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TSTA PIPING AND FLAME ARRESTOR OPERATING EXPERIENCE DATA

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Abstract. The Tritium Systems Test Assembly (TSTA) was a facility dedicated to tritium handling technology and experiment research at the Los Alamos National Laboratory. The facility operated from 1984 to 2000, running a prototype fusion fuel processing loop with ~100 grams of tritium as well as small experiments. There have been several operating experience reports written on this facility's operation and maintenance experience. This paper describes analysis of two additional components from TSTA, small diameter gas piping that handled tritium in a nitrogen carrier gas, and the flame arrestor used in this piping system. The operating experiences and the component failure rates for these components are discussed in this paper. Comparison data from other applications are also presented.

I. Introduction.

The failure rates of equipment are sought to support fusion safety assessment and reliability studies. When fusion experiments use tritium, the safety assessment and reliability of confinement both become more important for machine operation. It is widely regarded that the most optimum failure rate data come from the same or similar components operating in the same application as the components under examination. When components operate in the same application, they are exposed to the same operating environment and the same stressors that can lead to failures. Work is ongoing in fusion to collect the operating experiences of fusion components and apply these to the components to be used in the next generation of fusion experiments (Pinna, 2010). This paper presents data on tritium piping and flame arrestors that were used at the Tritium Systems Test Assembly.

II. Tritium-bearing piping.

Past reliability work on the TSTA Tritium Waste Treatment (TWT) system (Cadwallader, 1990) did not include the system piping due to lack of information on the piping runs used in the TWT system. Additional data allows the TWT piping to be addressed here. The TWT piping held a low concentration of tritium and hydrogen isotopes, with levels from < 1 ppm to 4% concentration but typically ~0.01 ppm. Given the low level of tritium in the piping secondary confinement was not necessary – that is, no guard pipe surrounded the TWT process pipe. The pipe was made of stainless steel 304L, and it was small diameter (TSTA SAR, 1996). Additional information on the TWT piping is that there were 19 m of 5-cm diameter pipe, 83.5 m of 2.5-cm diameter pipe, and 0.7 m of 1.27-cm diameter pipe for a total of 103.2 m of piping of these three diameters which are all considered to be small diameter piping. The piping was typically welded rather than using flanged connections. Despite these modest pipe lengths, this was the largest piping system at TSTA. The typical TWT flow rate was 0.025 m^3/s, and the nitrogen and other gases were typically just below atmospheric pressure. The piping had some vibration, the principal vibration arising from the compressors that drew gas from the Low Pressure Receiver (LPR) tank. This tank was operated at less than 0.5 atmosphere pressure so that gas flowed to the LPR from the outlet gas valves on the gloveboxes. The TWT piping also operated at room temperature rather than elevated temperatures that are often one of the parameters of a gas piping system.

