same for the channel of flow meter) the shunting effect of channel walls is rather small as electrical conductivity of stainless steel is essentially lower in comparison with electrical conductivity of liquid sodium. Additionally, especially for the round stainless steel channel having relatively thin walls their shunting effect also is relatively small. Therefore the sensitivity of flow meter can be close to the sensitivity of flow meter having electrically non-conducting walls.

The calculated sensitivity of electromagnetic conduction flow meter having the two inches stainless steel round channel having following dimensions: outer diameter 60.3 mm. inner diameter 54.3mm and the thickness of wall 3 mm at  $T = 3000\text{C}$ ,  $B = 0.3\text{ Tesla}$  is shown in Figure 2.5.

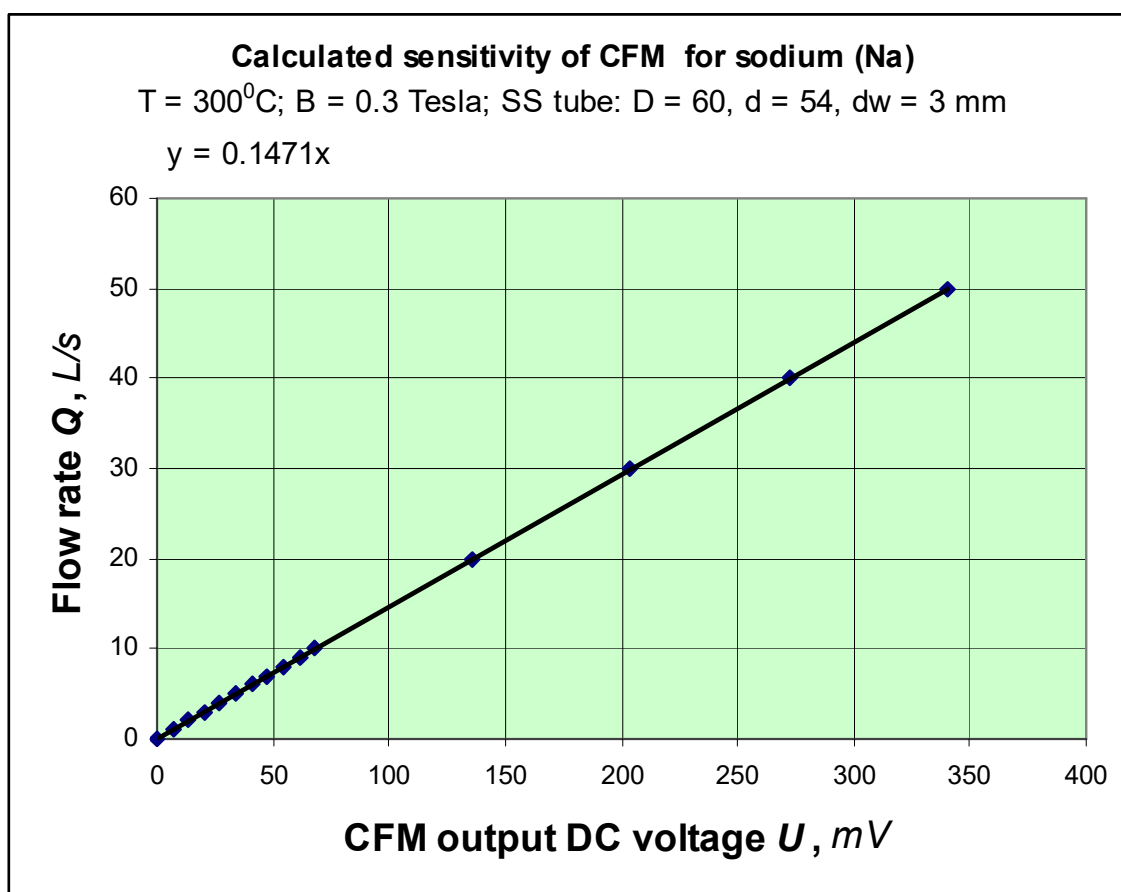


Figure 2.9 Results of CFM calibration for Na.

### 2.2.2 Eddy current flow meters and its calibration in sodium flows

The Eddy Current Flow Meter (ECFM) is an inductive sensor, which allows flow rate measurements of liquid metals. The working principle is based on the application of at least one excitation coil fed by an alternating electrical current. The flow-induced change of this alternating magnetic field is then



measured by typically two coils, and the measured voltage or phase difference between those two receiver or detection coils is proportional to the mean flow. There are external and immersed versions of such ECFM: in the external version the coils are placed outside of the pipe with the liquid metal flow, whereas in the immersed version the coils are inside a preventing thimble surrounded by the flow. First results on the application of external ECFMs and their calibration by comparison with independent local velocity measurements using the Ultrasonic Doppler Velocimetry (UDV) measurement technique were given in [14]. In the following we present results on the calibration of immersed ECFMs in sodium flows by comparison with UDV measurements, as well as a very recent solution for a Transient ECFM (TECFM) which does not require any calibration at all [15].

### 2.2.2.1 Immersed ECFM and UDV measurements in a sodium flow

A miniaturized high temperature ECFM is being developed at HZDR in frame of WP2.4 in frame of the ESFR-Smart project. Its purpose is to detect flow rate variations or for example, blockages above fuel subassemblies in liquid metal cooled reactors. The sensor is installed inside a cylindrical stainless steel thimble that protects the sensor coils from direct contact with the liquid sodium. The ECFM measures the mean flow velocity in a certain volume around the sensor. Here we report on the test and calibration of this sensor by comparison with UDV measurements in a bended sodium pipe flow.

Usually an ECFM consists of three magnetic coils (see Figure 2.10). An excitation coil induces eddy currents within the liquid metal and two detection coils measure the magnetic flux density at two positions – up- and down-stream of the excitation coil. Without any flow at the sensor, the same voltage can be measured at each detection coil as they have the same distance from the excitation coil and because the magnitude of the eddy currents in their vicinity is equal. The voltage at each detection coil is influenced by the magnetic field of the excitation coil and the oppositely directed magnetic field of the eddy currents within the liquid metal. When the liquid metal begins to flow, further eddy currents are induced due to the motion of the liquid metal through the magnetic field. Their magnitude is proportional to the flow velocity. Because the radial component of the magnetic field is opposite up- and downstream of the excitation coil, the motion induced eddy currents have opposite directions. This results in an increase of the total eddy currents at the upstream coil, because the motion induced currents have the same direction as the currents which are induced by the excitation field, causing a further reduction of the upstream detection coil voltage. The eddy currents at the downstream coil are weakened because they have opposite directions and thus, the downstream detection coil voltage is increasing. The change of the coil voltages is linearly dependent of the flow velocity.

