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# Electrical Detection of Liquid Lithium Leaks from Pipe Joints

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# Electrical detection of liquid lithium leaks from pipe joints[a]

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A test stand for flowing liquid lithium is under construction at Princeton Plasma Physics Laboratory. As liquid lithium reacts with atmospheric gases and water, an electrical interlock system for detecting leaks and safely shutting down the apparatus has been constructed. A defense in depth strategy is taken to minimize the risk and impact of potential leaks. Each demountable joint is diagnosed with a cylindrical copper shell electrically isolated from the loop. By monitoring the electrical resistance between the pipe and the copper shell, a leak of (conductive) liquid lithium can be detected. Any resistance of less than 2 kΩ trips a relay, shutting off power to the heaters and pump. The system has been successfully tested with liquid gallium as a surrogate liquid metal. The circuit features an extensible number of channels to allow for future expansion of the loop. To ease diagnosis of faults, the status of each channel is shown with an analog front panel LED, and monitored and logged digitally by LabVIEW. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4894002]

## I. INTRODUCTION

Liquid lithium is a candidate plasma facing component (PFC) material for a fusion reactor, and lithium PFCs have been shown to improve plasma confinement and reduce impurities in tokamaks such as TFTR,[1] CDX-U,[2] NSTX,[3,4] FTU,[5] and HT-7.[6] In a reactor, the liquid lithium would have to be circulated in a loop system for power handling and the removal of impurities including tritium. A circulating system is more complicated than the static configurations used to date in fusion devices, and so requires further development and testing: for example, in a liquid lithium system, the ability of a system to safely freeze, reliquefy, and then continue operation without leaks is essential. The Liquid Lithium Test Stand (LLTS) is being constructed at Princeton Plasma Physics Laboratory (PPPL) to gain experience with flowing lithium systems, and as a prototype for circulating lithium in future PFC test modules.

The LLTS consists of an upper and lower reservoir, a rotating permanent magnet pump, and an electromagnetic flowmeter. The top of the reservoirs are kept under vacuum. The LLTS is designed to operate at up to 500 °C and contain up to 2 l of lithium. Connections of the pipe to the reservoirs are welded, but all other joints are demountable VCR fittings to ease construction, maintenance, and reconfiguration of the loop. Compared to a weld, a demountable joint is more likely to leak, which is a major safety concern since liquid lithium is hot (over 200 °C) and reacts with atmospheric gases, water, and concrete. The LLTS therefore requires a design to minimize the impact of potential leaks, including a system to detect leaks and actuate control systems.

Other flowing liquid liquid systems also incorporate electrical leak detectors: ALEX used etched printed circuit board conductivity detectors and wire conductivity detectors in joints,[7] and IFMIF uses a conductivity detection wire system.[8] The LLTS is the first to use copper shells as leak sensors surrounding demountable joints.

## II. THEORY OF OPERATION

We monitor for leaks of liquid lithium from a pipe joint by using the conductivity of the leaking liquid metal to complete a circuit.

Liquid lithium at 400 °C has a resistivity[9] of 32 $\mu\Omega$ cm, roughly three times less than that of 316 stainless steel at the same temperature,[10] 102 $\mu\Omega$ cm.

A conducting shell, normally electrically isolated from the pipe, surrounds each VCR fitting. If lithium leaks it will contact the shell, which will no longer be electrically isolated from the pipe. A circuit monitors for continuity between the pipe and the shell. If continuity is detected, the control systems are actuated: power to the heaters and pump motor is turned off so that the lithium in the loop can cool down and solidify.

## III. HARDWARE AND ELECTRICAL CIRCUIT

The loop is constructed from 316 stainless steel, which is resistant to corrosion by liquid lithium. The pipe of the loop has a 3/8 in. diameter and pipe joints are 5/8 in. Swagelock VCR fittings, with special non-silver-coated stainless steel gaskets.

Each VCR fitting is surrounded by a 0.050 in. thick cylindrical copper shell, electrically isolated from the pipe by Cotronics Ultra Temp 390 ceramic tape. A mockup of the shell around VCR fittings is shown in Figure 1. The ends of the cylinders are attached to the body by a temperature-compatible braze. The shell is cut in half so that it can be positioned around the fitting. The two halves then are fastened in place by a metal band. A wire lug for the leak detector circuit is attached by a tapped hole on one cylinder end face.

