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Leakage Rate Measurement and Durability Testing of Field-made Mechanical Joints for Systems with Flammable Refrigerants (ASHRAE RP-1808)

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Assessment of Leakage Rate and Durability of Field-made Mechanical Joints for Systems Using Low-GWP Flammable Refrigerants (ASHRAE RP-1808)

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ABSTRACT

Much concern has been raised recently about the flammability of several low-GWP replacement refrigerant options, such as HFO's, lower-GWP HFC's, and flammable natural refrigerant options, regarding the potential leakage or failure of joints in systems using these refrigerants. This paper presents the results of a study investigating the assembly, durability, and leakage rate of different types of field-made joints used in refrigeration and air-conditioning systems. The focus of the project is on flame-free joining methods; in particular, three different types of joints were investigated: Press/crimp fittings, compression fittings, and flare fittings. For each type of joint, two different sizes were used as well as two different tubing materials (copper and aluminum). Brazed copper joints were also investigated as a baseline. Each type of joint was assembled by a combination of both experienced and inexperience refrigeration technicians. A total of 100 of each type of joint (excluding brazed) were assembled, and the results for average assembly time and failed joint assemblies are presented. Durability testing in the form of pressure-temperature thermal cycling, freeze-thaw cycling, and vibration testing was performed on all combinations of joints. Failures observed on each type of joint during durability testing are also presented. Finally, the measured refrigerant leakage rate using R32 is presented for each type of joint. The results show that press fittings generally have the quickest assembly time and fewest assembly leaks and are the most durable of the fittings tested. However, compression and flare fittings, if tightened properly and not damaged during durability testing, can have lower leak rates than press fittings.

1. INTRODUCTION

The move towards using lower-GWP refrigerants in vapor-compression systems has led to increased interested in and research on systems using flammable and mildly-flammable refrigerants (A2L, A2, and A3 refrigerants), such as R290, R600a, R1234yf, and R32 to name a few. Because of this flammability issue, the durability and leakage through joints in systems using these flammable refrigerant is of significant concern. This paper presents the results of a study investigating the assembly, durability, and leakage of different methods of joining tubes to each other and to system components, with specific focuses on field-made mechanical joints and use of flammable or mildly-flammable refrigerants. Clodic and Yu (2014) presented the results of a study in which the leak rates of different fittings as well as different valve types were measured and analyzed; this reference also presented a detailed review of each fitting or valve type and of different leak detection methods. Previous studies on durability testing of fittings include the studies of Wilson and Bowers (2014) and Elbel *et al.* (2016), which performed extensive thermal cycling and vibration tests on press/crimp fittings, though leakage information was not part of either of these studies. This paper presents the results of study investigating assembly, harshness testing, and leak rate measurements on the same sets of fittings for multiple different fitting types.

Three different types of joints were considered for evaluation in the study: Press/crimp fittings, compression fittings, and flare fittings. For each type of fitting, two different sizes were evaluated: 3/8” and 1-1/8” for press fittings and 3/8” and 3/4” for compression and flare fittings. Additionally, a set of 1-1/8” brazed joints was evaluated as a baseline leak-free case. For each fitting type, a total of 100 fittings were evaluated (50 of each size). The time required to assemble each fitting was recorded as well as any leaks after assembly or assembly failures. Both experienced and inexperienced technicians were used to assemble fittings, and fittings were assembled under both normal and difficult (elevated in a confined space) conditions. The fittings were then each sent through one of three types of harshness or durability tests: Pressure-temperature cycling, freezing-thawing cycling, and vibration testing. After harshness testing, averaged leak rates (positive-pressure with R32) for the different fitting types and sizes were determined. The results of each fitting evaluation method are presented in the sections below.

2. FITTING TYPES AND TEST MATRIX

The characteristics of the selected fittings are shown in Table 1. The different fitting types are shown in Figure 1. For each of the three fitting types, two different sizes were chosen, as shown in the table. Additionally, a set of brazed joints was also included to serve as a leak free baseline. It can be seen from the table that all fitting types have sufficient pressure range of a typical HFC or HFO system, and the temperature range also seems mostly suitable (with the exception of the maximum temperature of compression fittings, which may by slightly too low for some systems). It is also worth noting that the press fitting is a permanent fitting (like a brazed joint), while compression and flare fittings are removable and reusable.

Table 1: Characteristics of fittings evaluated in this study; temperature range, maximum working pressure, and compatible tubing materials are per the specifications of the manufacturers.