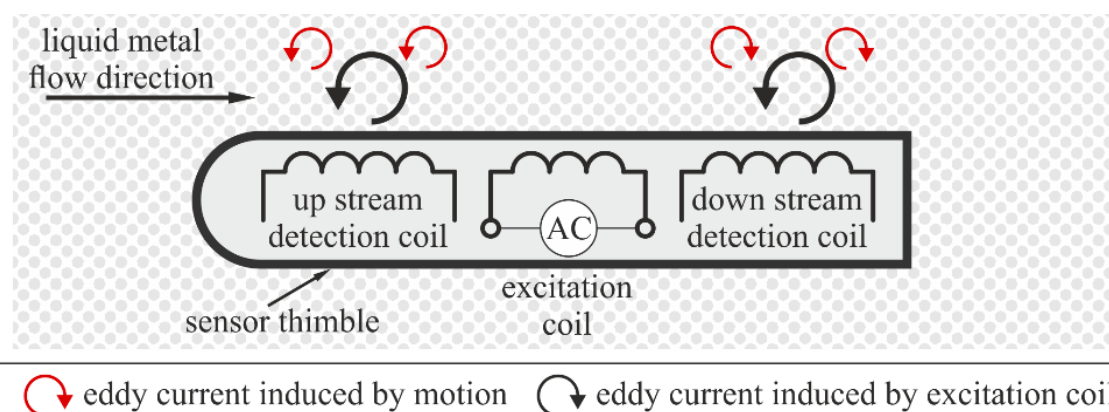


Figure 2.10 Simplified scheme of the immersed ECFM

The wire and coil holder of this high temperature ECFM consist of temperature resistant materials since the sensor shall be operated up to a maximum coolant temperature of 650 °C. As wire material a nickel plated copper wire with a diameter of 0.25 mm and ceramic insulation is used (note that conventional coil wire can only be used for maximum ambient temperatures of around 250 °C). The coil holder is made of the ceramic Macor, which has the advantage of preventing any inductive losses within the coil holder, as it would be the case with a stainless steel or iron coil holder, for example. The ECFM consists of three coils (see Figure 2.11): there are two receiver coils with 250 turns each and one excitation coil with 125 turns. The ECFM has a diameter of 11 mm and a total length of 50 mm. The stainless steel thimble has an inner diameter of 11 mm and a wall thickness of 2 mm, hence an outer diameter of 15 mm. As any electrically conducting material between the coils and the liquid metal flow represents a kind of shielding, a reduction of the wall thickness would improve the accuracy and sensitivity of the ECFM measurements. During the experiments, the magnitude and phase of the voltage difference between both receiver coils is measured using a lock-in amplifier that allows a very accurate measurement of sinusoidal signals. The measured values are recorded automatically and used to calculate the mean value of the surrounding liquid metal flow velocity.

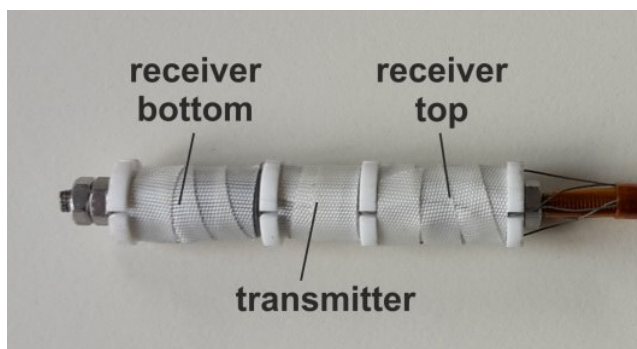


Figure 2.11 ECFM sensor that was used for the measurements at the NATAN loop

For the qualification of the ECFM in liquid sodium, measurements were conducted at the HZDR sodium loop NATAN (see section 7.4) at sodium temperatures of 160 °C and 240 °C for flow velocities ranging from 0 m/s to 1.4 m/s. Since the output signal of the ECFM depends not only on the flow velocity of the liquid metal but also on its electrical conductivity/temperature, it has to be calibrated. This can be achieved by using the results of ultrasound Doppler Velocimetry (UDV) measurements, which deliver spatially resolved velocity profiles along a line in real time. The UDV technique will be explained in more detail in the next section. A special test section (Figure 2.12) has been constructed to allow simultaneous measurements with the ECFM and UDV sensors.

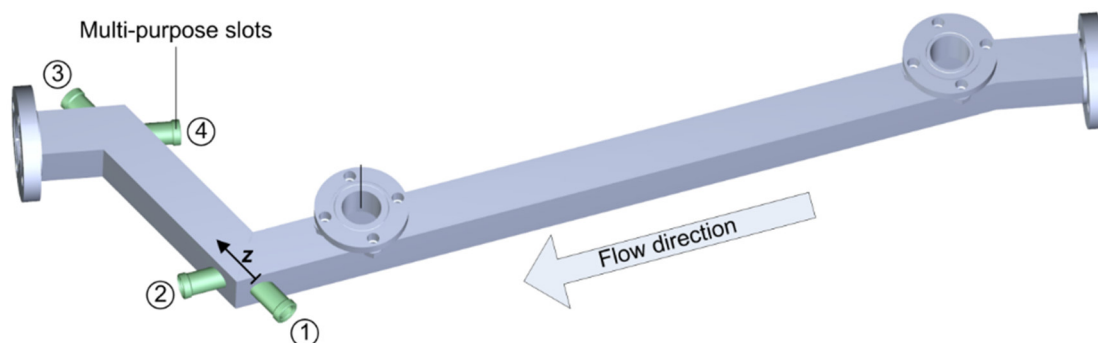


Figure 2.12 Test channel for simultaneous measurements with ECFM and UDV at the NATAN loop.

It features four small multi-purpose slots (HZDR design) allow for the application of various ECFM or UDV sensors, as well as two larger slots for other UDV sensors. The bended path of the channel permits to measure the flow in axial direction (by UDV as well as by ECFM) with these multi-purpose slots without substantially influencing the flow. The two opposing slots provide various measuring arrangements and alternative measuring principles (as ultrasonic flowmeter method). Furthermore, the influence of the narrow channel geometry on the velocity profile can be investigated by measuring from both sides and comparing with each other. The test section has a square cross section of 62 x 62 mm<sup>2</sup>. By using flange no. 4 higher velocities can be achieved with the same flow rate because the ECFM extends into another section of the NATAN loop which features a cross section of 44 x 44 mm<sup>2</sup>.

Numerical simulations have shown that there is a conductivity-dependent optimal excitation frequency with the highest ECFM sensitivity. This frequency can also be determined by sweeping over a wide range of excitation frequencies and determining the corresponding magnitude or phase of the receiver voltage difference. For the operation of the ECFM it is not strictly required to measure at the optimal frequency but it is recommended to achieve the most accurate results. For applying an ECFM in sodium a value of 500 Hz has been determined to be the optimal frequency. It can be seen in Figure 2.13 that the sensor has its highest sensitivity at about 500 Hz.

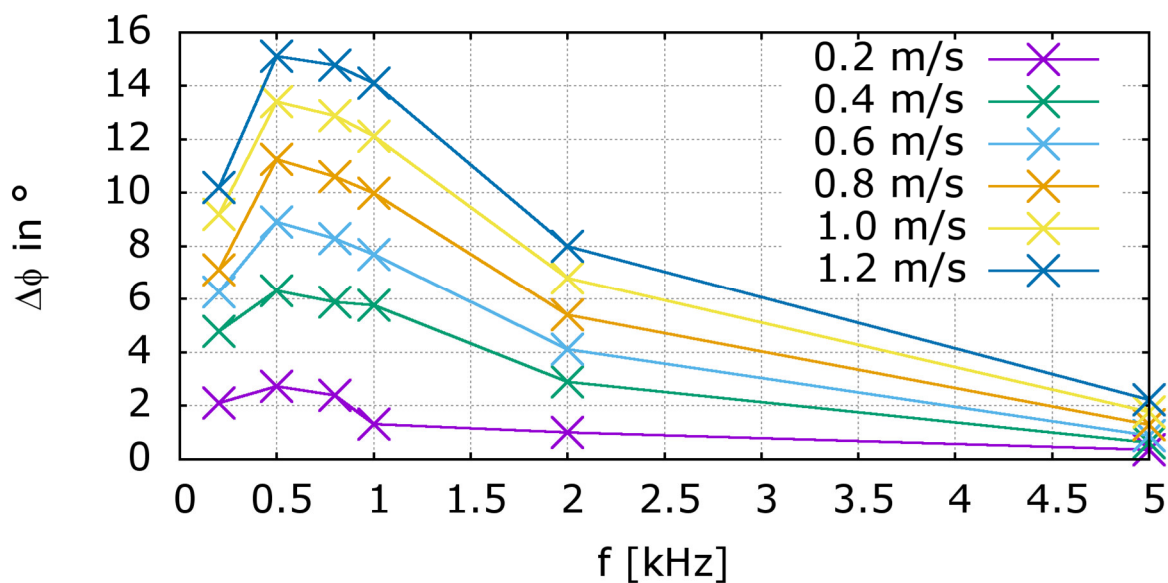


Figure 2.13 Frequency sweep to determine the optimal excitation frequency of the ECFM in sodium.

