

## Data acquisition and control system for lead-bismuth loop KYLIN-II-M Postprint

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**Date:** 2023-06-18T00:00:00+00:00

### Abstract

Among different heavy liquid metals (HLMs), lead-bismuth eutectic (LBE) is considered at present as a potential candidate for the coolant of new generation fast reactors (critical and subcritical) and for liquid spallation neutron sources and accelerator driven systems (ADS). A high temperature liquid LBE loop, KYLIN-II-M, has been built to study the characteristics of corrosion and fluidity of LBE at the Institute of Nuclear Energy Safety Technology. However, due to the sensors and execution components of the loop work at high temperatures and in severely corrosive environments, the reliability and security of the data acquisition and control system (DACS) of KYLIN-II-M face challenges during the loop operation. In order to meet the urgent needs for KYLIN-II-M's long-term stable operation, a virtualization and redundancy control system has been developed. The onsite operation result shows that the DACS is stable and reliable. In this paper, the experimental results are described in detail.

### Full Text

### Preamble

#### Data Acquisition and Control System for Lead-Bismuth Loop KYLIN-II-M

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(Received April 14, 2014; accepted in revised form June 12, 2014; published online February 2, 2015)

Among different heavy liquid metals (HLMs), lead-bismuth eutectic (LBE) is currently considered a potential candidate coolant for next-generation fast reactors (both critical and subcritical), liquid spallation neutron sources, and accelerator-driven systems (ADS). A high-temperature liquid LBE loop named KYLIN-II-M has been constructed at the Institute of Nuclear Energy Safety Technology to study LBE corrosion and fluid dynamics characteristics. However, since the sensors and actuators operate in high-temperature, severely corrosive environments, the reliability and safety of the KYLIN-II-M data acquisition and control system (DACS) face significant challenges during loop operation. To meet the urgent requirements for long-term stable operation of KYLIN-II-M, a virtualization and redundancy control system has been developed. On-site operational results demonstrate that the DACS is stable and reliable. This paper describes the experimental results in detail.

**Keywords:** Lead-bismuth eutectic, KYLIN-II-M, Data acquisition and control system, Redundancy control system

**DOI:** 10.13538/j.1001-8042/nst.26.010401

## Introduction

To study lead-bismuth eutectic (LBE) related technologies, a multifunctional LBE loop named KYLIN-II-M was built at the Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, and has been in operation since 2013. The loop is designed for corrosion studies, oxygen measurement, and control tests for LBE fast reactors [1]. Characterized by a “figure-8” structure with forced circulation, the loop consists of a molten tank, storage tank, flow meter, pump, cooler, heater, heat exchanger, oxygen control facility, and three experimental sections, as shown in Fig. 1 [Figure 1: see original paper].

Compared to other LBE loops [2–4], KYLIN-II-M’s distinctive features include an operating temperature reaching 800°C and continuous running time exceeding 10,000 hours. To ensure normal operation of this high-temperature LBE loop, process variables such as flow rate, pressure, liquid level, and temperature must be monitored in real time, along with control valves and other components. Although the LBE loop is a non-nuclear facility, high performance in safety, stability, and reliability is essential. To meet experimental requirements, a DACS based on programmable logic controllers (PLC) and data acquisition cards was developed. The PLC measures low-frequency sensor signals and controls actuators, while the data acquisition card system measures high-frequency sensor signals.

Most existing LBE loop DACSs are developed using PLC systems with “point-to-point” hardware measurement and control technologies [5, 6]. However, when an I/O port problem occurs, the entire system may malfunction, affecting normal and safe loop operation. Additionally, many DACSs rely on data acquisition card systems [7, 8]. Although hardware redundancy technology is adopted to meet reliability requirements, such systems cannot monitor and control the

LBE loop flexibly. Since data acquisition systems typically lack CPU and storage modules, the entire system fails when the monitoring computer goes down. To address these limitations, redundancy control and virtualization technologies have been implemented in the KYLIN-II-M DACS. Redundancy control technology significantly improves DACS reliability and provides a foundation for system expansion. Database server-based virtualization technology enables centralized management and storage of experimental data, while Virtual Desktop Infrastructure (VDI) technology allows loop control via different operation terminals at different times. Thus, if one monitoring computer shuts down, another can assume control to ensure system reliability and operational integrity.

