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THE CONVERSION OF A ROOM TEMPERATURE NaK LOOP TO A HIGH TEMPERATURE MHD FACILITY FOR Li/V BLANKET TESTING

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ABSTRACT

The Vanadium/Lithium system has been the recent focus of ANL's Blanket Technology Program, and for the last several years, ANL's Liquid Metal Blanket activities have been carried out in direct support of the ITER (International Thermonuclear Experimental Reactor) breeding blanket task area. A key feasibility issue for the ITER Vanadium/Lithium breeding blanket is the development of insulator coatings. Design calculations, Hua and Gohar,[1] show that an electrically insulating layer is necessary to maintain an acceptably low magneto-hydrodynamic (MHD) pressure drop in the current ITER design. Consequently, the decision was made to convert Argonne's Liquid Metal EXperiment (ALEX) from a 200°C NaK facility to a 350°C lithium facility. The upgraded facility was designed to produce MHD pressure drop data, test section voltage distributions, and heat transfer data for mid-scale test sections and blanket mockups at Hartmann numbers (M) and interaction parameters (N) in the range of 10^3 to 10^5 in lithium at 350°C.

Following completion of the upgrade work, a short performance test was conducted, followed by two longer, multiple-hour, MHD tests, all at 230°C. The modified ALEX facility performed up to expectations in the testing. MHD pressure drop and test section voltage distributions were collected at Hartmann numbers of 1000.

I. INTRODUCTION

Initial experimental investigations of the MHD performance of candidate insulator materials and the technology for putting them in place occurred in 1993 using a test section with an insulating coating. Aluminum oxide was chosen as the first candidate insulating material (on a 304 SS pipe) because it was being considered, in combination with NaK, for use in the ITER vacuum vessel and/or the divertor, Natesan et al.,[2] and MHD performance tests could begin immediately in ALEX because NaK was already the working fluid in use. The results of this NaK testing, up to 200°C, showed that the aluminum oxide coating could significantly reduce MHD pressure drop, Reed et al.,[3] almost as low as expected for perfect electrical insulation.

Near the end of the fabrication phase of the aluminum oxide coated test section, it became clear that all future work must be as ITER-relevant as possible. This meant ANL's liquid metal blanket activities should be directed toward performing tests on vanadium components using lithium as the working fluid so that lithium-compatible coatings could be developed and tested. Consequently, the decision was made to convert ALEX from a 200°C NaK facility to a 350°C lithium facility. This upgrade was undertaken in parallel with finishing up the previously planned NaK testing. The objective of the upgrade was to modify the existing facility to the minimum extent necessary, consistent with providing a safe, flexible, and easy to operate MHD test facility which uses lithium at ITER-relevant temperatures, Hartmann numbers, and interaction parameters. The upgraded facility was designed to produce MHD pressure drop data, test section voltage distributions, and heat transfer data for mid-scale test sections and blanket mockups at Hartmann numbers (M) and interaction parameters (N) in the range of 10^3 to 10^5 in lithium at 350°C.[4]

The design conditions for the upgraded ALEX facility are:

Design pressure:	1.0 MPa	(150 psig)
Design flow:	22 l/s	(350 gpm)
Design Temperature:	350°C	(660°F)

II. SYSTEM CONFIGURATION AND ESSENTIAL FEATURES

The ALEX facility is a pressurized, closed loop system for performing high temperature isothermal liquid-metal MHD experiments. Lithium (Li) was chosen as the working fluid because it is the coolant of choice for fusion reactors, helps produce conditions as close as possible to reactor relevant conditions (given the size and strength of the ALEX magnet), and because coating compatibility questions can only be addressed with Li as the working fluid. The overall system consists of the following major sub-systems: Lithium System, Argon System, Instrumentation and Data Acquisition System (DAS), Pressure Measurement System, Control and Interlock System, Secondary Containment Systems, Leak Detection, Smoke Detection and Scrubber Systems, Magnet and Magnet Traversing System, and Heating System.