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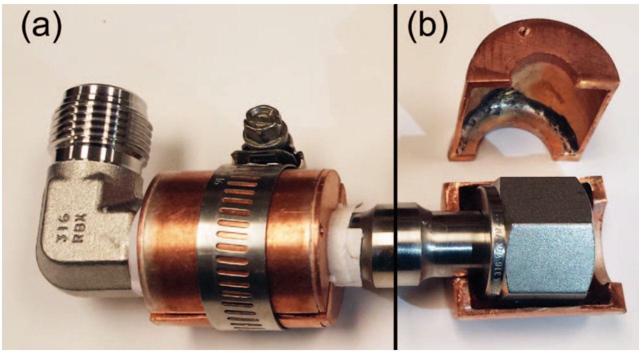


FIG. 1. A mockup of a copper shell surrounding the 5/8 in. VCR joint. In (a), note the white ceramic insulating tape between each end of the shell and the pipe. In (b), note the tapped hole (near top) for connection to a wire lug.

While copper readily alloys with lithium, it was chosen as the shell material because of its high thermal diffusivity. The shells will not be thermally insulated as the pipes will, so they will be cooler than the liquid lithium inside the pipe. If lithium leaks out of a VCR fitting, it will be physically contained by the shell and cooled down by the copper acting as a heat sink. The combination of alloying and lower temperature reduces reactivity. On this principle, copper powder fire extinguishers for lithium fires were developed.[11] In order to prevent lithium from reacting with air, and that which might leak from the shells from contacting the concrete floor, the loop will be surrounded by an argon-filled stainless steel enclosure which includes a floor plate with walls sufficiently high to contain the entire inventory of liquid lithium.

An electrical circuit, shown in Figure 2, monitors for continuity between the copper shell and the pipe. The inputs to the circuit are the two leads in the lower left of the figure: the upper lead is attached to a copper shell, and the lower (ground) lead is attached to the loop. Normally, the "+" input of the comparator is pulled up above the "–" Comparator Reference Voltage by a 100 kΩ resistor attached to a 5 V supply. If there is a fault in the loop such as a leak of lithium or a physical contact between some part of the copper shell and the pipe that allows current to flow from the upper lead to ground, the "+" input of the comparator is pulled below the reference voltage. This causes the comparator to output 0 V and the relay latches off the power to the heaters and pump.

A fault draws current through the 100 kΩ pullup resistor and also through a front panel LED, which lights. The 220 Ω resistor in series with the LED limits the current that flows through the fault. A capacitor to ground before the input to the comparator chip acts as a 1 kHz RC low pass filter in order to prevent electrical noise from artificially triggering the interlock circuit.

The comparator, a TI TLC3704, was chosen for its push-pull output: if power to one of the boards of the interlock circuit was lost, pulldown resistors (not shown) before the AND gates would cause the signal to be "low," opening the relay. A 10 kΩ resistor and Zener diode act as protection to the comparator chip against unexpected currents.

The Comparator Reference Voltage is the wiper of a potentiometer between the 5 V supply and ground. By tuning the potentiometer to output a voltage close to but lower than the normal voltage at the "+" input of the comparator, the fault current required to flip the comparator can be minimized, resulting in maximum sensitivity.

The output of the comparator is sent to a PC for monitoring and logging (see below).

There are at present 24 leak detector channels: three boards of eight channels each. The output of the comparators of each channel are ANDed together. The output of the AND gates controls a power transistor which keeps a normally open 5 V relay closed. If any of the channels detects a fault, a "low" digital signal will propagate through the AND gates and open the relay. The system is easily extensible by adding up to three additional boards for a total of 48 channels, and further by adding additional levels of AND gates.

The interlock system is designed to latch off power to the heaters and pump motor if a fault is detected, and only latch the power on again when, while there is no longer any fault, the operator pushes a "Start" button. Figure 3 shows a block diagram of the interlock system. If the operator pushes "Start" while there is still a fault condition, the power will remain off. If the leak detector circuit is not powered, the relays will be open and the heaters and pump will not be powered.

A clearly visible and accessible E-Stop button on the front panel is also capable of directly switching off power to the system. Power will only be restored once the E-Stop is reset and the "Start" button is pushed while the leak detector registers no fault.

Even if the interlock is triggered and power to the heaters and pump is turned off, the heater proportional-integral-derivative (PID) controllers remain on, which could help an operator infer the present conditions of the loop.

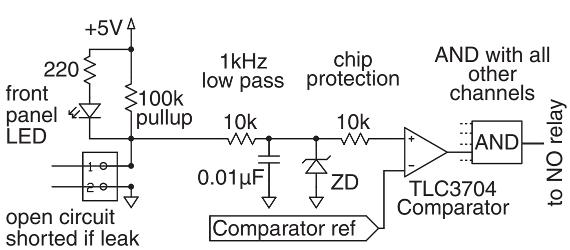


FIG. 2. One channel of the interlock circuit. If there is a fault (such as a leak) that causes the open circuit at left to be shorted, the "+" input of the comparator will be pulled down, the comparator will output 0 V, and the relay will open, latching off the power to the heaters and pump.