Fitting type	**Press**	**Compression**	**Flare (45°)**
Sizes evaluated	3/8”, 1-1/8”	3/8”, 3/4”	3/8”, 3/4”
Max. working pressure	48 bar (700 psi)	38 bar (550 psi)	38 bar (550 psi)
Temperature range	-40 to 149°C (-40 to 300°F)	-54 to 93°C (-65 to 200°F)	-54 to 121°C (-65 to 250°F)
Available tube sizes	1/4 in. – 1-3/8 in.	1/8 in. – 1 in.	1/8 in. – 3/4 in.
Compatible tube materials	Copper	Copper, Aluminum, Plastics	Copper, Aluminum, Brass, Steel
Removable?	No	Yes	Yes

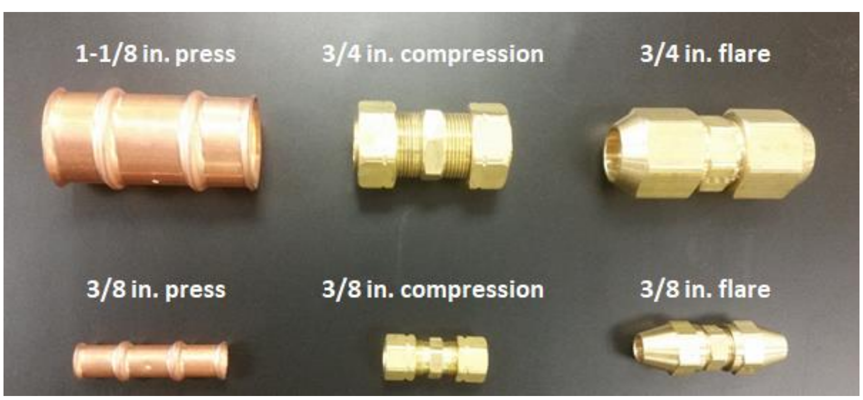

Figure 1: Fittings selected for evaluation in this study.

In addition to the different fitting types and sizes, two different combinations of tubing material were used: Copper-copper (Cu-Cu) joints and copper-aluminum (Cu-Al) joints. The full test matrix showing the breakdown of different fitting types, tube material combinations, and fitting sizes, and including a set of 1-1/8" brazed joints, is shown in Figure 2. A total of 13 different fitting type-size-material combinations were tested, and for each type-material-size combination, a total of 25 fittings were tested.

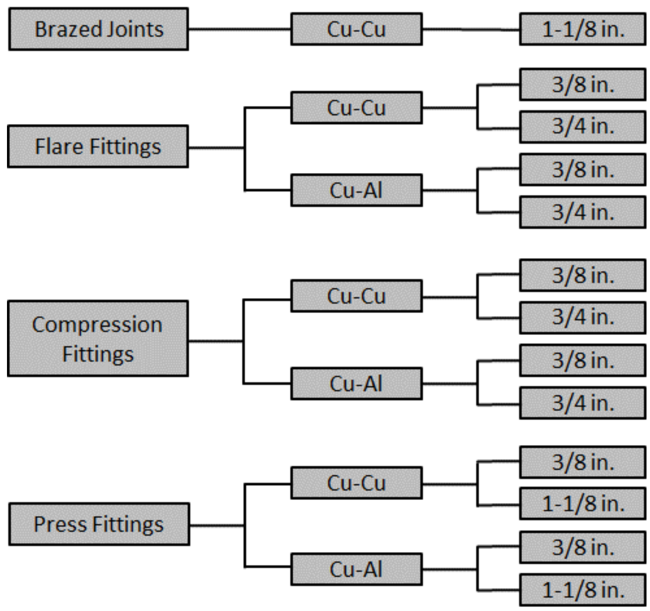

Figure 2: Overview of fitting type-size-material combinations.

The effects of technician experience level and difficulty of assembly conditions (human factors) on fitting assembly were also incorporated into the test matrix. Experienced technicians were considered to be those that had several years of experience assembling air-conditioning and refrigeration systems, while inexperienced technicians were considered to be those that had familiarity with air-conditioning and refrigeration systems from an engineering point-of-view but limited or no hands-on experience with these types of fittings. Fittings were either assembled under normal conditions (on a work bench with freedom to access fitting however needed) or difficult conditions (fitting at top of confined space). For a set of 25 fittings, assembly was completed with the following combination of human factors:

- 10 fittings assembled by experienced technicians under normal assembly conditions
- 5 fittings assembled by experienced technicians under difficult assembly conditions
- 5 fittings assembled by inexperienced technicians under normal assembly conditions
- 5 fittings assembled by inexperienced technicians under difficult assembly conditions

3. FITTING EVALUATION PROCEDURE

The procedure for evaluation of each fitting is shown in Figure 3. The fittings were first assembled taking into account different technician experience levels and assembly difficulties. The fitting were then leak checked by pressurizing with nitrogen (30 bar) and submersing in water. Passing or failing the leak check was a binary decision; the fittings were determined to have passed if no bubbles were visible in the water after about 5 minutes of leak checking. Each fitting then underwent one of three types of harshness testing. For each set of 25 fittings of the same type-size-material, 10 underwent pressure-temperature cycling together, 10 underwent freeze-thaw cycling together, and 5 underwent vibration testing individually. The fittings were again leak checked after harshness testing to see if any failures occurred during harshness testing; it was ensured that all fitting either showed no visible leaks or were removed (if they failed during harshness testing) before proceeding to leak rate measurement. Finally, the fittings underwent a leak rate measurement tests with all other fittings of the same type-size-material combination.

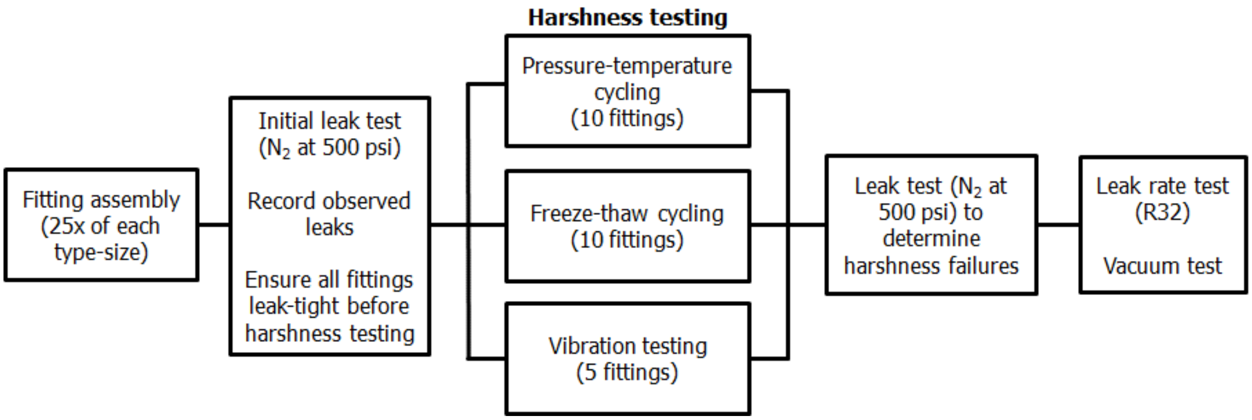

Figure 3: Procedure for evaluation of each fitting in terms of assembly, durability (harshness), and leak rate.

4. FITTING ASSEMBLY RESULTS

The results for the average assembly times, broken down for different technician experience level and assembly difficulty, are shown for all fitting types and sizes in Table 2. Results have been combined for Cu-Cu and Cu-Al joints, as no meaningful difference was observed in assembly statistics between the two sets. It can be seen from the table that press fittings consistently have the shortest assembly time regardless of technician experience level or assembly difficulty when comparing all small fittings to each other and all large fittings to each other. Compared to compression fittings, which seem to have the next closest assembly time, press fittings can generally be assembled in 20 – 30 % less time. Compression fittings and brazed joints seem to have similar assembly time for experienced technicians under normal assembly conditions, though brazed fittings have significantly longer assembly time for inexperienced technicians or under difficult assembly conditions; this indicates that in comparison to other fitting types, the assembly time for brazed joints depends more significantly on the experience level of the technician as well as the difficulty of the assembly. While there are certainly noticeable differences in assembly time between press, compression, and brazed joints, a much more significant difference appears when comparing flare fittings to the other types. Comparing flare and compression fittings (both thread-on types of fittings), it is seen that flare fittings generally take 3 to 4 times longer to assemble than compression fittings; the cause of this significant difference would mainly be attributed to the time required to make the flare on the end of the tube.

Table 2: Summary of fitting assembly time for all fitting types and sizes for different technician experience level and assembly difficulty (results combined for Cu-Cu and Cu-Al joints).