ALEX is located in a high-bay building with access to a 3.2×10^4 kg (35 ton) overhead crane, for handling the magnet halves and test sections. The overall facility layout is shown in Figs. 1 and 2. The magnet system description and several additional facility photos can be found elsewhere.[4] Test sections are oriented in a horizontal position with a small slope to aid in Li draining. The lithium working fluid is stored in a dump tank, under an argon cover gas to minimize the formation of lithium oxides and other lithium compounds. The lithium drains automatically into the dump tank upon shutdown of the pump and remains there when the loop is not operating. Lithium pockets are limited to the main flow control valve and the pump casing. The dump tank occupies the lowest loop component elevation. The loop drip pan forms the base of a metal enclosure (loop equipment room) around the major loop components. The drip pan protects the concrete floor under the loop from a lithium system spill or leak. An additional steel pan surrounds the dump tank. The following major loop components are located outside the metal enclosure: test section, magnet and magnet traversing system, heat exchanger, and pressure measurement system.

The magnet is protected from a test section lithium leak or spill by a non-magnetic stainless steel tray and tray cover. Test sections utilize OTECO® type flange connections at each end. Stainless steel sheet metal boxes at each end of the test section provide terminations for the tray as well as permit removal and installation of test sections. The boxes and the tray are ducted to the loop equipment room. The loop equipment room is ducted to a wet scrubber system for removal of combustion product aerosols which may be produced by lithium reactions or fires.

The lithium circulation pump is a seal-less centrifugal pump, an enclosed canned motor pump with no rotating seals. Flow rate is controlled by adjusting the pump speed and throttling bellows-sealed valves.

The lithium is pumped out of the dump tank, through the test section, the heat exchanger, and the primary electromagnetic (EM) flowmeter before returning to the dump tank. There are two selectable separate flow paths from the primary EM flowmeter to the dump tank. The flow can be routed through these two paths to meet the needs of an experiment. The typical flow path for testing flows $\leq$ 9.5 l/s (150 gpm) is through a 3.8 cm (1.5 in) EM flow meter, and a bellows-sealed manual control valve. An argon cover gas is maintained inside the lithium and pressure measurement systems at all times. Lithium temperature is controlled by a 16-zone electric heater system.

III. LITHIUM SYSTEM

The lithium system consists of the following major components: dump tank - for storing the lithium between experiment runs, circulation pump - for pumping the lithium through the loop and test section, test section - for collecting experimental data in the presence of a magnetic field, heat exchanger - for removing heat from the NaK/lithium to maintain desired operating conditions (to be completed in the future), heat exchanger surge tank - for collecting Ar gas bubbles purged from the heat exchanger, loop surge tank - for collecting Ar gas from loop piping, valves, etc., valves - for adjustment of the lithium flow, and a flanged connection system - for connecting components, including the test section, and piping segments together.

By means of the above components, the lithium system contains, circulates, and controls the flowrate and temperature of the Li. All lithium system piping is 7.62 cm (3 in, Sch. 40) except the low flow leg which is 3.81 cm (1.5 in, Sch. 40). Three flange types are used in the flanged connection system, OTECO®, LEVI, and ANSI weld neck.

The Li metal, 181 kg total, was loaded into the dump tank at room temperature in the form of 400 cylindrical ingots 7 cm dia. x 23 cm long. The lithium purity was 99.95 wt.%. No lithium purification system is used; the loop piping is constantly maintained under 99.999% Ar cover gas at a minimum positive pressure of 7 kPa (1 psig) to prevent inward contamination.

IV. LITHIUM SYSTEM COMPONENT DESIGN DESCRIPTIONS

The dump tank provides lithium storage when the loop is inactive between runs. The dump tank is fabricated of all welded construction using 50.8 cm (20 in) standard weight 9.5 mm (3/8 in) wall pipe. Standard 50.8

cm (20 in) end caps are welded to the pipe to make a horizontal tank, 244 cm (96 in) in overall length. Li-wetted materials of construction are ASTM-A-312, TP304L. The tank has five top penetrations; the ones for outflow and inflow of lithium are both 7.62 cm (3 in, Sch. 40) pipe size.

The circulation pump is a Crane Chempump, Model GVHSH-3S, a high-temperature seal-less centrifugal pump. The pump has only one moving part - a rotor and impeller assembly which is driven by the rotating magnetic field of the induction motor.

Pump motor cooling and bearing lubrication are provided by the flow of circulating lithium through the motor section. The stator winding cavity of the pump is filled with air. Class C insulation is furnished. This, coupled with the air-filled stator cavity and the cooling and lubrication system, allows the unit to handle fluids at temperatures up to 343°C (~350°C, 650°F).

