TITLE

Seismic Intensity Analysis of Laboratory Testing of Installed Stainless Steel Swagelok® Tube Fittings

ABSTRACT

Installed stainless steel Swagelok tube fittings were reported to have survived as many as two severe earthquake events intact without leakage. Subsequent customer requests have prompted completion of a product line seismic intensity analysis of laboratory tests to observe this capability.

Laboratory vibration testing of stainless steel Swagelok tube fittings simulated seismic Peak Ground Acceleration (PGA) intensities transmitted to assembled tube fittings both with and without amplification that can result from tubing system resonance during seismic excitation.

- **When there is no tubing system resonance**, vibration testing demonstrated leak-tight performance at simulated seismic PGA intensities corresponding to earthquake events up to a **10** on the **Modified Mercalli** scale, **7** on the **Omori** scale, and **9** on the **Richter** scale.
- **When tubing system resonance effects are present**, vibration testing demonstrated leak-tight performance corresponding to earthquake events up to an **8** on the **Modified Mercalli** scale, **7** on the **Omori** scale, and **8** on the **Richter** scale.

This analysis comprises a seismic intensity scale comparison with Vibration Table and High Impact Shock laboratory tests and does not represent a seismic intensity product rating.

PRODUCT TESTED

Original test date: September 2012

The following stainless steel Swagelok tube fittings were tested with stainless steel tubing.

Table 1

Tube OD	Tube Fitting Ordering Number	Number of Test Fitting Ends	Tube Wall Thickness
Vibration Table Tests			
Fractional Tube, in. (mm)			
1/4	SS-400-6	2	0.035 (0.89)
1/4	SS-400-6	2	0.065 (1.65)
1/2	SS-810-6	6	0.049 (1.24)
1	SS-1610-6	2	0.109 (2.77)
1 1/2	SS-2400-6	6	0.134 (3.40)
Metric Tube, mm (in.)			
10	SS-10M0-6	1	1.0 (0.039)
15	SS-15M0-6	1	1.5 (0.059)
18	SS-18M0-6	1	1.5 (0.059)
22	SS-22M0-6	1	2.0 (0.079)
28	SS-28M0-6	1	2.0 (0.079)
High Impact Shock Tests, in. (mm)			
1/4 (test A)	SS-400-6	2	0.035 (0.89)
1/4 (test A)	SS-400-6	2	0.065 (1.65)
1 (test A)	SS-1610-6	2	0.109 (2.77)
1 (test B)	SS-1610-6	10	0.109 (2.77)

A principle measure of earthquake intensity is Peak Ground Acceleration (PGA) [ref 1]. Earthquake intensities and corresponding nominal PGAs were compared between the Richter seismic intensity scale and two other major seismic intensity scales, the Modified Mercalli scale [ref 2] [ref 3] and the Omori scale [ref 4] [ref 5]. Nominal PGAs based on the Richter scale magnitudes are correlated in Equation 1 [ref 6]. **Appendix One** shows a PGA aligned comparison of these three seismic intensity scales. Comparisons of Peak Ground Velocity and Peak Ground Displacement were not made.

$$\log a_0 = -2.1 + 0.81\,M - 0.027\,M^2 \qquad (1)$$

M = Richter seismic intensity magnitude
a_0 = PGA (cm/sec^2)

Laboratory tests of installed Swagelok tube fittings were examined with a computed equivalent PGA, or maximum vibratory acceleration of the driving vibration in the test. The PGAs were calculated according to Equation 2 in terms of gravitational acceleration at the Earth's surface (G). In test conditions where the Swagelok tube fittings successfully retained a no-leak performance, the equivalent PGAs were then compared to the nominal PGAs of corresponding seismic intensity scale magnitudes.

$$\text{equivalent PGA} = d_{max}\,(2\,\pi\,f)^{2} / (981\ \text{cm/sec}^2) \qquad (2)$$

d_{max} = maximum deflection of driving vibration (cm), *half of full displacement amplitude*
f = frequency of driving vibration (Hz)
G = a_0 / (981 cm/sec^2)

TEST PROCEEDURES

(a) **Table Vibration Tests (Part 1)**—Table vibration tests were performed on Swagelok tube fittings installed on a run of tubing between two tube supports attached to a vibration table as shown in Figure 1.

Figure 1: Table Vibration Setup

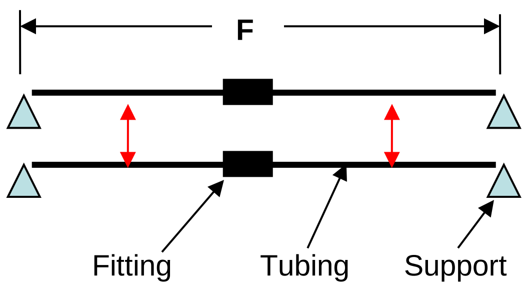


Table vibration tests were performed at room temperature under laboratory conditions at the Southwest Research Institute facilities [ref 7] in accordance with ASTM F1387 [ref 8]. The setup used in the testing is shown in Figure 1. The length "F" between tube supports (also from ASTM F1387) and the tube fitting test pressures, during and after vibration testing, for each size tube fitting were specified as shown in **Table 2**.