## General Description

The primary requirements for the KYLIN-II-M DACS are remote monitoring and control from the central control room. During experiment startup, an initialization process performs self-checks on 562 data acquisition channels and 123 digital output channels. Additionally, 7 analog output channels control electrically operated valves (EOVs). A large volume of measurement data is stored in the database server in string format using Structured Query Language (SQL) [9] statements during loop operation. The transmission bandwidth is estimated at 100 MB, and all operational parameters meet system requirements.

The major functions of the DACS are as follows:

- To acquire experimental data from field sensors, including all sensor signals, fault signals, environmental signals, and operation parameters.
- To control loop equipment, including all actuators (EOVs, solenoid valves, vacuum pumps, etc.), the pump, heat exchanger, insulation system, and gas system.
- To implement online fault detection and diagnosis. To effectively prevent accidents caused by operational errors, a fault-tolerant control and interlock protection program has also been developed.
- To design a VDI system.
- To support remote access and control, a virtual digital loop (VDL) was developed to simulate LBE loop operating conditions in real time.

## The DACS Architecture

The DACS of KYLIN-II-M consists of a main DACS, a data processing system, a user interface system, and a virtual laboratory, as shown in Fig. 2 [Figure 2: see original paper]. Communication between systems is conducted via local area network (LAN). The main design parameters are listed in Table 1. The number of designed I/O ports includes more than 10% channel allowance to ensure system extensibility and ease of updating.

## A. The Main DACS

The main DACS hardware comprises Siemens S7-300 series PLC modules, NI PXI series modules, and an alarm system. The architecture is a distributed and centralized system (DCS). Independent systems such as the drive, heater, and oxygen control systems are distributed on-site as field ET200 substation systems for the PLC master station. This significantly reduces signal transmission distance, thereby improving signal detection capabilities.

For low-speed data acquisition and logic control, PLC AI and DI modules are used, offering advantages including robust software and hardware support, cost-effectiveness, reliability, and especially strong anti-environmental disturbance capability. For high-speed data acquisition, PXI series data acquisition cards collect high-frequency signals in dynamic measurement experiments. To adequately preserve signal shape, the sampling rate must be much higher than the Nyquist frequency. Therefore, the DACS sampling rate is set at 5 times the maximum frequency component of the signals.

To ensure loop operation safety and reliability, an alarm system has been developed, consisting of a fault detection system, fault diagnosis system, and safety interlock system. Fault definitions and classifications are shown in Table 2. Fault classification “A” represents serious accidents, “B” normal accidents, and “C” minor accidents. The system must shut down immediately when a serious accident occurs. Figure 3 [Figure 3: see original paper] presents the system shutdown process flow chart. Considering KYLIN-II-M’s operational integrity, when a minor accident occurs, the system should continue alarming until the failure is recovered rather than shutting down. However, noise affects DACS reliability in fault detection and estimation. To address this, a multipoint measurement system, safety barriers, and isolators are used. Various alarm modules have been developed, including text alarms, voice alarms, GSM alarms, and web distribution alarms. A notable feature is the GSM alarm, which sends text messages to registered cell phones when abnormal loop status is detected.

## B. Data Processing System

The data processing system consists of a database server, two LAN switches, and a VDI system. Large amounts of data are recorded in real time in the database server. Experimental and diagnostic data transfer to the data processing system through the LAN. The VDI system distributes 20 virtual workstations for researchers, with each workstation provisioned with 2 processor cores, 128 GB memory, and two 300 GB 15K SAS hard disks via virtualization technology. Two repositories are configured: a core repository for system data and a platform-specific repository for workstation buffers. Each device transfers data through a 1 GB Ethernet adapter running in full-duplex mode.

An OPC server [10] serves as a shared database, enabling data distribution to any system connected via LAN. Remote client and server applications exchange data using OPC Unified Architecture (OPC UA) client and server application

programming interfaces (APIs).