The following figures show how the measurement results of the magnitude (Figure 2.14) and phase (Figure 2.15) difference of the receiver voltages depend on the flow rate, for two different sodium temperatures with an excitation frequency of 500 Hz. Each point represents the mean value of 20 separate measurements, each taken during approximately 1 second. The variation of the flow rate between 0.2 m<sup>3</sup>/h and 9 m<sup>3</sup>/h corresponds to a velocity range between 0.03 m/s to about 1.4 m/s. The straight line is a linear fit of the dataset.

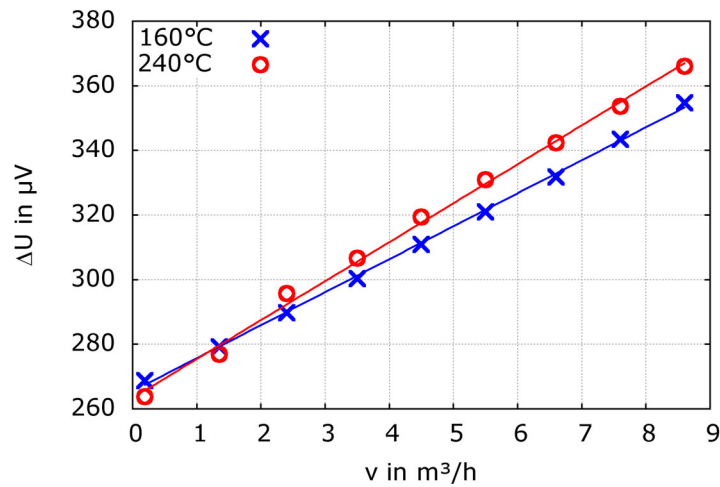


Figure 2.14 Measurement results for the voltage magnitude at sodium temperatures of 160 °C and 240 °C.

It can be seen that there is an offset in magnitude and phase. It is caused by slight, almost unavoidable asymmetries in the structure of the ECFM and should be determined in the calibration process. Note that this offset has no impact on the accuracy of the flow rate measurements. Furthermore, it becomes obvious that the slope of the linear fit changes with the sodium temperature. This is the result of the decreasing electrical conductivity of the sodium and of the increasing resistance of the coil wires. To take into account these changes, the ECFM has to be calibrated for different temperatures in order to achieve accurate results.

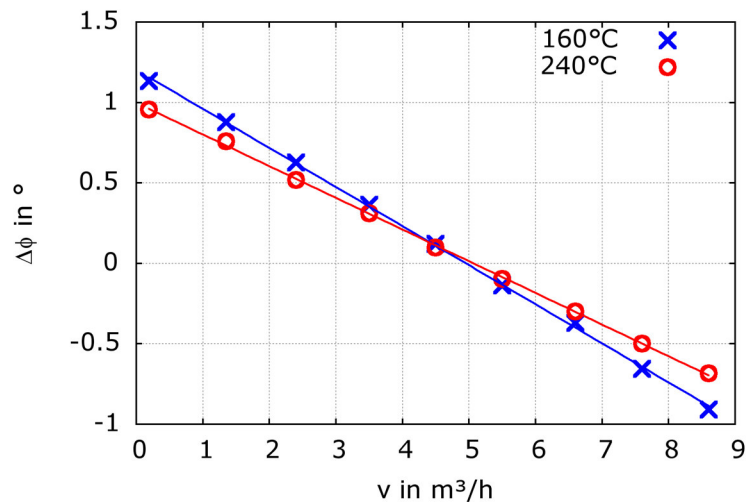


Figure 2.15 Measurement results for the phase shift at sodium temperatures of 160 °C and 240 °C.

The ECFM has proven to be a robust sensor for an instant determination of the local flow rate of liquid sodium around the cylindrical thimble containing the sensor. This prototype was tested at HZDR up to temperatures of 240 °C, however, is designed to work up to 650 °C. Since phase measurements yield more accurate results than the measurements of the magnitude, a higher resolution of the flow rate can be achieved by using phase measurements. A very good linear dependence between



magnitude/phase and flow rate/velocity has been demonstrated. There is an obvious disadvantage of the ECFM arising from the need for calibration mainly due to the temperature variation of the electrical conductivity of the liquid sodium.

The measuring principle of UDV is based on the pulse-wave echo technique. Narrow ultrasonic pulses of a few cycles emitted from an acoustic transducer propagate into the fluid along a measuring line which is identical to the axis of the ultrasonic beam. A part of the ultrasonic pulse is scattered by micro particles suspended in the liquid. Their echo signal is received by the same transducer within the time period between two pulse emissions. A short sequence of such echo signals contains the entire information of the velocity profile along the ultrasonic beam. Knowing the sound velocity of the liquid, the axial position of the scattering particles along the beam axis is determined from the measured time span between the pulse emission and the reception of the respective echo signals. The movement of the scattering particles inside the measuring volume between two consecutive bursts results in a small time shift of the echo signal. A correlation analysis between the echo signals of consecutive bursts reveals the velocity component of the velocity vector in direction of the beam axis for all positions along the beam. Owing to the Nyquist theorem, the product of measurable maximum velocity and penetration depth is limited by the sound velocity and the ultrasonic frequency. Ultrasonic methods are non-invasive, but not contactless since a continuous acoustic path from the ultrasonic transducer to the fluid under investigation is required.

In case of hot metallic melts the user is confronted with a number of specific problems: First of all, the application of the ultrasonic transducers is usually restricted by temperature. Furthermore, the transmission of a sufficient amount of ultrasonic energy from the transducer into the fluid has to be guaranteed. Here, the acoustic coupling between transducer and wall, the acoustic transmittance of the wall (due to safety reasons the sensors are typically not in direct contact to the fluid) and the wetting conditions have to be considered as important issues. Moreover, a balanced concentration of scattering particles has to be provided to obtain reliable velocity information from the fluid. On the one hand, a very high concentration attenuates the signal in the front region to such an extent that the acoustic waves cannot propagate into larger measurement depths. On the other hand, a lack of scattering particles in certain measurement depths impedes to determine the flow velocity correspondingly.

First results from ultrasonic flow measurements carried out at the multi-purpose of the test section slots are presented here: Figure 2.16 shows time-averaged velocity profiles (mean flow) measured at the multi-purpose slot 1 (in z-direction, see Figure 2.12) for different coil currents of the MHD pump at NATAN. The elevations of flow velocity at the beginning and the end of the profile arise from the bends in the pipe. Additionally, the persistent slope of the velocity profile after the first elevation is a result of the flow, which centralizes again after being squeezed at the wall in the first bending. The profiles for  $I_{\text{pump}} = 5 \text{ A}$  and  $I_{\text{pump}} = 10 \text{ A}$  are reliable but the profile for  $I_{\text{pump}} = 15 \text{ A}$  decreases significantly in the last third of the measurement depth. Furthermore, the shape of the profile of  $I_{\text{pump}} = 20 \text{ A}$  corresponds to the other profiles only in the first segment.

At higher flow rates probably more scattering particles are stirred into the bulk flow causing an increased attenuation of the ultrasonic pulse in larger depths resulting in a low signal-to-noise ratio and underestimated velocity values. This assumption is supported by the energy profile of the scatterers provided by the measurement device revealing a slow decreasing energy level with z for low flow rates and an intense energy level at the beginning with almost no energy at the end for high flow rates. In this case the required balanced concentration of scatterers is not guaranteed anymore.

