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Reliability and Maintainability Data for Liquid Metal Cooling Systems

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***Abstract*—This paper presents component failure rate data for use in assessment of liquid metal cooling systems. Best estimate data applicable to fusion liquid metal coolants is presented. Repair times for similar components are also referenced in this work. These data support probabilistic safety assessment and reliability, availability, maintainability and inspectability analyses**

Keywords—reliability; maintainability; cooling system

I. INTRODUCTION

One of the coolants of interest for future fusion breeding blankets is lead-lithium. As a liquid metal it offers the advantages of high temperature operation for good station efficiency, low pressure, and moderate flow rate. This coolant is also under examination for use in test blanket modules to be used in the ITER international project. To perform reliability, availability, maintainability and inspectability (RAMI) assessment and probabilistic safety assessment (PSA) of these cooling systems, component failure rate data are needed to quantify the system models. RAMI also requires repair time data. This paper presents the data that are available at present to support quantification and recommendations are given for the best values to use when quantifying system models.

II. FAILURE RATE DATA SOURCES

There are no known component failure rate datasets on cooling system components using lead-lithium coolant. The next best option is to use data from other liquid metals since liquid metal systems share similarities of high operating temperature, moderate flow rate, and low pressure operation. Alkali metal cooling systems have been used and have generated component failure rate data. However, coolants such as sodium often use austenitic stainless steel components, while lead-lithium can corrode this material [1]. The TRITEX experiment, a lead-lithium flow loop, used a ferritic stainless steel labeled 1.4922 [2]. This and austenitic stainless steel are different materials even though they have comparable mechanical properties. There is little failure rate data for components made from ferritic stainless steels, but one report shows that HT-9 ferritic steel failure rates are directly comparable to those of 304 stainless [3]. Failure rates of carbon steel and stainless steel piping [4] have been compared and tend to be less than an order of magnitude difference, often averaging about a half-order of magnitude difference for the same operating environment. This comparison is not wholly applicable to ferritic and austenitic stainless steel, but it is indicative that the failure rates of different steels are not widely different. As a first approximation the sodium component failure rate data can be applied to components handling PbLi liquid metal coolant until more pertinent data become available.

There are a few sources of component failure rate data that have been collected from operating experiences of sodium-cooled fission reactors. Boisseau [5] made estimates of failure rates for valves, motors, centrifugal and electromagnetic pumps, cold traps, heat exchangers, steam generators, and sensors based on the Rapsodie and Phenix plants as well as test loop experiences. Pamme [6] gave some KNK-II and other operating experience-based estimates for components in secondary sodium systems, including the steam generators, pumps, valves, and piping. Wood [7] published globe valve failure rates in a sodium environment using a database called the Centralized Reliability Data Organization (CREDO). Eide [8] published a large data set that also CREDO. Bott [9] published an earlier data set from CREDO data that addressed sodium valves and electromagnetic pumps. In the 1980's, the CREDO database collected operating experiences from sodium-cooled US and Japanese fission reactor facilities to support risk assessment. There is also the Experimental Breeder Reactor II risk assessment that has failure rate values from CREDO and its own operating experience [10]. Although dated, the Clinch River Breeder Reactor risk assessment can also be a resource for component failure rates [11].

John [12] presented analyst judgment failure rates for lead-lithium system components, based on existing operating experiences that were presumably from sodium systems. Schnauder [13] gave tube and weld failure rates that were applied to not only helium-cooled blankets but also water-cooled lead-lithium breeding blankets. Schnauder stated that the values were a combination of data from the fission industry with some expert judgments on multipliers to account for enhanced welding techniques and weld inspection.

There is also guidance on applying data from water-cooled fission reactors to liquid metal cooled reactors [14, 15]. Typically, water coolant system component average failure rate values are upper bounds to sodium component failure rates. With these data sources, performing probabilistic safety assessment on a liquid metal cooling system is possible.

III. Recommended Failure Rates

The quantitative data values were compared. Some data sources were not as robust as others. Definitions of the equipment failure mode and the statistical error values for the failure rates were not always given. These omissions indicate that some data values were not arrived at as diligently as they were in other datasets. In general, the Eide data [8] compared well with other values, often within a factor of 3. The recommended failure rates for components to be used in Pb-Li cooling systems are given in Table 1. Readers may argue that the datasets are aged, but it is noted that these sodium values have been used recently [16]. The approach is to use these data until new facilities generate enough experience data to perform a Bayesian update to these existing values.

Table 1. Recommended failure rate data for liquid metal cooling systems

Component	Failure mode	Failure rate	Error factor
Manual valve	Fail to open/close	3.0E-04/d	5
	Plugging	5.0E-08/h	10
	Internal leakage	5.0E-08/h	10
	Internal rupture	1.0E-08/h	10
	External leakage	3.0E-07/h	10
	External rupture	1.0E-08/h	10
Motor operated valve	Fail to open/close	1.0E-03/d	5
	Spurious operation	5.0E-07/h	10
	Plugging	5.0E-08/h	10
	Internal leakage	5.0E-07/h	10
	Internal rupture	5.0E-08/h	10
	External leakage	5.0E-07/h	10
	External rupture	5.0E-08/h	10
Pneumatic operated valve	Fail to open/close	3.0E-03/d	5
	Spurious operation	3.0E-07/h	10
	Plugging	3.0E-08/h	10
	Internal leakage	1.0E-07/h	10
	Internal rupture	3.0E-08/h	10
	External leakage	1.0E-06/h	10
	External rupture	3.0E-08/h	10