The TWT experiences from 1984 through 1989 showed that system leaks did not originate from the piping or pipe welds, the three small leaks (e.g., fractions of milliCuries of tritium released) that did occur came from a pinhole leak in a filter casing, a leak from a flexible tubing line connected to the stainless steel piping, and a corrosion-induced leak on a compressor exhaust line. Continued operation of the TWT through 2000 did not result in any piping leaks – there were no events entered into the US Department of Energy (US DOE) Occurrence Reporting and Processing System that holds reports from its inception in 1990 through decommissioning of TSTA in the 2000's. It is not clear if the compressor exhaust line was stainless steel, but it will be included in the failure rate calculation. Including the compressor exhaust line corrosion event with the system piping, then the TWT piping operated for over 16 years with one small leakage failure. For the mid-1984 to 1989 time frame, in those 5.5 years the TWT operated 47,531 hours (Cadwallader, 1990), which averages to 8642 hours/year or all but approximately 118 hours per year. A one-week outage allowance of 168 h was subtracted from each year in the span of 1990-2000 to conservatively account for downtimes that are not precisely known for the later years of TSTA operation. This calculation is 47,531 h + (11 y)(8760 h – 168 h per y)= 142,043 operating hours for the TWT. Then the failure rate calculation, λ=n/T, where n=number of failure events and T=total component operating time can be performed (Atwood, 2003). The formula gives λ=1 leak/(103.2 m)(142,043 h) = 6.8E-08/m-h for leakage from the small diameter stainless steel tritium piping and its welds. An upper bound failure rate with a 95% Chi-square distribution and 2n + 2 degrees of freedom is $\lambda_{95\%} = \chi^2(0.95,4)/2T$. The $\chi^2(0.95,4)$ = 9.49 as found from Chi-square tables in O'Connor (1985). The upper bound failure rate calculation is $\lambda_{95\%}$ = 9.49/(2 × 103.2 m × 142,043 h) or 3.2E−07/m-h. The Chi-square 5% lower bound failure rate calculation uses 2n + 1 degrees of freedom. The $\chi^2(0.05,3)$ = 0.352 as found from Chi-square tables in O'Connor (1985). The 5% lower bound failure rate, $\lambda_{5\%}$ = 0.352/(2 × 103.2 m × 142,043 h) or 1.2E−08/m-h. There were no reports of the failure modes of pipe plugging or large leakage. For zero failures over the time period, the failure rate for these modes is calculated as λ=0.5/T (Atwood, 2003). For these failure modes, λ=0.5/(103.2 m)(142,043 h) = 3.4E-08/m-h. The upper bound is $\lambda_{95\%}$ = 5.99/(2 × 103.2 m × 142,043 h) or 2E−07/m-h. The 5% lower bound failure rate, $\lambda_{5\%}$ = 0.00393/(2 × 103.2 m × 142,043 h) or 1.3E−10/m-h. Pipe rupture is a very rare failure mode, so it is treated separately. Based on information from Eide (1991) the analyst judgment average failure rate for pipe rupture is assumed to be 100x lower than the small leakage failure rate, or 6.8E-10/h-m.

Other tritium piping failure rate data were sought for comparison to determine if this leakage failure rate calculated from a small length of piping and long operating time is accurate. Tritium system information from fusion facilities was sought (Pinna, 2003; Gordon, 1988). Unfortunately, Pinna (2003) did not address piping. Gordon (1988) gave an engineering judgment of 0.01/year for his plant's tritium piping leakage. Gordon provided enough information to allow estimation of a piping failure rate from his estimated 0.01/year frequency. Using 48 pulses/16-h operating day, 1E+04 pulses/year, and 160 m piping allows an estimate. (0.01 leak/pipe run-year)(1 y/1E+04 shots)(48 shots/16-h)(1 pipe run/160 m) = 1.9E-08/h-m. Therefore, Gordon's estimate is that the stainless steel lines with low concentration tritium have a leakage failure rate of about 1.9E-08/h-m. This is a factor of 3.6 less than the TSTA value, slightly greater than a half-order of magnitude difference. Since Gordon's value was an engineering judgment rather than experience, failure rates from other operating experiences were sought for comparison.

A literature search was undertaken to identify gas piping failure rate data from commercial applications. It was found that gas piping datasets are few, dealing mainly with fuel gases (natural gas, propane, etc.) at ambient temperature and pressures of 1.0 MPa and higher. The piping used to transmit and distribute these gases is carbon steel rather than stainless steel, is often larger than 0.1 m diameter (e.g., 0.3 to ~1 m diameter) (Jones, 1986; Eiber, 1992) and is sometimes buried underground. Small diameter gas distribution piping is not well reported in the literature; no datasets were found on commercial small diameter piping. Overall, the information and datasets that were located are not very applicable to the TSTA piping.