The pump is powered by a solid state, variable frequency, variable torque AC drive (Emerson model AS5290, type 5VT-30), which is capable of running the pump at speeds from 690 rpm to 3450 rpm (full rated speed) and maintaining the pump speed constant within ±1% of set point.

All Li-wetted pump surfaces are 304/316 SS except for the WC-coated shaft, the SiC bearing material, and the nitrided thrust surface.

The pump is externally heated by two 6 kW each heating zones, one for the ends of the pump and one for the recirculation/lubrication line. The pump is instrumented with 26 thermocouples for measuring the external surface temperature, for control, and for over-temperature.

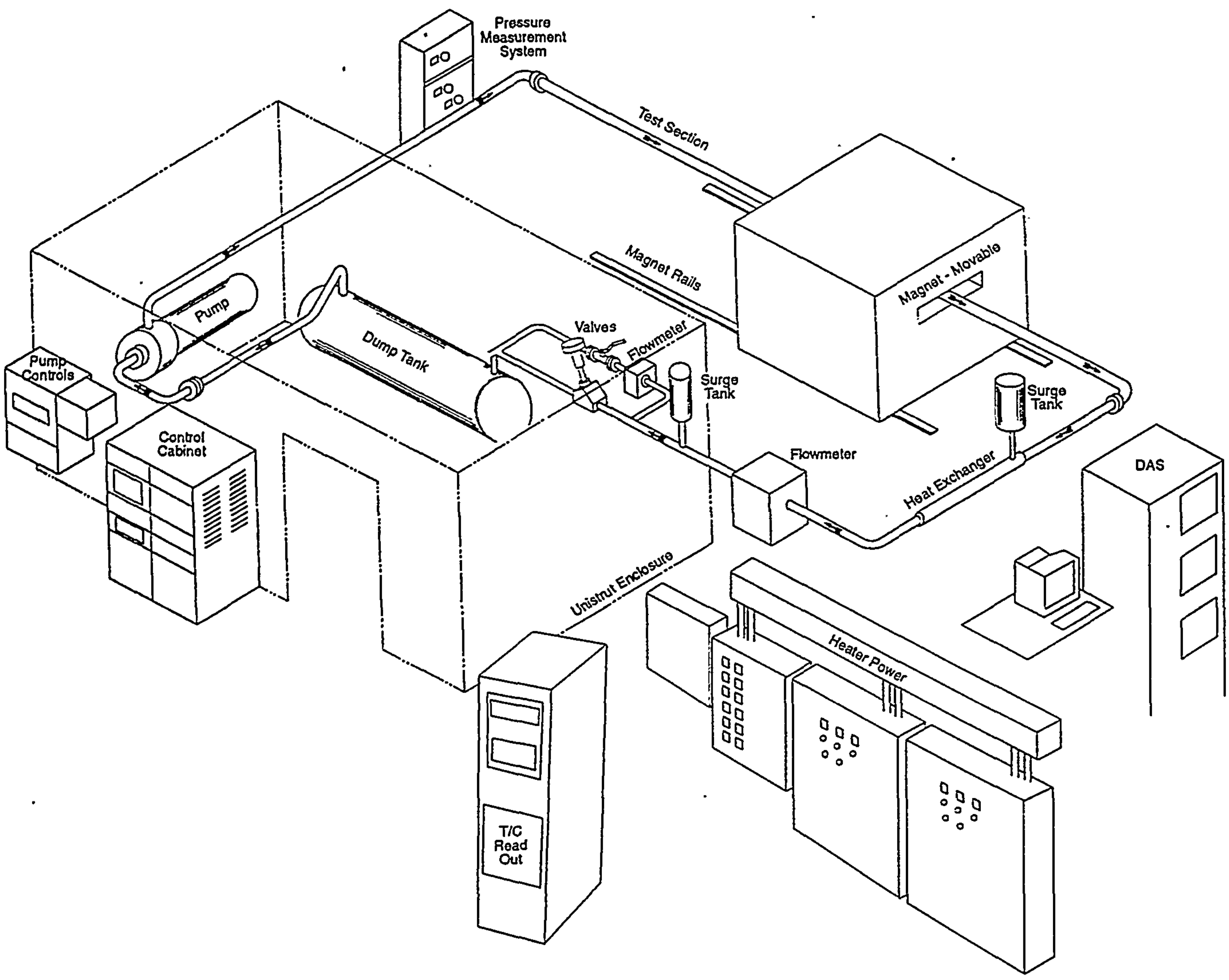

Figure 1. Isometric view of upgraded ALEX facility.