### C. User Interface System

The user interface system provides 20 VMs for researchers in the central control room. While the data processing system distributes 20 virtual workstations and 20 VMs, all must be monitored and controlled remotely. The user interface system is designed and constructed with LAN support, displaying and monitoring all experiment data. Twenty virtual desktops (VDs) monitor loop operation, and these VDs can be switched. Thus, when the primary monitoring computer shuts down, the standby VD assumes control to ensure system reliability and operational integrity. Watchdog technology facilitates this transfer. The instructions for switching between primary and standby computers are shown in Fig. 4 [Figure 4: see original paper]. When the primary monitored VD operates normally, it periodically sends reset instructions to the standby VD, which is then periodically reset without executing the control program. However, if the primary VD fails, reset instruction transfer aborts, and the standby VD executes the control program to gain DACS control.

### D. Virtual Laboratory

The virtual laboratory system includes a virtual digital loop (VDL) that enables three-dimensional loop structure modeling, simulation, and analysis; an online data backup server; a remote fault diagnosis system for analyzing predefined fault data; and a web client for distributing experimental data and monitoring loop operation. Data originates from the OPC server via LAN communication interfaces. The VDL, established using computer virtualization technology, graphics processing, and Ethernet, provides visual information for KYLIN-II-M researchers. The pump system, oxygen control system, and heater can be displayed sequentially or simultaneously. The VDL is not merely a virtual display system but also a high-temperature liquid LBE loop physics calculation and simulation system. For data security, a disaster recovery (DR) system enhances experimental data reliability and availability.

## Redundancy Control System

The DACS software is developed using configuration and graphical programming languages. Matlab and C language are employed for efficient development of special system functions. PLC software is developed using SIMATIC, as well as HMI (Human-Machine Interface) based on WinCC and WinCC Flexible configuration software. LabVIEW, a graphical software development tool, provides another reason for choosing the PXI platform, as it enables code development through graphical icons and greatly enhances productivity.

Based on this work, remote monitoring software has been developed. The DACS software interface design principles are simplicity, support, accessibility, and versatility. The monitoring software interface is presented in Fig. 5 [Figure 5: see

original paper], consisting of five interfaces with different functions. The main interface provides operators with experimental data display and key component control functions, enabling emergency measures during critical situations. Gas valves and subsystems (e.g., electromagnetic pump) can be controlled and monitored through the gas valve interface and subsystem interface. The alarm interface displays and modifies system alarm information and parameters. Additionally, the most recent data can be viewed with automatic refresh, and historical data can also be accessed.

To ensure DACS reliability, a redundancy control system was designed. Both redundant methods and redundancy levels were studied and analyzed to improve reliability and cost-effectiveness. Two redundant methods were established to research their effects on DACS reliability, as shown in the schematic diagram in Fig. 6 [Figure 6: see original paper]. The system consists of several control components  $A_n$ . Neglecting intermediate influences, DACS reliability can be calculated through the following formulas:

$$R_1(t) = \prod_{i=1}^n [1 - (1 - R_{A_i}(t))^2]$$

$$R_2(t) = 1 - \left[ 1 - \prod_{i=1}^n R_{A_i}(t) \right]^2$$

where  $R_1(t)$  is the reliability of the series-after-parallel system,  $R_2(t)$  is the reliability of the parallel-after-series system,  $R_{A_i}(t)$  is the reliability of control component  $A_i$ , and  $0 < R_{A_i}(t) < 1$ . Numerical calculation yields  $R_1(t) > R_2(t)$ , where  $i$  is the number of control components and  $i > 1$ . Therefore, the parallel-then-series redundancy mode is adopted.

To study the relationship between redundancy and reliability, a parallel control components model was established, as shown in Fig. 6. When component life distributions are exponential, control system reliability can be calculated as:

$$R_s(t) = 1 - (1 - e^{-\lambda t})^n$$

where  $\lambda$  is the failure rate of the control component and  $n$  is the system redundancy. Considering the mean time between failures (MTBF) of PLC components is nearly 300,000 h [11], the failure rate can be calculated as  $\text{MTBF} = 3/2\lambda$ . With  $\text{MTBF} = 300,000$  h, the failure rate  $\lambda$  is  $5.0 \times 10^{-6}$ .