One data source from US DOE operations (Blanchard, 1998) gave an experience-based failure rate value for compressed gas piping leakage as 9.84E-08/m-h with an error factor of 10. Making a simple comparison of this average value to the TSTA result shows that Blanchard's value is a factor of 1.45 larger than the TSTA value. Hale (1999) gave small (< 50 mm diameter) refrigerant/coolant piping an 'all modes' failure rate of 1.2E-07/h-foot, or 3.9E-07/h-m. This value is a factor of 5.7 larger than the TSTA value. Both of these data sources require analyst inference about the nature of the piping. The Blanchard value is most likely small diameter (50 mm and smaller) air distribution piping, likely carbon steel, at ambient temperature and an operating pressure on the order of 9 bar. Hale's value was calculated from refrigerant (e.g., Freon) piping experience, and this could mean copper piping rather than steel, small diameters (< 50 mm), probably operating at < 4 bar. Since copper is more malleable than steel, and refrigeration systems experience many thermal cycles (e.g., -15 C to 60 C), these attributes could result in high failure rates. In any case, both of these failure rates were greater than the TSTA value.

It is noted that fission reactor stainless steel piping for high pressure and high temperature water cooling systems has shown much lower failure rates than the gas piping. Water piping has failure rates on the order of 1E-10 to 1E-11/m-h (Fleming,

2006) for large leaks. However, the water piping experience is not directly applicable to gas piping. The water piping reported by Fleming tends to be thicker walled, follows a prescribed set of operations practices for heatup and cooldown, and follows a design code for stresses and corrosion allowances.

The TSTA piping failure rate value from operating experience is a fair comparison with the Gordon (1988) engineering judgment value and both of these tritium piping values are less than other published values for small diameter gas piping. The conclusion is that the TSTA value is reasonable to use when modeling tritium piping. If the designer finds this failure rate is predicting leakage due to the lengths of pipe in use, then secondary containment is a possible means to address the concern. The leakage failure for secondary containment pipe is addressed by Cadwallader (2013).

III. Flame arrestors.

At TSTA, the Tritium Waste Treatment (TWT) system handled gaseous effluent streams, primarily nitrogen with varying amounts of oxygen, argon, neon, helium, and hydrogen isotopes varying from a few parts per million to 4% concentration, as well as some water vapor, ammonia, carbon dioxide, carbon monoxide, acetylene, methane, some light hydrocarbons and traces of vacuum pump oil (TSTA SAR, 1996). The effluent gas came from gloveboxes and flowed to the LPR to collect the effluent gases for tritium removal with subsequent stacking to the atmosphere. The TWT design prudently used a dry-type deflagration flame arrestor in the main piping from the LPR. This flame arrestor was designed to reside in-line in the gas stream and passively remove heat from the flowing, burning gas so that the gas would cool below the point of supporting a flame. These units are typically either a set of wire mesh screens or a crimped metal ribbon that forms flow channels that the gas must traverse (Grossel, 2002). A drawing of a crimped metal flame arrestor is given in Figure 1. The TWT flame arrestor operated over the life of TSTA and did not leak, or become fouled. The TWT system operated almost continually for over sixteen years (July 1984 to late 2000, or 142,043 hours), and there were no failures of this arrestor unit cited in Cadwallader (1990), which examined early operation, or in the DOE ORPS database, which collected information from TSTA mid-life to decommissioning. Using Atwood (2003) guidance on zero failure events, the failure rate for this unit is calculated as $\lambda = 0.5/T$, where T is the total operating time of the component. Then $\lambda = 0.5/(142{,}043\ h)(1\ arrestor)$ or 3.5E-06/hour. This failure rate would be applied to any hourly failure mode; the main hourly failure modes for arrestors are leakage and plugging. The upper and lower bounds for this failure rate are calculated by the Chi-square distribution. An upper bound failure rate (Atwood, 2003) with a 95% Chi-square distribution and 2n + 2 degrees of freedom (where n = number of failure events, in this case $n = 0$) is $\chi^2(0.95,2)/2T$. The $\chi^2(0.95,2) = 5.99$ as found from Chi-square tables in O'Connor (1985). The upper bound failure rate calculation is $5.99/(2 \times 142{,}043\ hr)$ or 2.1E−05/h. The Chi-square 5% lower bound failure rate calculation for zero failures uses 2n + 1 degrees of freedom. The $\chi^2(0.05,1) = 0.103$ as found from Chi-square tables in O'Connor (1985). The 5% lower bound failure rate is 0.103/(2 × 142,043 h) or 3.6E−07/h.