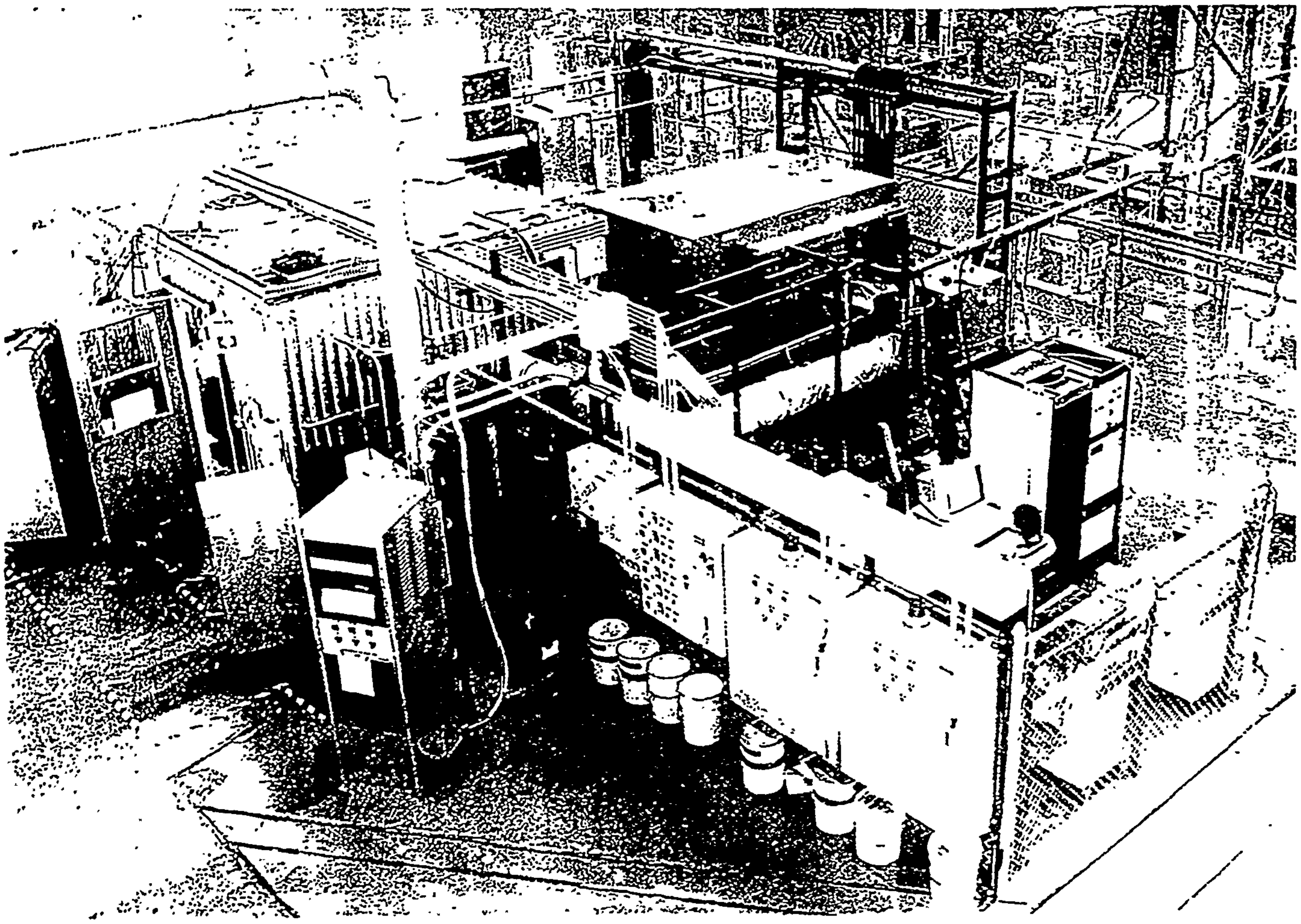

Figure 2. Upgraded ALEX facility.