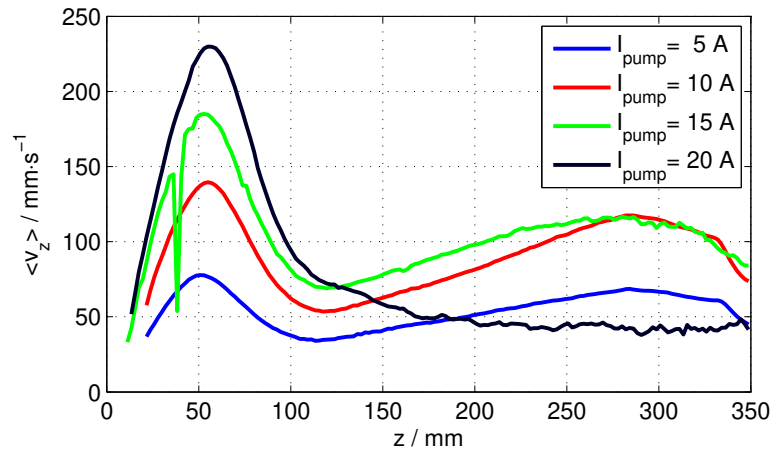


Figure 2.16 Velocity profiles measured at slot 1 for different pump currents

The peak at the beginning of the velocity profile for  $I_{\text{pump}} = 15 \text{ A}$  is an artifact caused by a strong stationary echo. The effect of the narrow channel geometry associated with the significant beam divergence for such high measurement depths is presented in figure 7 where the velocity profile was measured from one side (from slot 1, see Figure 2.12) and from the other side (from slot 3). By mirroring the profile obtained from slot 3 the profiles can be directly compared to each other. It should be noted that the profiles were shifted a little bit to compensate the spatial filtering by the measurement device. Furthermore, an artifact occurs at the end of the profile of slot 1. Figure 2.17 reveals that strong velocity gradients are smoothened and sharp velocity elevations are spread with increasing measurement depth.

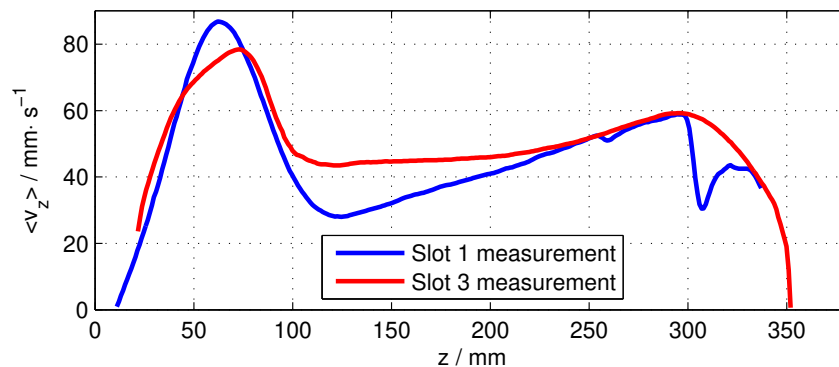


Figure 2.17 Velocity profiles ( $I_{\text{pump}} = 5 \text{ A}$ ) measured from opposite sides (slot 1 and slot 3).

Here we have shown, that measurement depths of at least 350 mm can be achieved with the ultrasonic velocimetry in sodium; however, an unbalanced particle concentration may be a major issue for such measurements depending on the flow conditions at different flow rates since the concentration of these natural scatterers is difficult to adjust. In our case the sodium in the loop exhibits a too high concentration impeding reliable measurements at higher flow rates. Furthermore, the measured flow velocity may suffer from an increasing systematic measurement error with increasing measurement depth in narrow geometries. This has to be considered in the measurement analysis.



### 2.2.2.2 Immersed TECFM allowing calibration free velocity measurements

Eddy Current Flow Meters (ECFM) are widely used for measuring the flow velocity of electrically conducting fluids. Since the flow induced perturbations of a magnetic field depend both on the geometry and the conductivity of the fluid, extensive calibration is needed to get accurate results. Transient Eddy Current Flow Metering (TECFM) has been developed to overcome this problem. It relies on tracking the position of an impressed eddy current system that is moving with the same velocity as the conductive fluid. Since the eddy current moves with the velocity of the liquid, there is no need for a calibration of the sensor.

Compared to the ECFM, the TECFM sensor has an almost similar design. By adding one additional excitation coil, calibration free velocity measurements can be achieved by creating two oppositely directed eddy current rings with the same amplitude (see Figure 2.18).

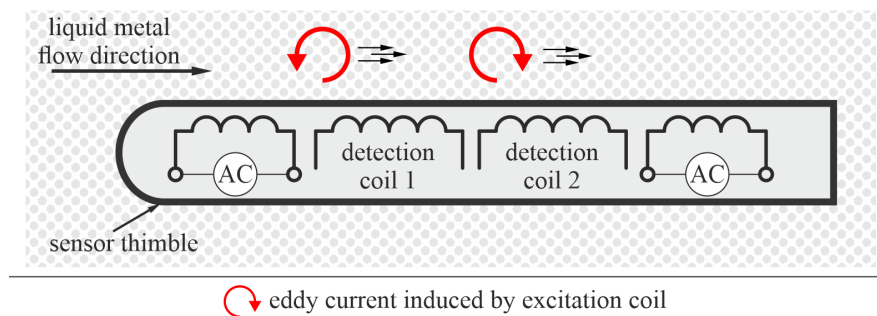


Figure 2.18 Simplified scheme of the TECFM sensor.

The two detection coils are used to track the movement of the eddy current system that was imprinted into the liquid metal by suddenly switching off the excitation current of the excitation coils. It is important, that the excitation currents are oppositely directed, so that the resulting magnetic fields and induced eddy currents also have an opposite orientation. This creates an area in the middle between both eddy currents rings where the magnetic field strength equals zero. The position of this so called zero crossing can be identified from the induced voltage within the two detection coils. Since the whole eddy current system is moving with the flow of the liquid metal, the location of the zero crossing can be monitored for a certain time period and from this the flow rate or flow velocity can be derived (see Figure 2.19). Here, the resulting slopes fit very well with the predefined flow velocities.

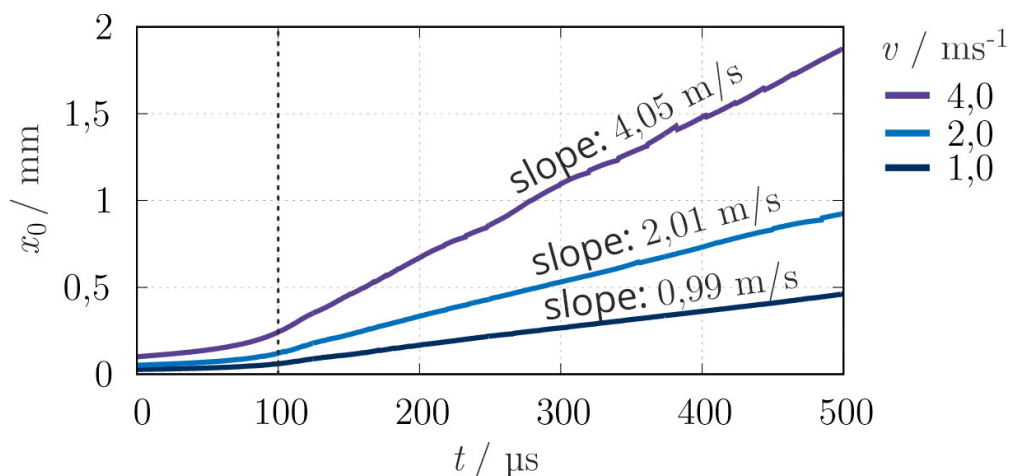


Figure 2.19 Numerical simulation results of the sensor output for the movement of the zero crossing point  $x_0$  over 500  $\mu\text{s}$  at three different flow velocities  $v$ .

In addition to the numerical simulation, measurements in liquid sodium at 180 °C in the NATAN loop were performed, using slot 4 of the multi-purpose slots (see Figure 2.12) of the test section. Some of the results are shown in Figure 2.20 for measurements at six different flow velocities. It can be seen, that the slope of the sensor output is increasing, for higher velocities. The flow velocity can be extracted from the results by calculating the linear regression line of the respective measurement. The flow velocity of the liquid sodium is equal to the slope of the regression line.