Fitting Type	Fitting Size	Experienced Normal	Experienced Difficult	Inexperienced Normal	Inexperienced Difficult
Brazed	1-1/8 in.	85 s	137 s	197 s	376 s
Press	3/8 in.	42 s	62 s	108 s	97 s
Press	1-1/8 in.	64 s	90 s	105 s	131 s
Compression	3/8 in.	77 s	88 s	141 s	123 s
Compression	3/4 in.	90 s	95 s	107 s	173 s
Flare	3/8 in.	234 s	283 s	481 s	439 s
Flare	3/4 in.	299 s	344 s	495 s	659 s

It can also be seen from Table 2 that, as would be expected, inexperienced technicians take longer to assemble the fitting compared to experienced technicians, with inexperienced technicians taking 35 – 50 % longer to assemble press fittings, 20 – 40 % longer to assemble compression fittings, and 55 – 105 % longer to assemble flare fittings. Assembly difficulty has a less significant but still noticeable effect on assembly time. Interestingly, inexperienced technicians actually assembly some joints more quickly under difficult conditions; it is expected that this is caused by a learning curve that inexperienced technicians go through with certain fittings. Additionally, larger-sized fittings consistently take longer to assemble than smaller-sized fittings for both experienced and inexperience technicians.

The results for the number of leaking fittings after assembly, broken down for different technician experience level and assembly difficulty, are shown for all fitting types and sizes in Table 3. Results have again been combined for Cu-Cu-joints and Cu-Al joints. It can be seen from the table that of 100 total press fittings that were assembled, only a single leaking fitting was observed, which was assembled by an inexperienced technician. In comparison to the other types of fittings, leaks are observed in press fittings at a significantly lower rate; in total, initial leaks after assembly were observed in 1 % of press fittings, 12 % of brazed joints, 33 % of compression fittings, and 56 % of flare fittings. It can also be seen from Table 3 that for the smaller compression fittings, the frequency of initial leaks is about the same for experienced and inexperienced technicians, while the frequency of initial leaks is noticeably higher for inexperienced technicians for the larger fittings, likely due to the greater amount of force/strength needed to tighten the larger fittings. Similar observations can be made for flare fittings, though with technician experience having a more significant effect and with a higher number of total leaks. Note that the difference in number of initial leaks between large and small flare and compression fittings is likely actually more due to technician strength, which coincided with experience in this case. It also seems assembly difficulty does not have a noticeable effect on the number of observed leaks for experienced technicians, while inexperienced technicians seem to have fewer leaks in some cases under difficult conditions.

Table 3: Summary of leaks after initial assembly for all fitting types and sizes for different technician experience level and assembly difficulty (results combined for Cu-Cu and Cu-Al joints).

Fitting Type	Fitting Size	Experienced Normal	Experienced Difficult	Inexperienced Normal	Inexperienced Difficult
Brazed	1-1/8 in.	0/10	0/5	0/5	3/5
Press	3/8 in.	0/20	0/10	0/10	0/10
Press	1-1/8 in.	0/20	0/10	1/10	0/10
Compression	3/8 in.	4/20	3/10	4/10	0/10
Compression	3/4 in.	8/20	3/10	6/10	5/10
Flare	3/8 in.	3/20	3/10	3/10	4/10
Flare	3/4 in.	14/20	9/10	10/10	10/10

It should be noted here that the number of leaks reported for the compression and flare fittings is very significant, indicating the importance of proper leak checking of the systems using compression and flare fittings. The majority, though not all, of the leaks observed in flare and compression fittings could be fixed simply by further tightening the fittings. The number of assembly failures requiring replacement of the fitting (defined as a leak on a press fitting or brazed joint or as a compression or flare fitting that could not be made leak-tight by further tightening) are shown in Table 4. All three leaking brazed joints and the single leaking press fitting were counted as failed assembly failures, as further tightening of the fitting was not possible in this case. The table also shows that while little or no difference in number of initial leaks on compression fittings was observed between experienced and inexperienced technicians, the assembly is noticeably less likely to fail when assembled by an experienced technician.