Figure 7 [Figure 7: see original paper] presents system reliability under different redundancies, particularly for  $n = 1, 2, 3$ , and 4. The results clearly show that DACS reliability improves with increasing redundancy, but when  $n > 2$ , reliability improvement becomes insignificant. With redundancy  $n = 2$  and after 50,000 hours of operation, reliability reaches nearly 0.97, meeting DACS

stability requirements. Therefore, double redundancy is employed in the DACS, including redundant PLC CPUs and functional modules.

Based on this analysis, a double redundancy DACS using the parallel-then-series redundant mode was designed, as shown in Fig. 8 [Figure 8: see original paper]. While meeting safety and reliability requirements, the redundant DACS is designed economically with minimized control components. Key control components ensure experimental data reliability during loop operation emergencies. Experimental data is stored in both local and remote database servers to ensure data security. The DACS employs double redundant PLC CPU hot standby and functional modules (AI and DI modules). This simple hardware structure, with two CPUs connected by Ethernet, greatly enhances DACS safety and reliability.

## Experimental and Results

The DACS has operated for thousands of hours, obtaining preliminary results for temperature and flow rate using analog input modules. Traditional LBE temperature measurement uses temperature sensors placed on the loop pipe, but results may be inaccurate due to uneven pipe heat transfer. To overcome this limitation, multipoint measurement is employed. Temperature average data for specific stations is automatically computed through the DACS. The outlet temperature measurement method and results are shown in Fig. 9 [Figure 9: see original paper]. The average temperature reasonably reflects the true LBE temperature, with temperature variation less than 3°C, demonstrating DACS reliability and ability to meet loop operation demands. This method's advantage is that if one temperature sensor fails, two remaining sensors continue measuring temperature.

LBE flow rate is measured using a Venturi Pitot tube flow meter. To ensure linear operation range, pump current must not be less than 50 A and LBE flow rate must exceed 1 m<sup>3</sup>/h. Flow rate measurements at 302°C are presented in Fig. 10 [Figure 10: see original paper]. Results indicate that as pump current increases, LBE flow rate increases gradually but does not maintain a strictly linear relationship, primarily due to pumping pressure characteristics.

The liquid LBE level meter enables local level measurement, consisting of an electrode, DC power supply, and signal processing unit. This method measures two states: whether contact height has been reached. The technique is simple and uses custom construction, leveraging LBE's good electrical conductivity. When an initially open electric circuit stressed by 24 VDC closes as the liquid LBE surface contacts the electrode spike, the potential decreases. This is captured by an optocoupler and level translator—the optocoupler primarily isolates the liquid level signal transmission, while level translators meet PLC DI module trigger level requirements. Liquid level signals are acquired by both PLC and PXI systems to ensure loop level remains below safe limits. To gather more comprehensive liquid level information, an array of these level meters is installed. A sketch of the level meters and measurement results is shown in Fig. 11 [Figure

11: see original paper].

To ensure precise and smooth liquid level control, three level meters are used in the control process. When LBE reaches the first level meter, gas pressure is decreased to limit LBE flow rate. Once LBE reaches the second level meter, the gas valve is immediately closed. When LBE reaches the third level meter, the DACS triggers an alarm.

## Conclusion

The hardware architecture solution for the high-temperature liquid LBE loop KYLIN-II-M has been presented. Virtualization technology successfully solved the problem of inflexible DACS monitoring. Redundancy control improved DACS reliability. Fault diagnosis was designed to ensure loop security. The DACS has operated for thousands of hours, demonstrating reliability, flexibility, and security. Future work will further optimize the DACS software to satisfy loop stability and seamless operation requirements, and a new operating system such as Linux will be employed.

## Acknowledgements

The authors thank the staff and students of the Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, for their assistance in this research.

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