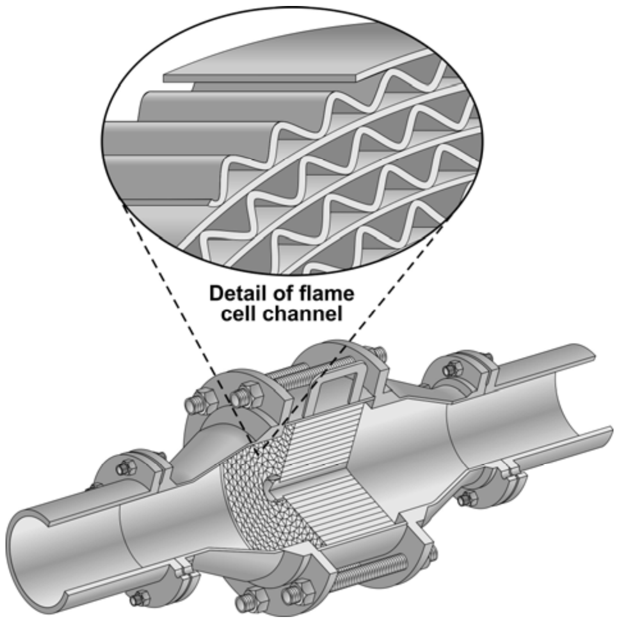

Figure 1. Sketch of a crimped metal ribbon, in-line flame arrestor.

Fortunately, TSTA did not have any combustion flame fronts created in the TWT piping. However, this means that the flame arrestor was never challenged to operate. With no demands to function, then no 'failure to function on demand' failure rate can be calculated from the TSTA operating experience. No demand failure rate was found in the literature for flame arrestors used in other industries. Grossel (2002) described that the failures of flame arrestors are typically in four areas: arrestors used under conditions that exceeded their test limitations, arrestors not subjected to any official testing (hence test limitations were not known and likely inadequate for the application), arrestors failing due to their channels being distorted by the flame front overpressure, and failures due to structural or design flaws that allowed a flame pathway through the element. A fifth failure mechanism would be foreign material fouling the arrestor flow channels. Arrestors do fail, so experience data was sought to quantify a failure on demand value.

Wilson (1978) reported results of tests of crimped metal ribbon and other types of arrestors. This report is of interest due to the type of arrestors tested and the large number of tests performed. The crimped metal design results are reviewed here because this is the type believed to be used at TSTA and Grossel (2002) stated this is the most widely used design. Examining the crimped metal arrestor performance in tests with butane and gasoline vapor, the arrestors stopped flame propagation past the arrestor in all but one case where the flame speed was very high. In 34 tests there was one failure, giving a demand failure rate of 1/34 = 2.9E-02 per demand. An upper bound failure rate with a 95% Chi-square distribution and 2n+2 degrees of freedom with n=1 failure on demand would be $\lambda_{95\%}=(\chi^2(0.95,4)/2D)$, that is, $\lambda_{95\%}=(9.49)/[2\cdot34]$ or 1.4E-01/demand. The lower bound failure rate would be $\lambda_{5\%}=(\chi^2(0.05,3)/2D)$, that is, $\lambda_{5\%}=(0.352)/[2 \times 34]$ or 5.2E-03/demand. The 34 tests varied the gas mixture, the gas pressure and temperature, and flame speed conditions within the arrestor ratings and the arrestors functioned well. In the single test where an arrestor failed to stop flame propagation, the flame speed was 20% greater than the rating of the arrestor. The fast-moving flame front did not cool enough as the burning gas traversed the arrestor channels, so flame passed through and continued to burn on the downstream side of the arrestor. A probability of failure on demand is expected to vary with the flame front conditions exceeding the limitations of the flame arrestor unit. As an initial analyst judgment, flame front conditions (temperature, speed, pressure) exceeding the flame arrestor rating by 5% will give a 0.5/demand failure rate, and exceeding by 10% will give a 1/demand failure rate. Grossel (2002) stated that conditions exceeding the flame arrestor's design parameters even by a small amount will lead to flame propagation past the arrestor. Roussakis (1991) stated that pressure conditions falling below the flame arrestor design point by 10% can also fail the arrestor.