The three brazed joint failures occurred because the inexperienced technician was unable to sufficiently access the entire joint due to the difficult conditions under which the joint was assembled, resulting in portions of the joint that did not receive braze material, as can be seen in Figure 4(a). Examples of compression fitting assembly failures can be seen in Figure 4(b). It was observed that two compression fitting assemblies failed due to damaged threads, three failed due to the tube not being inserted into the fitting far enough and the ferule not biting the tube (all on the larger size), and three failed due to overtightening of the ferule. The single press fitting failure was due to the tube not being inserted far enough into the fitting; this caused the O-ring to be displaced from its groove, as can be seen in Figure 4(c), such that it could not create a proper seal between the fitting and the tube. Examples of flare fitting assembly failures can be seen in Figure 4(d). It was observed that two flare fitting assemblies failed due to a cracked flare, one failed due to the tube being flared at an angle, and two failed due to the flare not being large enough to hold the nut. Interestingly, all flare fitting assembly failures were due to problems with the flared tube, not the nut or union portion of the fitting. It should also be noted here that all assembly failures were due to technician error; none of the failures were caused by defective fittings.

Table 4: Summary of fitting assembly failures (requiring replacement of the fitting) for all fitting types and sizes for different technician experience level and assembly difficulty (results combined for Cu-Cu and Cu-Al joints).

Fitting Type	**Fitting Size**	**Experienced Normal**	**Experienced Difficult**	**Inexperienced Normal**	**Inexperienced Difficult**
Brazed	1-1/8 in.	0/10	0/5	0/5	3/5
Press	3/8 in.	0/20	0/10	0/10	0/10
Press	1-1/8 in.	0/20	0/10	1/10	0/10
Compression	3/8 in.	1/20	0/10	2/10	0/10
Compression	3/4 in.	1/20	1/10	2/10	1/10
Flare	3/8 in.	0/20	0/10	1/10	0/10
Flare	3/4 in.	1/20	0/10	1/10	2/10

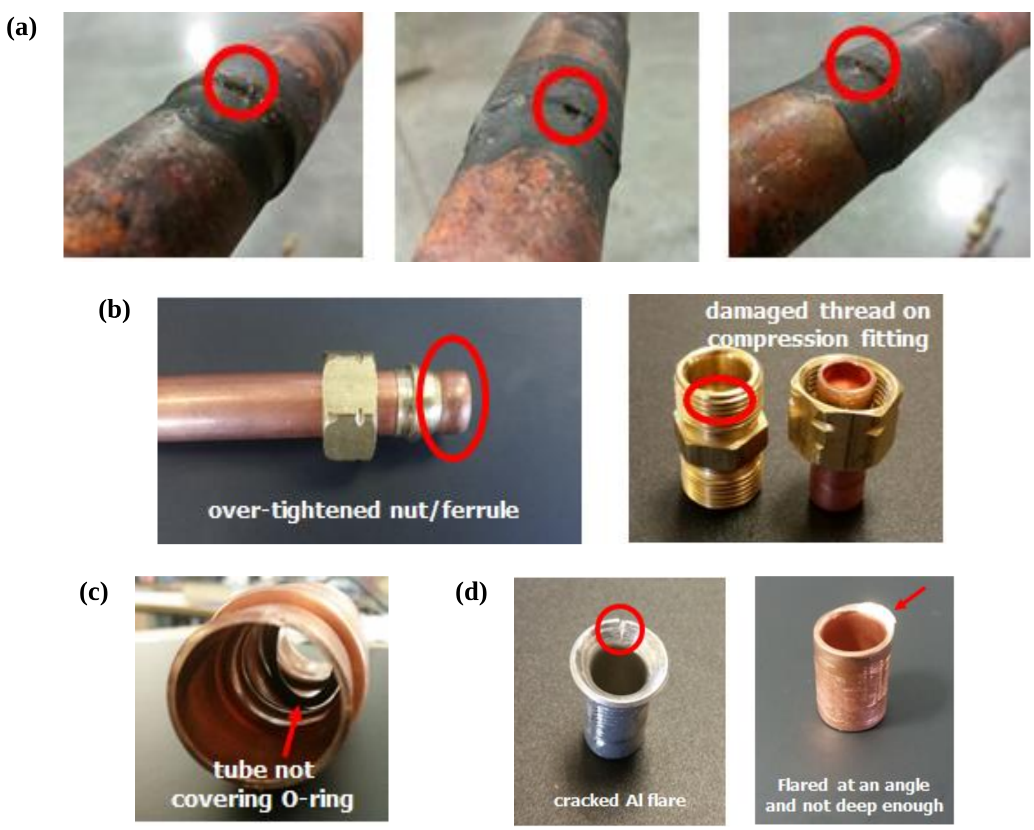

Figure 4: Images of fitting assembly failures: (a) brazed joint, (b) compression fitting, (c) press fitting, and (d) flare fitting.