V. FLANGED CONNECTION SYSTEM

Standard, 300 series, 150# and 300# stainless steel ANSI weldneck flanges are used to connect major components and piping segments together. Each flange configuration was analyzed to determine the recommended gasket seating load and recommended bolting torques according to "improved" ASME Code guidelines (which are far more rigorous than existing procedures).

The OTECO® flanges are used to connect the test section to the loop piping. OTECO® flanges are a proprietary design having a metal-to-metal seal between the two 316SS hubs and a 17-4 PH SS seal ring; their pressure and temperature ratings are 12.7 MPa and 540°C, respectively. OTECO® flanged connections have been successfully used previously in ALEX with 200°C NaK and 550°C Li.

VI. PIPING SYSTEM ANALYSIS

Thermal stress analyses were performed on the 7.62 cm (3 in, Sch. 40) pipe, dump tank, and loop piping. A transient thermal analysis of an empty segment of 7.62 cm (3 in, Sch. 40) pipe calculated the [primary plus secondary stress intensity : ASME code allowable] to be [29 : 276] MPa, [4.4 : 41.4] ksi. A steady state, 3D finite element analysis was carried out for the dump tank using COSMOS; the resulting [primary plus secondary stress intensity : ASME Code allowable] in the neighborhood of welds was [73 : 280] MPa, [10.9 : 42] ksi. The ANSYS code was used to perform a steady state piping flexibility analysis; the un-restrained [primary plus secondary stress intensity : ASME code allowable] was [60 : 280] MPa, [9.0 : 42] ksi.

VII. ARGON SYSTEM

The argon system consists of 3 standard compressed gas cylinders of high purity argon, associated valving, pressure regulators, argon rotameter, and an argon purifier. The argon is 99.999% pure, with 10 ppm of the following impurities: O_2, H_2O, N_2, CH_4, and total hydrocarbons. The argon system includes disposable argon purifiers which are capable of reducing the O_2 and H_2O levels to less than 10 ppm. The argon system serves the following two functions: it provides an inert cover gas over the lithium to minimize oxidation, and it is used to force the lithium out of the dump tank and up into the loop, prior to initiation of lithium circulation.

VIII. INSTRUMENTATION AND DAS SYSTEM

Flowmeters employed are DC EM flowmeters FM102 and FM103, made by Mine Safety Appliances and Sechrist Industries, respectively. Their calibration factors were determined by applying temperature- and working-fluid-dependent correction factors to NaK calibration factors which were previously determined in ALEX by using NIST-traceable turbine flowmeters. Lithium flow rate is measured in the main flow loop and in the low flow loop as well. Types K and T thermocouples are used throughout the loop.

Lithium level detectors indicate a full and low level in the dump tank. In the surge tank, low, high, and overflow levels are indicated. CONAX level probe fittings with Lava (magnesium silicate) packing are used. Level probe electrodes are 300 series SS rod.

Instrumentation is provided for measuring the lithium system pressure in the cover gases of the loop surge tank and dump tank. Instruments that may be connected to the DAS include flowmeters, the differential pressure measurement system and test section thermocouples.

A thirty-channel digital thermocouple chart recorder/relay alarm unit is provided for monitoring selected piping and component temperatures during heatup and operation.

The Pressure Measurement System employs argon gas-filled pressure transmitters connected to three existing Rosemount Model 1151 DP differential pressure sensors. The three DP sensors have ranges of (0-1.2, 0-7.5, and 0-25) kPa (0-5 in, 0-30, in and 0-100 in H_2O, respectively). The argon gas-filled system transmits loop pressure to the DP sensors through piping surge tanks.

IX. CONTROL AND INTERLOCK SYSTEM

The control and interlock system was designed to achieve the following three objectives: to prevent pump cavitation, to assure the loop is full of lithium prior to starting the pump, and to prevent lithium from overflowing the surge tank. To accomplish the first two objectives one set of interlocks was developed which restricts the conditions under which the pump can be started; for the third objective, another set of interlocks was developed to restrict the conditions under which the pump will continue to operate, once started.