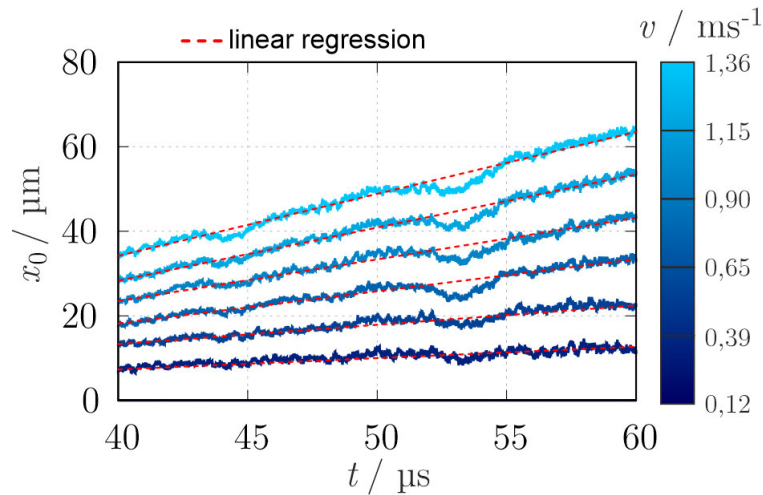


Figure 2.20 Measurement results for the flow velocity of the TECFM sensor in liquid sodium at 180 °C. The slope of the dashed red line is equal to the respective measured velocity.

Although there is considerable noise superimposed with the sensor signal, we have achieved measurement errors in the range of only a few percent. Further measurements in other liquid metals have been done for an additional validation of this new, calibration free measurement technique.





### 3 SENSOR INTERPRETATION

#### 3.1 Signal analysis and interpretation

The measurements in sodium facilities are influenced by many factors, which have to be taken into account. Important factors are:

- Temperature dependence of sodium properties and sensor readings;
- Influence of vibrations;
- Electromagnetic induction caused induced voltages, a.o.

The temperature dependence of sodium properties (Table 3.1.) influences many physical processes and must be taken into account by interpreting sensor measurements.

Table 3.1 Summary of the recommended correlations for main thermophysical properties of liquid sodium (Na) ( $p \sim 0.1$  Mpa, except critical parameters and the saturated vapour pressure) [10].

Property, parameter	SI unit	Correlation	Temperature range (K)	Estimated error $\pm$
Molar mass	kg mol <sup>-1</sup>	$M_A = 0.0229898$	n/a	-
Melting temperature	K	$T_{M,0} = 371.0$	n/a	0.1
Latent heat of melting	kJ kg <sup>-1</sup>	$Q_{M,0} = 113$	n/a	1
Boiling temperature	K	$T_{B,0} = 1155$	n/a	2
Latent heat of boiling	kJ kg <sup>-1</sup>	$Q_{B,0} = 4237$	n/a	9
Critical temperature	K	$T_c = 2500$	n/a	12
Critical density	kg m <sup>-3</sup>	$\rho_c = 220$	n/a	20
Critical pressure	MPa	$p_c = 25.6$	n/a	0.4
Saturated vapour pressure	Pa	$\ln(p_s) = 11.9463 - \frac{12633.73}{T} - 0.4672 \cdot \ln(T)$	371-1600	5 %
Surface tension	N m <sup>-1</sup>	$\sigma = (231 - 0.0966 \cdot T) \times 10^{-3}$	371-1155	6 %
Density	kg m <sup>-3</sup>	$\rho = 1014 - 0.235 \cdot T$	371-1155	0.5 %
Sound velocity	m s <sup>-1</sup>	$u = 2660.7 - 0.37667 \cdot T - 9.0356 \times 10^{-5} \cdot T^2$	371-1773	2 %
Bulk modulus	Pa	$B_s = (7.542 - 4.634 \times 10^{-3} \cdot T + 8.326 \times 10^{-7} \cdot T^2) \times 10^9$	371-1155	5 %
Isobaric specific heat	J kg <sup>-1</sup> K <sup>-1</sup>	$c_p = -3.001 \times 10^{-6} \cdot T^2 + 1658 - 0.8479 \cdot T + 4.454 \times 10^{-4} \cdot T^2$	371-1155	1 %
Dynamic viscosity	Pa s	$\ln \eta = \frac{556.835}{T} - 0.3958 \cdot \ln T - 6.4406$	371-1155	5 %
Electric resistivity	$\Omega$ m	$r_{Na}(T) = (3.126 + 6.218 \times 10^{-3} \cdot T + 3.093 \times 10^{-5} \cdot T^2) \times 10^{-8} \Omega$ m	371-1155	4 %
Thermal conductivity	W m <sup>-1</sup> K <sup>-1</sup>	$\lambda = 104 - 0.047 \cdot T$	371-1155	8 %

The measured potential differences might be also influenced by the thermoelectric properties of sodium (Figure 3.1).

The temperature dependence of other parameters might be important as well. For instance, the sensitivity of CFM depends on the operating temperature as both electrical conductivities of walls and LM are changing with temperature. So the corresponding corrections must be introduced in the following formula:

$$S = \frac{U_{AD}}{2b \cdot B \cdot V} = \frac{2a^2}{(a^2 + b^2) + (\sigma_w / \sigma) \cdot (b^2 - a^2)}$$

Additionally, there may be need for correction of magnetic field strength if magnetic poles are overheated to some extent over room temperature due to heat flux from the channel of CFM having high temperature. For example, for Sm2Co17 permanent magnets the coefficient of magnetic field

diminishing is  $\alpha = 0.03\%$  per one grade, but for NdFeB magnets its value is  $0.1\%$ . So at measuring operating temperature of LM in the CFM channel as well the temperature of magnetic poles should be measured during flow meter operation and correction for value of  $B$  must be introduced:  $B_T = B_0(1 - \alpha\Delta T)$ , where  $\Delta T$  is magnetic poles overheating in comparison with room temperature. Correspondingly, at this the sensitivity of flow meter will be smaller - proportional to smaller magnetic field value:  $B_T/B_0$ .

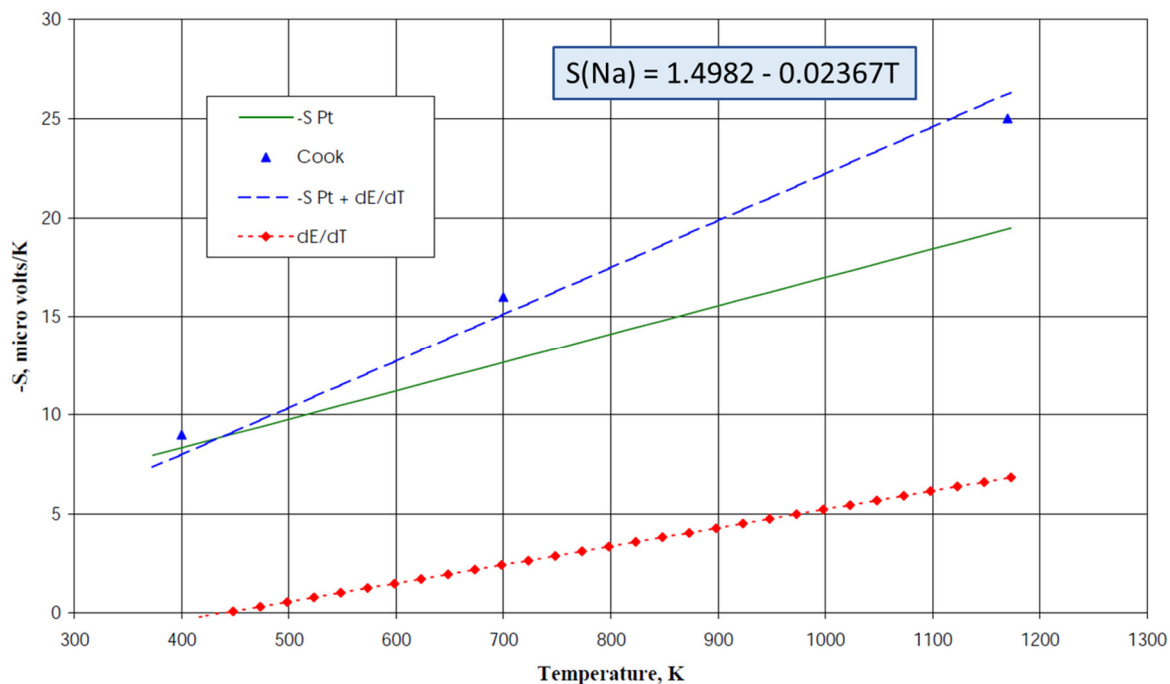


Figure 3.1 The negative of the absolute thermoelectric power for Na and for Pt and values given by Cook and Fritsch for Na [11]. The thermoelectric power of Pt relative to Na ( $dE/dT$ ) is Included [12].