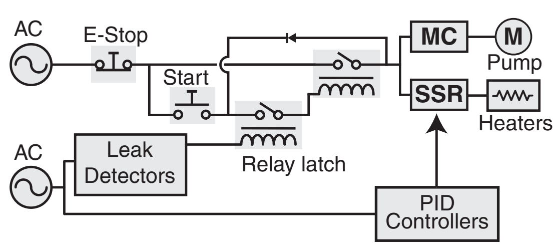


FIG. 3. Block diagram of the interlock system for the heaters and pump motor. If the leak detector circuit detects a fault, or the E-stop button is pushed, power to the pump motor and heaters will be turned off until the leak detectors register no fault on all channels and the start button is pushed. "MC" is the motor controller and "SSR" is the solid state relays.

In order to ensure that it is easy to identify the location of a fault, for each channel there is an analog LED on a front panel display that will light up in case of a fault. One additional normally-on LED for each board shows that the interlock system itself is powered on.

The fault status of each channel in the interlock system is monitored and recorded by a PC with LabVIEW. The digital output of the comparator for each channel is sent to a SCB-68A connector box which is attached to a 6323 National Instruments card in the PC. The LabVIEW program polls each interlock channel at 1 kHz, in order to record intermittent faults. Each channel has two displays in LabVIEW: one for its present status, and one indicating whether there has ever been a fault in the time since a "reset" was clicked. Since the analog front panel display shows the present status, this LabVIEW display would allow an operator to see where a past fault occurred. Additionally, for ease of monitoring, a schematic of the loop shows the status of each leak detector in its proper location. Every second, for each channel, the program logs to a file whether there has been any fault during that 1 s period. Along with thermocouple and pressure data in the same file, this could aid in reconstruction of the circumstances surrounding a fault.

Note that the PC with LabVIEW is for monitoring and logging only, and it is not at present part of any control loop.

## IV. RESULT FROM TEST OF CIRCUIT

The electrical systems described were constructed. The open-circuit voltage between the sensing terminals was 3.5 V, and the short-circuit current (limited by the 220 Ω resistor) was 15 mA. The reference voltage potentiometers were adjusted for maximum sensitivity so that any resistance between the sensing terminals of less than 2 kΩ triggers the interlock.

A test of the interlock system was performed in air with gallium as a surrogate liquid metal. Gallium was poured into a section of pipe with a VCR fitting gasket that was intentionally damaged by cutting a small slit. As expected, gallium leaked out from the damaged gasket, contacted the copper shell, and triggered the interlock.

## V. DISCUSSION AND SUMMARY

The resistance of a liquid lithium leak should be much less than the 2 kΩ maximum resistance to trigger the interlock: even a 1 cm long, 1 $\mu$m radius cylinder of liquid lithium between the copper shell and pipe would have a resistance of only 1 kΩ and would trigger the interlock. The LLTS will be in an argon-filled enclosure to minimize lithium reactions if leaks occur. Lithium compounds that do form with any residual gases will dissolve in the liquid lithium,[12] and should not affect its electrical conductivity in the time it takes to trigger the interlock system.

One potential problem of this system is that an open circuit between the two sensing terminals is the normal condition: if one of the sensing wires were to become disconnected or be cut, that channel would cease to be able to detect a fault, but there would be no indication in the system of a problem. A testing procedure or additional system could be developed to ensure operation of all leak detector channels.

Another issue is that only VCR fitting joints are monitored. A leak elsewhere in the LLTS would not trigger the interlock system. It could be advantageous to have an additional non-localized leak detection system, for example, by monitoring for a sudden change in pressure in the loop. While the vacuum pressure above the reservoirs is monitored and logged, pressure readings are not at present incorporated into the interlock system.

The LLTS, a test stand for flowing liquid lithium and liquid lithium PFC test modules at PPPL, is being constructed. A circuit to detect leaks at the demountable joints in the loop has been constructed and tested with a surrogate liquid metal, gallium. If a leak is detected, the circuit actuates a control system, latching off power to the heaters and pump in order to bring the loop to a safer state. Liquid lithium leaking from a joint contacts the surrounding copper shell, completing the leak detector circuit. The copper shell helps lower the reactivity of leaking lithium by alloying with the lithium and by acting as a heat sink.

## ACKNOWLEDGMENTS

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