Lees (1996) described that even if an in-line flame arrestor stops the flame from passing through and combusting downstream of the arrestor, the hot gases leaving the arrestor may re-ignite downstream. Re-ignition is likely if the gas remains hot, so the gas cooling conditions in the downstream volume are important to mitigate re-ignition. Gas turbulence promotes mixing with cooler gases downstream, greatly reducing the likelihood of re-ignition. Lees (1996) also described that designers have had debates over flame arrestor deployment in the chemical industry since these units present the opportunity for flow blockage when the arrestor collects dust, corrosion products, and other impurities in the gas stream. There was one event of flame arrestor failure due to flow blockage in the US DOE Occurrence Reporting and Processing System (DOE, 2004). An in-line arrestor with an aluminum body was flanged in a 76-mm diameter carbon steel pipe from a methane gas production wellhead. As a controlled test of the arrestor, the methane gas was ignited by an electric ignitor. The flame arrestor was later found to have been clogged with dirt that was left inside the piping from construction. The burning gas flame front encountered the plugged flame arrestor. Combustion pressure built up to ~35 atmospheres and the flame arrestor body failed catastrophically. The energy release also whipped about 30 m of the steel pipe in a 90° arc horizontally across the ground at the site. Fortunately, the gases used in fusion facilities tend to be clean, and impurities such as dirt, metal shavings, weld beads, etc., are cleaned from the pipework before placing the piping into service. Catastrophic events like the methane event described above are not expected to occur in a fusion facility. However, flame arrestors in a fusion facility must be resistant to corrosion by process gases, water vapor, air, and should not accumulate any vacuum pump oil that may be found in the gas stream.