X. SECONDARY CONTAINMENT SYSTEMS

To protect neighboring experiments and to assist in potential fire fighting efforts, major loop components including all flanged and threaded penetrations of the NaK/lithium piping are located inside metal containments. The main components of the loop, e.g., the pump, dump tank, flow control valves, and all of the ANSI flanges, are located inside a metal containment building, which has a metal floor.

A stainless steel "secondary" containment surrounds the test section including its flanged connections to the loop piping. This test section secondary protects the magnet coil windings from potential lithium leaks. It also contains and directs any combustion aerosols into the scrubber system. The metal thickness of the test section secondary is 1.5 mm (0.0598 in, 16 gauge). The secondary containment is not air tight; the negative pressure created by the scrubber system is designed to minimize aerosol release.

All pressure taps, pressure lines, transducers, and valves of the pressure measurement system are inside a secondary containment, as are the leak detectors, which are located at each position where a credible NaK/lithium leak is possible.

The non-welded connections on each end of the NaK-filled heat exchanger are surrounded by a 1.5 mm (0.0598 in, 16 gauge) stainless steel containment system made from cylindrical, flat-bottomed containers. Low temperature leak detectors (as described below) are positioned at the bottom of each container.

XI. LEAK DETECTION, SMOKE DETECTION, AND SCRUBBER SYSTEM

The leak detection system consists of more than 20 sensors and a single detector chassis. The system detects NaK/lithium leaks by taking advantage of the high electrical conductivity of NaK/Li. Leak detector sensors are of two types:

<u>Low-temperature sensors</u> are printed circuit boards covered by rows of current paths etched into one side. When adjacent current paths are bridged by a drop or more of NaK/Li, the short circuit condition is detected by the

chassis, giving both an audible tone and illuminating an indicating light.

High-temperature sensors are comprised of a single loop of electrical hook-up wire wrapped around each ANSI flange, in the gap between the mating flanges. A portion of the high-temperature electrical insulation at the bottom of each loop of sensor wire is removed, so that any lithium leak will contact the wire and complete the electrical circuit between the flange and the high-temperature wire.

Each leak detector sensor is identified separately on the indicator panel so that NaK/lithium leaks can be located quickly. Every flanged connection has a dedicated leak detector sensor.

The smoke detector is a commercially available photo-electric device which initiates the following three actions when smoke is detected, it: (1) signals the ANL fire department, (2) starts the loop wet scrubber system, and (3) turns off the aerosol containment building exhaust fan.

The scrubber system is a commercially available wet venturi-eductor system which removes aerosols by scrubbing with fresh water in a converging-diverging hypermixing eductor. An induction fan raises the scrubbed gas pressure back up to slightly above atmospheric and ducts it to an exhaust stack. The scrubber starts automatically in the event of a fire.

XII. TEMPERATURE CONTROL SYSTEM

The loop heating system consists of 16 independent zones of 208 VAC resistance-heated ceramic band heaters. All zones have four main components: temperature controller; receives input from control thermocouple, (solid state, PID); power controller: driven by temperature controller (SCR-based or SSR-based); high limit controller: monitors over-temperature thermocouple (digital for 6 kW zones, analog for all other zones); and double break contactor: driven by high limit controller, interrupts heater power circuit to provide independent, redundant over-temperature protection.

This system is designed to permit the unattended maintenance of component temperatures such as the dump tank, pump, flow control valves, etc. thus minimizing startup time for loop circulation.

XIII. THERMAL INSULATION SYSTEM

Custom-made removable thermal insulation covers are provided for all major loop components except the test section. The insulation consists of 5 cm (2 inch) thick of ALPHAMAT-D® 100% fiberglass high-temperature insulation, with a natural fiberglass cloth and wire mesh inner liner, a silicone impregnated fiberglass cloth outer liner, Velcro® seam covers and belt straps.

The test section, dump tank, pump body, OTECO® flanges, and miscellaneous parts of the loop are insulated with ceramic fiber insulation, usually 1 and 2 cm thick blankets. Around the dump tank, ceramic fiber insulation is used in loose form.

XIV. FACILITY PERFORMANCE

Following completion of the upgrade work, a short performance test was conducted, followed by 7.5 and 4.5 hr MHD tests, all at 230°C. The modified ALEX facility performed up to expectations in all testing. MHD pressure drop and test section voltage distributions were collected at Hartmann numbers of 1000.

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