The sensors themselves are subject to many factors determining their performance (Figure 3.2 shows 85 Hall sensor signal output at two different temperatures). Selection of matched pairs of sensors using differential measurement schemes and/or measurement temperature correction might be necessary.

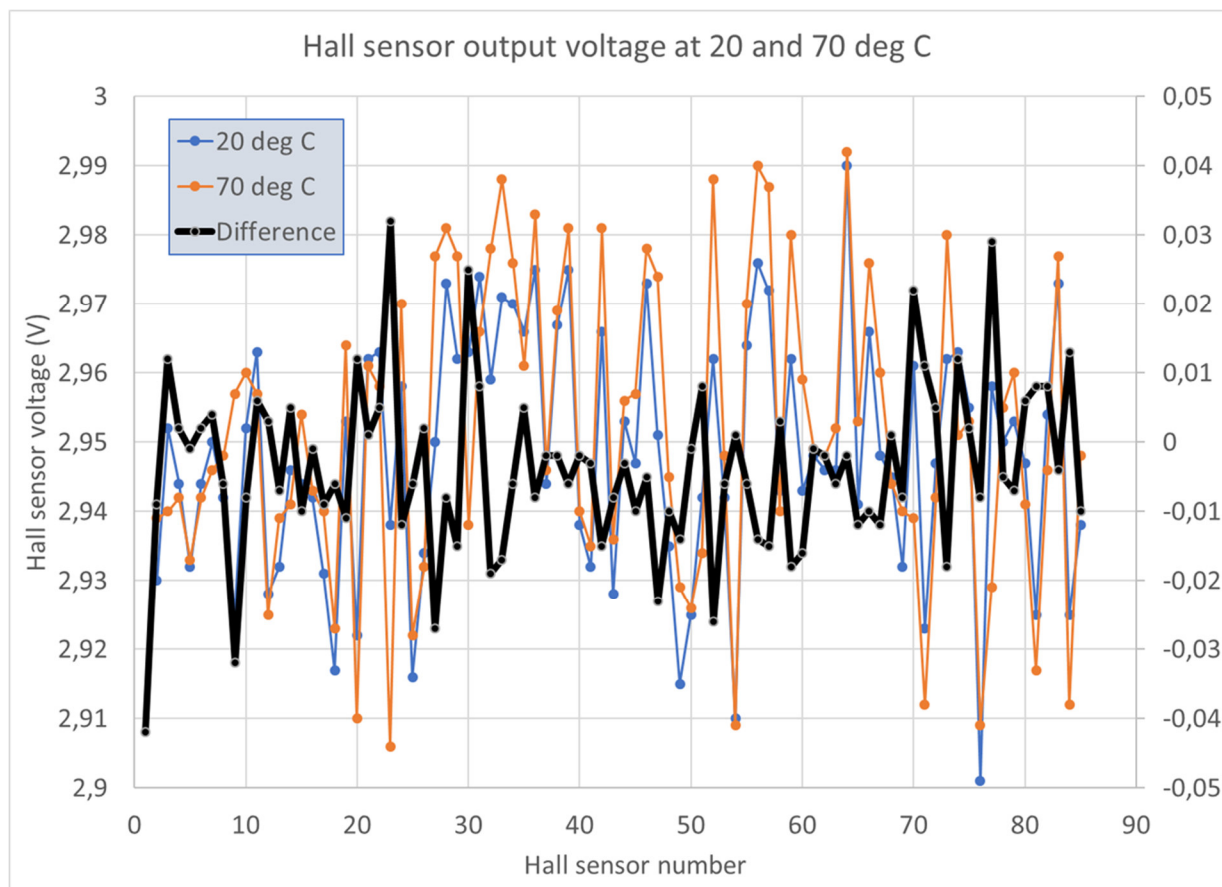


Figure 3.2 Honeywell SS490 Series Hall sensor signal dependence on temperature at zero magnetic field.

The sodium facilities are often subject to vibrations of different origin:

- Construction vibrations,
- Hydrodynamic fluctuations,
- Double supply frequency of EMP,
- Any other

Care must be taken to assess the influence of the vibrations on the sensor operation, in particular, if analysing transient processes. Acceleration measurement at sensor locations might be useful.

Electromagnetic induction induced parasitic signals originate from several sources:

- High current power supply lines with main frequency,
- Frequency inverters with wide spectrum of EM noise,
- EM induced currents from inductors, transformers, coils a.o. equipment.



## 3.2 Signal to noise ratio

Depending on the measured parameter, the signal voltages can be in interval from several millivolts till tenth of volts or even higher, for instance, a typical CFM signal is in millivolt range.

To increase the signal to noise ratio, differential inputs to measurement system are preferable. It might be beneficial to use several sensors measuring the difference of the parameters and/or compensating the outer noise.

Care must be taken by choosing the grounding points. Regardless of the good electrical conductivity of sodium, potential differences might exist at different points in sodium loop leading to errors in measurement system operation and/or measured values.

Hydrodynamic parameters (velocity, pressure) fluctuation frequency range is typically quite low – 10-100 Hz. A low pass filtering might help to improve the signal to noise ratio.

## 4 INTEGRATION OF TEST SECTIONS INTO FACILITY

Having ramped up a new facility, the next step is to exchange the test section. This requires some provisions as described below.

### 4.1 Design and interface definition

The interfaces defined by physical (geometry, design, standards), logical (fit to PLC) and thermo-fluid dynamics (flow rate, temperatures,...) as defined by the facility have to be met by the new test section or component in test or device under test (DuT).

### 4.2 Test section preparation

As described above the same phases have to be performed to integrate a new section into a running facility. First, the test section or device is optically inspected and the inner surface cleaned by hot dry argon to avoid moisture as far as possible, if necessary. The facility is opened while having a slight argon overpressure to avoid access of air and moisture.

The following processes rely on the stage approach shown in Figure 2.1 and start with an empty facility after all connections are closed and tested for leak-tightness.

#### 4.2.1 Commissioning phase

The facility is brought to wetting temperature, evacuated and flooded with Argon several times.

Start wetting of the test section depending on the tolerable temperature range. The wetting time is depending on the additional surface size and the material surface. After wetting, the sodium purification process is initiated, based on the additional new surfaces. Reaching the solubility limit, the plugging sensor is used to check the reached purification step. If necessary wetting and purification steps are repeated.



#### **4.2.2 Qualification phase**

Normally, test sections are equipped with sensors and active components such as heaters, valves and pumps, which have to be tested and qualified.

To get a broad basis and to check repeatability, the measurements should be repeated a second time.

If the variations between both runs are acceptable and explainable, the qualification is finished and the calibration curves can be imbedded into the PLC. A check of the PLC based safety margins can be added but this depends on the application range of the test section compared to that of the facility.

#### **4.2.3 Experimental phase**

In the experimental data from the qualification are used to interpret the sensor readings using the calibration curves in the PLC.

If external sensors such a TC or an flow meter give unclear signals, the reason has to be identified and the defect sensor replaced by a new one. The sensor specific calibration has to be rerun.