It is desirable to compare the TSTA flame arrestor failure rate result to other flame arrestor failure rates to determine if the TSTA operating experience is sufficient to provide data on a mature component in another tritium application. Flame arrestor failure rates were difficult to find in the literature. Some operating experience data were found from the air intake flame traps on diesel engine systems (Hughes, 2012; Mysore, 2013). These units are in a flanged housing in the air intake line and are typically the crimped metal dry-type flame arrestor, very comparable to the TSTA unit. The engine inlet air is close to atmospheric pressure and temperature, which is fairly similar to TSTA gas. Reducing these component operating experience data into a failure rate is performed as follows. Combining the Hughes and Mysore reports, over the three years of 2010-2012, there were 1,030 diesel engines in continuous use, each with one air intake flame trap. The reader should note that this diesel dataset is a snapshot in time from mature units in field operation, so the typical concern about new component 'infant mortality' skewing the data is not believed to be an issue with this dataset. This period of time and fairly large number of components in the sample should give a reasonable failure rate value. There were 17 failures in the first two years of the study and 11 failures in the third year, for a total of 28 flame arrestor failures. The run time of each diesel engine was not given, but the engines were meant for continuous operation, supporting three-shift daily operation at mines. A week of preventive maintenance outage was assumed for each engine per year, so 8760 h – 168 h = 8592 operating hours per year. The basic failure rate is assumed to be $\lambda = n/T$, so λ = 28 failures/(1,030 units × 3 y × 8592 h/y) or 1.1E-06/unit-hour. The failure modes or mechanisms that were identified in these reports are: gasket deterioration 7%, fatigue/cracks 7%, bolts, studs, and nuts loosening 11%, excessive gap in joints 54%, and "other" as 21%. The "other" category included issues such as arrestor excessive internal clearance and surface flatness being out of tolerance. It should be recognized that equipment mounted on a stationary diesel engine tends to have higher mechanical vibration than a modest-flow piping loop. Gas flow in piping may generate flow-induced vibration in both engine and plant piping applications, but the diesel engines (and their air intakes) are assumed to be higher vibration than at TSTA, which was a low gas flow rate and low vibration environment. The vibration in the diesel engines is believed to be responsible for gasket deterioration, metal fatigue, and bolts loosening. The failure rate 95% and 5% confidence bounds for the estimate calculated above are found from the Chi-square distribution with n=28 failures. An upper bound failure rate with a 95% Chi-square distribution and 2n + 2 degrees of freedom is $\lambda_{95\%} = \chi^2(0.95,58)/2T$. The $\chi^2(0.95,58)$ = 76.7 as found from Chi-square tables in O'Connor (1985). The upper bound failure rate calculation is $\lambda_{95\%}$ = 76.7/(2 × 1,030 units × 3 y × 8592 h/y) or 1.4E−06/h. The Chi-square 5% lower bound failure rate calculation for zero failures uses 2n + 1 degrees of freedom. The $\chi^2(0.05,57)$ = 40.8 as found from Chi-square tables in O'Connor (1985). The 5% lower bound failure rate, $\lambda_{5\%}$ = 40.8/(2 × 1,030 units × 3 y × 8592 h/y) or

7.7E−07/h. Hughes and Mysore did not discuss any flame front suppression events so it is assumed that none occurred in the 3-year time interval. No flame arrestor tests were mentioned, either. Therefore, there were no challenges to these flame arrestors and no estimate of a failure on demand has been calculated.

The TSTA flame arrestor value of 3.4E-06/h and the diesel air intake flame arrestor value of 1.1E-06/h are a factor of 3.1 apart. Failure rates that compare within a half-order of magnitude (~3.2) are regarded as a good comparison, and failure rates that compare within a factor of 10 are regarded as a fair comparison (Cadwallader, 1999). The hourly failure rate for the TSTA flame arrestor is a reasonable value to use for other flame arrestors in a tritium plant environment.

IV. Conclusions.

Failure rates for tritium piping and for flame arrestors have been calculated from TSTA operating experience. The failure rates are given in Table 1. These failure rates from TSTA operating experience gave good comparisons to other failure rates from mature industrial equipment, giving confidence that these values are also mature and can be applied to other tritium-bearing components operating under similar conditions. The TSTA flame arrestor was never challenged to operate. Some testing data on industrial flame arrestors were used to calculate a demand failure rate for these units. These failure rates from TSTA can be applied to other tritium systems whose operating parameters are similar to those from TSTA. Work will continue in reducing TSTA operating experiences to component failure rate values.

Table 1. Failure Rate Values for tritium-bearing components

Component	Failure Mode	Average Failure Rate	Lower bound Failure Rate	Upper bound Failure Rate
TSTA Piping	Small leakage	6.8E-08/h-m	1.2E-08/h-m	3.2E-07/h-m
	Large leakage	3.4E-08/h-m	1.3E-10/h-m	2.0E-07/h-m
	Plugging	3.4E-08/h-m	1.3E-10/h-m	2.0E-07/h-m
	Rupture	6.8E-10/h-m	1.2E-10/h-m	3.2E-09/h-m
TSTA Flame arrestor	Plugging	3.4E-06/h	3.5E-07/h	2.0E-05/h
	Leakage	3.4E-06/h	3.5E-07/h	2.0E-05/h
Industrial Flame arrestor	Fail on demand	2.9E-02/d	5.2E-03/d	1.4E-01/d

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