5. HARSHNESS TESTING FACILITES AND RESULTS

After completing assembly, all fittings were subjected to one of three types of harshness test: Pressure-temperature cycling, freeze-thaw cycling, or vibration testing. The conditions the fittings were subjected to during each harshness test are based on fitting testing standard ISO Standard 14903 (2012).

For each fitting type-size-material combination 10 (out of 25) fittings were subjected to repeated cycling between high-pressure, high-temperature refrigerant and low-pressure, low-temperature refrigerant; this harshness test simulates a system that switches between modes (such as a reversible system or a system with hot-gas defrost). This was achieved by employing a vapor-compression cycle to alternatively send cool liquid after expansion and hot compressor discharge gas through the test section in order to achieve the cycling effect. The system used flowing R32 refrigerant with POE oil. The maximum and minimum cycling pressures are approximately 30 bar and 10 bar, respectively, and the maximum and minimum fitting surface temperatures are about 60°C and 20°C, respectively. The cycle time (peak-to-peak) is approximately 45 s, though slightly higher for larger-sized fittings. A total of at least 6,000 cycles were performed on each tested fitting.

Forty percent of each type of fitting was subjected to freeze-thaw cycling. The objective of freeze-thaw cycling is to allow moisture that has condensed on the surface of the fitting to repeatedly freeze and thaw on the fitting (not necessarily to subject the fittings to temperature swings). This was achieved by alternatively circulating high- and low-temperature glycol through the fittings. The fitting surface temperatures were cycled between about 5 – 10°C on the high end and about -20°C on the low end. The fittings were kept in a moist external environment to ensure there would always be water on the surface of the fittings. Each heating and cooling cycle was about 4 minutes (8 minute peak-to-peak cycle time), and each fitting underwent at least 800 cycles.

The remaining 5 fittings were subjected to vibration testing. In vibration testing, the tube near one end of the fitting was fixed in place while tubing on the other side of the fitting was placed in an oscillating clamp a set distance away from the fitting. This oscillating length was set at 0.45 m for 3/8” and 3/4” fittings and at 0.61 m for 1-1/8” fittings, based on the recommendation of UL Standard 109 (1997). The oscillation amplitude was ± 3.0 mm. The vibration frequency was approximately 30 Hz, and each fitting underwent 2,000,000 cycles. The fittings were also pressurized to 30 bar with N_2 during the test.

After harshness testing, the fittings were checked for leaks with N_2. Any fitting that showed a leak after harshness testing was determined to have failed that harshness test (recall that all fittings were ensured to be leak free before beginning harshness testing). Table 5 summarizes the harshness testing failures that were observed with each type of fitting.

Table 5: Summary of fitting failures observed as a result of harshness testing for all fitting types and sizes.

Fitting Type	Fitting Size	Pressure-temperature Cycling	Freeze-thaw Cycling	Vibration Testing
Brazed	1-1/8 in.	0/10	0/10	1/5
Press	3/8 in.	0/20	0/20	0/10
Press	1-1/8 in.	0/20	0/20	0/10
Compression	3/8 in.	2/20	1/20	0/10
Compression	3/4 in.	1/20	2/20	6/10
Flare	3/8 in.	1/20	6/20	1/10
Flare	3/4 in.	0/20	0/20	5/10

It can be seen from Table 5 that none of the (100) press fittings suffered any failures on harshness testing. A single brazed joint failed during vibration testing; as only a single failure was observed, it is difficult to draw conclusions about brazed joints under vibration conditions. Figure 5(a) shows an image of the failed brazed joint; a small hole developed, likely due to insufficient braze material in the gap between the tube and the coupling. On pressure-temperature cycling, 3 of 40 (7.5 %) of compression fittings failed (developed leaks) during testing, while the same number of compression fittings also failed on freeze-thaw testing. These failed compression fittings could be fixed by retightening the fitting. On pressure-temperature cycling, 1 of 40 (2.5 %) of flare fittings failed during testing, while 6 of 20 (30 %) smaller-sized flares failed on freeze-thaw cycling. This is a very significant failure rate for the smaller-sized flare fittings on freeze-thaw cycling, indicating that flares may not be suitable for applications with temperatures below freezing. This is in agreement in ASHRAE Standard 147 (2013), which provides guidelines for the use of fittings in refrigeration systems and recommends against the use of flare fittings in applications near or below freezing. The flare fittings that failed on pressure-temperature and freeze-thaw cycling could be fixed be retightening. It can also be seen from Table 5 that the larger-sized flare and compression fittings failed at a very significant rate (50 % or greater) during vibration testing. The fittings that failed during vibration testing could not be fixed by re-tightening, indicating that some damage to the fitting had occurred during vibration testing. This indicates that the use of larger-sized flare and compression fittings should be avoided in locations where a significant amount of vibration is possible. An example of a failed flare fitting after vibration is shown in Figure 5(b).