### **4.3 Shut down**

Shut down is the termination of the qualification or experimental phase so that the facility is in a safe and reliable state. We separate two procedure leading to short or long term shut down. A third procedure, shut down to hibernation is describe in section 5.2.

#### **4.3.1 Shut down steps**

The shut down is divided into following procedures:

1. Shut down of heating power of the test sections
2. Cool down facility until defined storage temperature of the dump tank.
3. Draining procedure
4. Trace heating control
5. Cover gas pressure

#### **4.3.2 Emergency shut down steps**

This is only necessary if a leak is detected by the leak detection system.

1. Shut down of power of trace heating and test section heating and start emergency draining procedure (this is normally initiated by an ISS)
2. Check facility by video cameras to detect leaking sodium
3. Cover gas pressure

#### **4.3.3 Short term shut down**

1. Shut down of heating power of the test sections
2. Cool down facility using forces convection to heat exchanger but avoiding too high cool-down rates. This requires control of the heat sink to avoid unwanted thermal stresses. Target



temperature is dependent on the operation temperature of the most critical sensor/components etc. This procedure is often implemented in the control logic.

3. Draining procedure:
4. Command trace heating control to maintain facility for next campaign on filling temperature. That step is dependent on the thermal insulation and the duration of shut down. Normally this can last 1-2 days, since the high temperature insulation prevents effectively cool-down so that only small amount of trace heating power is necessary.
5. Control cover gas pressure to avoid diffusion of atmospheric gases. Pressure should be  $<0,15$  MPa.
6. Shut down trace heating control allowing to cool down to room temperature

#### **4.3.4 Long term shut down**

1. Command trace heating control to maintain facility for next campaign on filling temperature. That step is dependent on the thermal insulation and the duration of shut down. Normally this can last 1-2 days, since the high temperature insulation prevents effectively cool-down so that only small amount of trace heating power is necessary.
2. Control cover gas pressure to avoid diffusion of atmospheric gases. Pressure should be  $<0,15$  MPa.
3. Shut down trace heating control allowing to cool down to room temperature

### **4.4 Dismantling of components**

Principally connection in sodium facilities are welded to ensure leak-tightness. Test sections are connected depending on the size of the pipe by flanges or screwed connectors such as (Swagelok™). Flanges require a special sealing mad of metal (C-type) omitting any carbon based materials. In screwed connectors, the self-welding or diffusion welding has to be omitted by special lubricant.

#### **4.4.1 Safety provisions**

#### **4.4.2 Transport to cleaning station**

This is dependent on the remaining sodium/sodium-oxide inside the device/components. Normally, if at room temperature a simply plastic bag filled with inert gas is sufficient. For larger components, the openings are closed by a blind flange of a plastic cap. Cleaning station should be nearby the experimental building

#### **4.4.3 Cleaning procedure**

In most of the cases non-nuclear experiments are performed or sodium is coming form non-nuclear loops (secondary loop). For that situation, cleaning is described below. Nuclear contaminated sodium cleaning is described by CEA, having large experiences with huge amount of primary sodium coming from industrial (SPX) and research reactors (PHENIX).





Figure 4.1 Lattice box for cleaning of small components (left) and partially blocked pipe (right)

Cleaning process is dependent on the size of the components and the detected sodium oxide remnants. For small components a lattice-box as shown in Figure 4.1 (left) is used allow to mount the devices safely inside the box. Typical sodium remnants are shown in Figure 4.1 (right) where sodium was oxidized and thus frozen unintentionally.

The devices are then spayed either by steam or by soft spray water, resulting in release of hydrogen and NaOH, which is diluted and can be released.

## 5 HIBERNATION

The hibernation of sodium facilities is very important to preserve the investment and the expertise gained by that facility. Before going into details, one example, the sodium storage tank of KASOLA was preserved for more than 20 years until in 2015 the licencing authority request a review of wall thicknesses and welding by ultrasonic investigation. It turned out the original material thickness was preserved, no corrosion detectable.

### 5.1 Conditions for preservation

Before preservation and hibernation, the facility is inspected and documented for future used. Be aware that a lot of information gathered during operation is not collected for several reasons. Also protocols of the last operation and manuals are reviewed and checked for actuality.

The documentation report is extended to describe the step for hibernation and a proposal for re-activation. For our storage tank, the sodium inventory and the purity was documented carefully.



## 5.2 Shut down to hibernation

For long term shut down, here called hibernation, the facility must be cleaned in advance using high temperatures and several purification runs using cold trap. Finally, the sodium is collected in the storage tank, except for that in the cold-trap. It is not advised to use that part, even at low temperature because of the risk of impurity entrainment. In KASOLA this amounts to a loss of 4-5% of the whole inventory.

Two different procedures are feasible:

1. Preservation of the whole loop or
  2. Preservation of sodium in the storage tank separately from the facility.
- Both solutions have advantages and disadvantages.

## 5.3 Supervision of hibernation

This is depending on the hibernation state. If the sodium in a storage tank is solid and the pipes are closed by welded plugs, no supervision is necessary if sufficient inter gas pressure is applied before closure. This can be performed using screwable plugs, which are highly leak tight.

A good example is the KASOLA dump tank (see Figure 1.4, right) which is now approx. 50 years old housing 7 m<sup>3</sup> at temperature up to 350°C. During licensing the tank wall thicknesses were tested at different locations and found to be at original state.

# 6 SUMMARY

The document gives an overview and some insight coming from different research units not to operate sodium facilities of different sizes ranging from a few litres up to 7 m<sup>3</sup>.

The procedure varied between the different R&D periods and reflects the gain in supervision and demand in licensing efforts.

Since the development is ongoing as seen in the last three years in the SOLTEC [13] programme, the document should be considered as a living document comprising the knowledge for future engineers and scientists.

For the nuclear applications, it is essential to extend the application range to non-nuclear applications to maintain the competence and to incorporate new ideas. This has been done in extending the sodium technology to CSP actually in Australia and to accelerator driven targets and more generally sodium as an efficient heat transfer media.





## 7 APPENDIX

### 7.1 List of reference documents

- [1] Technical report NT-2012-012 - Recommandations de conception des circuits sodium.
- [2] Technical report NT 0212-015 - Note d'interfaces des maquettes et composants ASTRID.
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## 7.2 Example for KIT facility ramp-up procedures