Table 1. Continued

Component	Failure mode	Failure rate	Error factor
Solenoid operated valve	Fail to open/close	3.0E-03/d	5
	Spurious operation	3.0E-07/h	10
	Plugging	3.0E-08/h	10
	Internal leakage	1.0E-07/h	10
	Internal rupture	3.0E-08/h	10
	External leakage	1.0E-06/h	10
	External rupture	3.0E-08/h	10
Check valve	Fail to open or close	1.0E-04/d	5
	Plugging	5.0E-07/h	10
	Internal leakage	5.0E-07/h	10
	Internal rupture	5.0E-07/h	10
	External leakage	5.0E-07/h	10
	External rupture	5.0E-07/h	10
Pipe, 1 to 4 inch diameter (per foot)	Leakage	3.0E-09/h	10
	Rupture	3.0E-10/h	10
	Plugging	1.0E-09/h	10
Pipe, > 4 inch diameter (per foot)	Leakage	3.0E-09/h	10
	Rupture	3.0E-10/h	10
Strainer/filter	Plugging	3.0E-06/h	10
	Fail open	3.0E-06/h	10
Cold trap	Fail to trap	5.0E-07/h	10
	External leakage	5.0E-07/h	10
	External rupture	5.0E-07/h	10
	Plugging	5.0E-07/h	10
Motor driven centrifugal pump	Fail to start	5.0E-03/d	5
	Fail to run	5.0E-05/h	10
	External leakage	3.0E-06/h	10
	External rupture	5.0E-07/h	10
Electromagnetic pump	Fail to start	3.0E-03/d	5
	Fail to run	1.0E-05/h	10
	External leakage	3.0E-06/h	10
	External rupture	5.0E-07/h	10
Intermediate heat exchanger	Shell external leakage	1.0E-06/h	10
	Shell external rupture	1.0E-06/h	10
	Tube bank small leak	1.0E-06/h	10
	Tube bank leak	1.0E-06/h	10
	Tube bank rupture	1.0E-06/h	10

Table 1. Continued

Component	Failure mode	Failure rate	Error factor
Intermediate heat exchanger	Tube bank plugging	1.0E-06/h	10
Steam generator	Shell external leakage	1.0E-06/h	10
	Tube bank small leak	5.0E-06/h	10
	Tube bank medium leak	1.0E-06/h	10
	Tube bank large leak	3.0E-07/h	10
Tank	External leakage	1.0E-06/h	10
	External rupture	1.0E-07/h	10
Notes: /d indicates per demand to operate. /h indicates per operating hour			

IV. Repair Time Data

There are not many sources for hands-on repair times of liquid metal cooling system components. Like component failure rates described above, the majority of data available are from sodium coolant systems. Cadwallader [17] has a bibliography of documents that discuss some repair times for mechanical and electrical equipment used in nuclear facilities, including sodium-cooled fission reactors. There are some other values in the literature for sodium cooling systems [6,11,12,16,18]. Table 2 gives some representative repair times. It should be noted that for sodium systems, often a "freeze plug" is used, where fans are used to force room air over a section of pipe so that the pipe cools and sodium freezes in a small, localized section of the pipe to form a coolant plug. Setting up fans and establishing a freeze plug (and allowing reheating of the plug metal) adds some time to a repair of piping, flanges, valves, instruments, etc.

Table 2. Some component repair times [16,17]

Component	Failure Mode	Repair Time (days)
Tank	External leak	15
Piping	External leak	15
Heat exchanger	Shell leak	15
Heat exchanger	Tube leak	30
Pneumatic valve	External leak	3
Manual valve	External leak	0.167
Electromagnetic pump	External leak, replace	33

Sazonov [19] described repair activities on the USSR submarine reactors using lead-bismuth coolant (there were several Alfa class submarines with lead-bismuth cooled fission reactors [20]). The small reactor compartments in the submarines restricted the space available for maintenance work, making the work more difficult. Sazonov stated that there were positive features of the lead-bismuth coolant: low induced gamma activity, chemical inertness of the coolant (oxidation is a safety issue with this coolant [21]), no significant spills due to the high melting point, and no liquid radioactive waste as compared to water-cooled reactors. Sazonov also stated that coolant valves had no failures and that none of the major equipment items (e.g., pumps) in these reactor installations required significant reconditioning. There were some minor coolant leaks when samples were taken for chemical analysis; this was believed to be due to human error. Minor repairs to cooling systems were performed under hot conditions with no coolant flow but using a steam source on shore to maintain the metal coolant temperature above freezing; applying the steam source was stated to be a labor-intensive and complex procedure, but necessary to avoid the pipe stress issues with freezing and thawing lead-bismuth. Nitrogen was used as a gas blanket to prevent coolant oxidation in air. Pumps had gaskets and removable parts replaced (e.g., impellers), and oxygen sensors in the coolant were also replaced. Sazonov did not give task time durations or counts of workers needed for these activities, but given the complexity of the task (rigging temporary steam heat piping from the shore and nitrogen gas blanketing) compared to setting up fans to freeze-plug sodium coolant, it is obvious that the times for repairs of heavy liquid metal system components in submarine reactors were greater than those for sodium coolant. Analyst judgment is needed when applying repair time values in RAMI studies of PbLi cooling systems.

V. Conclusions

The information presented and referenced in this paper will give good support to analysts who are assessing the probabilistic safety or RAMI of a liquid metal cooling system. These data can be used until enough operating experience with liquid metal cooling systems has accumulated to allow a statistical Bayesian update to the values.

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