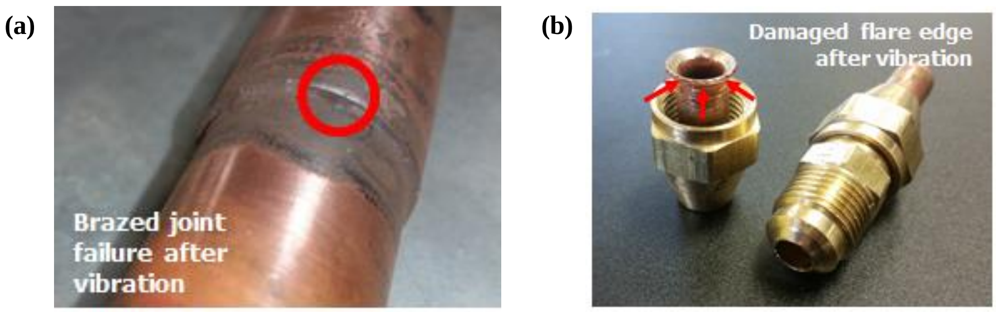

Figure 5: Images of fitting failures during vibration testing: (a) Brazed joint and (b) flare fitting.

6. FITTING LEAK RATE FACILITY AND RESULTS

The leak rate measurement was performed by placing the fittings inside a hermetically sealed box. The concentration of R32 in the test chamber is determined during testing using infrared (IR) photoacoustic multi-gas analyzers, which works on the principle of photoacoustic infrared spectroscopy to determine the concentration of various species of gas present in the sample; the sensor was calibrated for R32. The hermetically sealed box is placed in a controlled-environment chamber (maintained at 40°C) and connected to the gas concentration sensor. The fitting test section is placed inside the box before sealing and connected to an external refrigerant tank to supply the fitting test section with saturated R32 vapor at 40°C. A diagram of the leak rate measurement facility is shown in Figure 6.

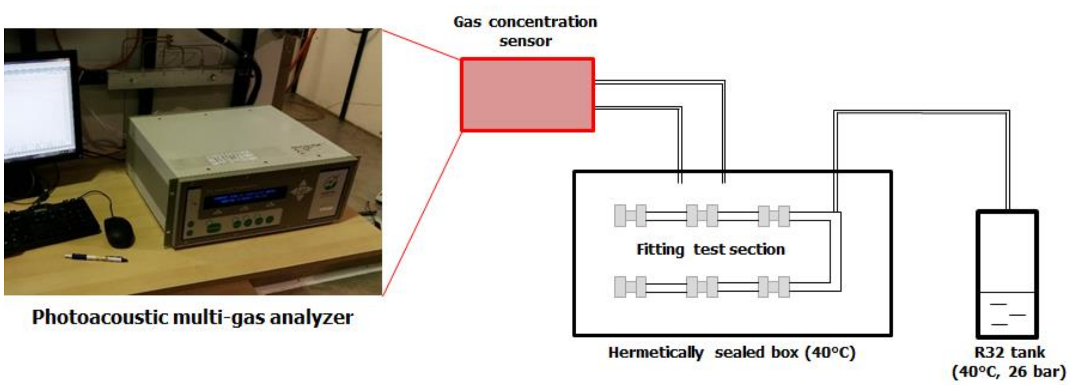

Figure 6: Diagram of leak rate measurement facility.

All fittings of the same type-size-material combination were tested at the same time and averaged per fitting (25 of each combination less any failed fittings that could not be repaired). The results are shown in Figure 7. It can be seen that the brazed fittings showed no noticeable leak, validating the testing method. Press fittings showed average leak rates in the range of 0.55 g yr^{-1} per fitting to 1.04 g yr^{-1} per fitting. The larger press fittings show a 33 % higher leak rate on average than the smaller press fittings. Flare fittings generally showed average leak rates of about 0.2 g yr^{-1} per fitting or less. However, one set of flares showed significantly higher leak rate; this is likely due to a single flare fitting with an unusually large leak (though not large enough to be detected with N_2 after harshness testing) and is not representative of the entire set. Compression fittings generally showed average leak rates in the range of 0.05 g yr^{-1} per fitting to 0.45 g yr^{-1} per fitting. However, as with flare fittings, there is a single compression fitting set with significantly higher leak rate, again likely due to a single compression fitting with unusually high leak rate. There does not seem to be any clear effect of fitting size or tubing material for the leak rates observed with the flare and compression fittings.