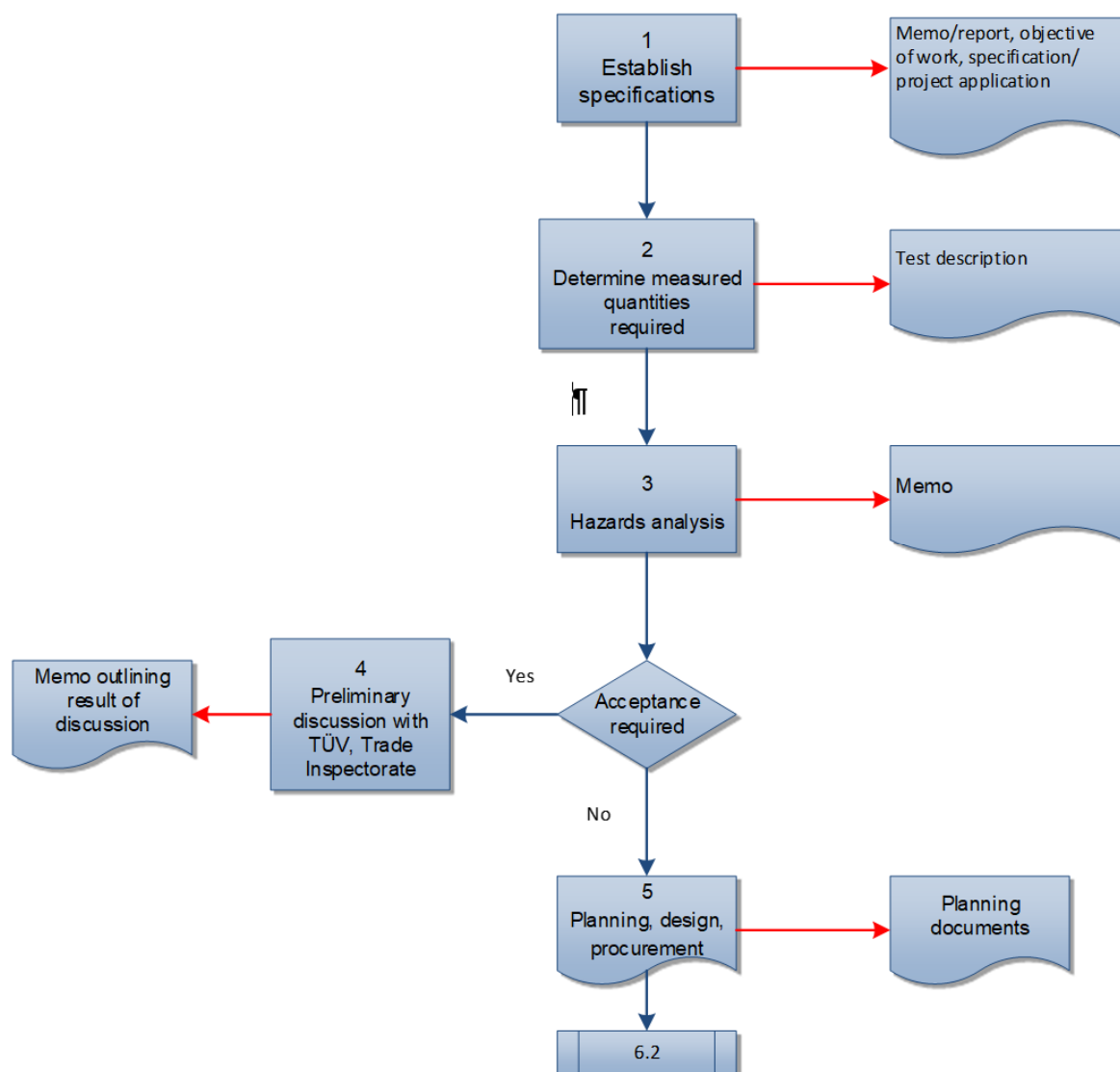


Figure 7.1 Example for test rig and facility planning and design



## 7.3 Facilities inside KIT in LIMCKA

Table 7.1 List of liquid metal facilities operate within Liquid Metal Competence Center Karlsruhe

Facility	Institute	Structure	Fluid	Built	Operation	Funding Sources
Thesis V2	IKET	KALLA	Pb	2006		Coolant Loops Programm des BMBF
TELEMAT	IKET	KALLA	PbBi	2006		Coolant Loops Programm des BMBF
THEADES	IKET	KALLA	PbBi	2003		HGF Programm (Helmholtz-5716)
ALINA	IKET	KALLA	Na			
CORRIDA	IAM-AWP		PbBi	2005		EU Vella
CORTINA	IAM-AWP	HEMCP	Na	2018		HEMCP
SOMMER	IKET	KALLA	PbBi	2016	2019	LIMTECH
MEKKA	IKET	KALLA	NaK	1990		FUSION
KASOLA	INR	KASOLA	Na	2015	2019	HEMCP, LIMTECH, Internal Funding INR
ATEFA	INR	HAC	Na	2016	2018	HEMCP, LIMTECH
SOLTEC I - III	INR	KASOLA	Na	2016	2018	HEMCP, LIMTECH
DITEFA	INR	HAC	Na	2018	2019	LIMTECH, internal Funding
KARIFA	INR	HAC	Na	2019		FUSION
AMTEC Lab	INR	HAC	Na/Li/NaK	2016	2017	HEMCP
Minipot	IHM		PbBi	2012		EU
CORELLA	IHM		Pb/PbBi	2008		IHM/Drittmittel
FRETHME	IHM		Pb/PbBi	2011		IHM
COSTA	IHM		Pb/PbBi/Sn	2000		IHM/Drittmittel
COSTA-Na	IHM		Na	2017	2018	IHM
GESA	IHM		Materials	2000		HGF, Protective coatings
Analytical Equipment	IHM, IAM, ...		Materials			HGF

## 7.4 Facilities and procedures at HZDR

### NATAN: NATtrium-VersuchsANlage

- Fluid inventory: 100 l
- Temperature range: 120 - 300°C
- Test sections: horizontal (1), vertical (2), rectangular cross section (45 x 50 mm<sup>2</sup>)
- Velocity range: up to 1.5 m/s
- Magnetic systems: electromagnets supplying a transverse magnetic field  
magnet 1: length of uniform field 320 mm, maximum field strength 0.45 T  
magnet 2: length of uniform field: 1100 mm, maximum field strength: 0.8 T
- Range of dimensionless parameters: Reynolds number Re up to about 10<sup>5</sup>  
Hartmann number Ha up to 2700 (magnet 1), up to 4800 (magnet 2)  
Interaction parameter N: 800 (magnet 1, v<sub>so</sub> = 0.1 m/s), 2500 (magnet 2, v<sub>so</sub> = 0.1 m/s)

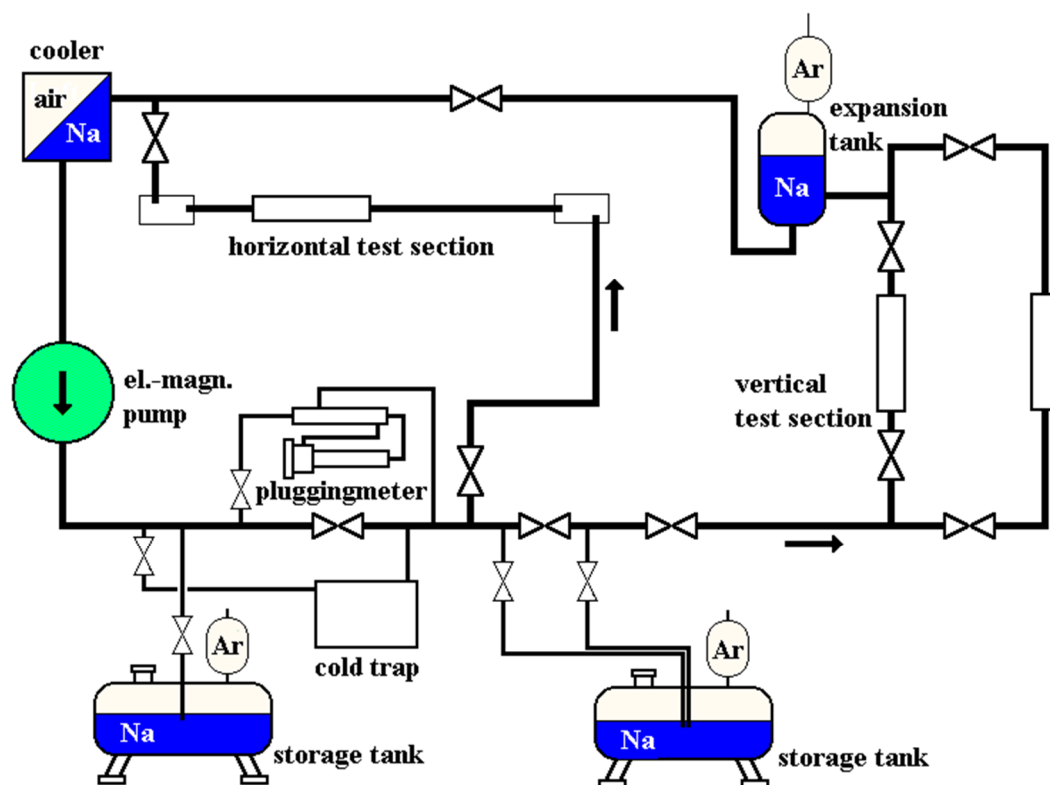


Figure 7.2 Schematic view of the sodium loop  
(<https://www.hzdr.de/db/Cms?pOid=52201&pNid=331> )