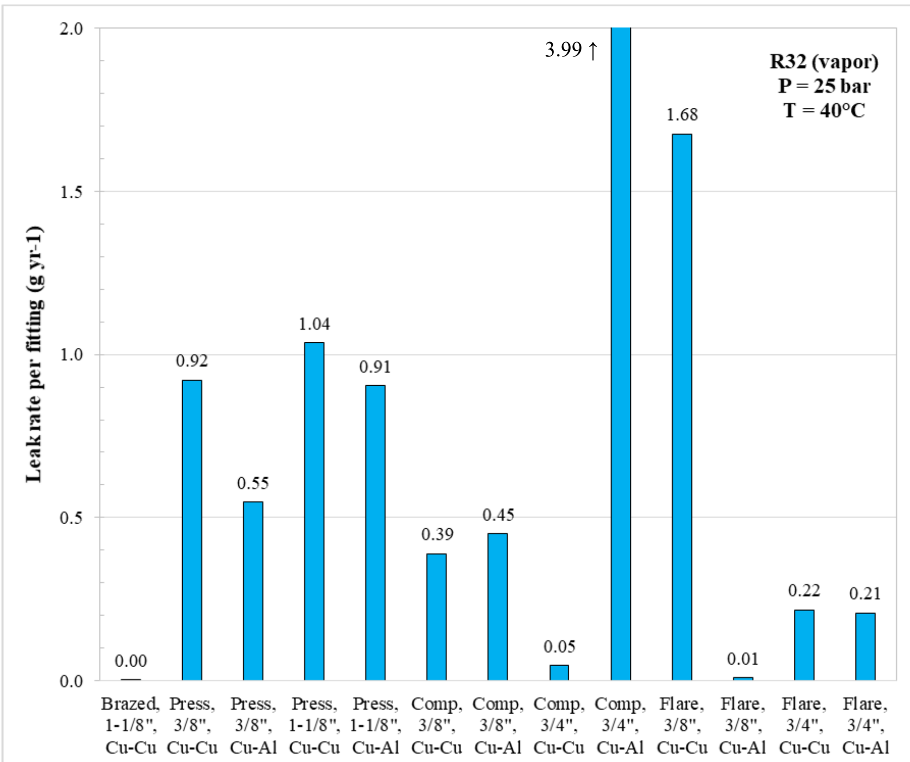

Figure 7: Summary of observed leak rates for different fitting type-size-material combinations (reported as average leak rate per fitting for entire combination set).

7. CONCLUSIONS

This paper has presented the results of a study investigating the assembly, durability (harshness), and leak rate of field-made mechanical joints, specifically press, compression, and flare fittings. The following conclusions can be drawn from the presented results:

- Press fittings result in the quickest assembly time and lowest assembly failure rate, and they resulted in zero failures during harshness testing, making them the most durable of the selected fittings. They have a higher, though still acceptable, leak rate of 0.5 – 1.0 g yr^{-1} per fitting on average.
- Compression fittings generally have low leak rate (generally around 0.4 g yr^{-1} per fitting on average) and the second shortest assembly time but are the most prone to assembly failure and the second most prone to leaks after assembly.
- Flare fittings take the longest time to assemble and are the most prone to leaks after assembly; however, they result in fewer assembly failures than compression fittings. Flare fittings also generally have the lowest leak rate (generally around 0.2 g yr^{-1} per fitting on average).

- Brazed joints were found to have similar assembly time compared to compression fittings, though their assembly time and success was found to be more dependent on technician experience and assembly difficulty; the brazed joints were observed to have no detectable leak rate, as would be expected.
- Technician experience level has a more significant effect on assembly time and success rate than assembly difficulty and fitting size (with the exception of flare fittings).
- Compression and flare fittings fail at a very significant rate (50 % or greater) when subjected to a vibration testing; use of these fittings in locations with a significant amount of vibration should be avoided if at all possible.
- Flare fittings seem prone to failure (30 % for the smaller-sized fittings) under conditions of repeated freezing and thawing of water on the fitting surface; the use of flare fittings should be avoided in applications with refrigerant temperatures near or below freezing (in agreement with ASHRAE 147).

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