Table 2: Vibration Test Tube Fitting Assembly Set-up (Part 1)

Tube OD in.	**Tube Wall Thickness** in. (mm)	**Tube Support Spacing "F"** mm	**Internal Hydraulic Test Pressure** MPa (psig)	**Post Vibration Test Hydraulic Pressure** MPa (psig)
1/4	0.035 (0.89)	420	25.9 (3750)	38.8 (5625)
1/4	0.065 (1.65)	420	25.9 (3750)	38.8 (5625)
1/2	0.049 (1.24)	480	22.7 (3300)	34.1 (4950)
1	0.109 (2.77)	640	25.9 (3750)	38.8 (5625)
11/2	0.134 (3.40)	790	22.7 (3300)	34.1 (4950)

The test fittings were assembled following Swagelok tube fitting installation instructions [ref 9], hydraulically pressurized to the specified pressure then subjected to table vibration testing according to MIL-STD-167 (type 1—environmental vibration) [ref 10]. This testing comprised a repeated sequence of three separate steps: **Variable Frequency**, **Exploratory**, and **Endurance** vibration. All three of these vibration test steps were each performed in sequence three times, each time varying the direction of input vibration displacement in each rectilinear axis of tube fitting assembly, longitudinal with the tube axis, and “x” and “y” perpendicular to the tube axis.

The **Variable Frequency** test ranged from 4 to 50 Hz, dwelling at every 1 Hz interval for 5 minutes, while holding specified single amplitude input displacements as shown in **Table 3**. Also shown are the ranges of equivalent PGAs, presuming no resonance amplification, (according to Equation 2) computed for the range of driving frequencies at each displacement.

Table 3: Variable Frequency Test Input Displacements and Equivalent PGAs

Variable Table Frequency (f) Range Hz	**Single Amplitude (d_{max}) Input Displacement** mm	**Equivalent PGA Range** G
4 to 15	0.76	0.05 to 0.69
16 to 25	0.51	0.53 to 1.28
26 to 33	0.25	0.68 to 1.10
34 to 40	0.13	0.60 to 0.84
41 to 50	0.08	0.54 to 0.80

No tube fitting leakage (hydraulic) was detected throughout any of the Variable Frequency testing, both during and post vibration. The testing applied equivalent PGAs on all the Swagelok tube fitting sizes up to 1.28 G. This magnitude corresponds to a **10** seismic intensity on the **Modified Mercalli** scale, a **7** on the **Omori** scale, and a **9** on the **Richter** scale, and would compare to installed tubing fittings that **do not** encounter a resonance induced amplification of PGA during an earthquake event.

The **Exploratory** testing specifically searched for resonance responses in the tube fitting assemblies on the vibration table. Accelerometers were positioned on the tube fittings and on the vibration table. Frequency sweeps were applied over a range of 4 to 33 Hz at a 0.25 mm single amplitude displacement of the table, followed by 34 to 50 Hz at 0.08 mm single amplitude, dwelling at every interval of 1 Hz for 15 seconds.

Resonance or near resonance responses in vibration are important because these induce a side-to-side oscillating bending flexure of the tube at the tube fitting connection that would not occur if there was a no resonance response.

Near resonance responses were found with some but not all sizes. (Table Vibration Tests [Part 2] was more successful.) For each tube fitting size, **Table 4** shows the greatest amplified transmitted acceleration ratio (maximum vibratory acceleration measured at the tube fitting over the same applied at the vibration table) and frequency where each greatest response was found. As the greatest responses were found at the low limit of the frequency sweeps, 4 Hz, the responses found may not have been at a resonance peak maximum.

Table 4: Vibration Resonance Response Findings [Part 1]

Tube OD in.	**Tube Wall Thickness** in. (mm)	**Greatest Transmitted Acceleration Ratio, Frequency Where Found**
1/4	0.035 (0.89)	6.0 at 4 Hz
1/4	0.065 (1.65)	3.0 at 4 Hz
1/2	0.049 (1.24)	1.0 across 4 to 50 Hz
1	0.109 (2.77)	6.5 at 4 Hz
11/2	0.134 (3.40)	1.0 across 4 to 50 Hz

The **Endurance** testing comprised a two-hour vibration dwell at the frequency showing the greatest ratio of transmitting acceleration, with specified vibration table amplitude the same as that used in the **Variable Frequency** tests. For those sizes where no resonance effect was found, the **Endurance** testing was conducted at 50 Hz, the high limit of the frequency sweeps.

No tube fitting leakage was detected throughout any of the **Endurance** testing, both during and post vibration. For those sizes of tube fittings installed wherein their vibration table tubing assemblies had shown a resonance response, the driving vibration at the table simulated an equivalent PGA no greater than 0.05 G (per **Table 3**). This magnitude corresponds to a 5 seismic intensity on the Modified Mercalli scale, a 2 on the Omori scale, and a 6 on the Richter scale. These maximums would correspond to tubing systems that do encounter a resonance induced amplification of PGA at installed Swagelok tube fittings during an earthquake event, but are too low to represent a meaningful Swagelok tube fitting performance comparison.

(b) **Table Vibration Tests [Part 2]** – To further explore resonance responses in tube fitting assemblies, table vibration tests were performed at room temperature at the Swagelok Company facilities under laboratory conditions in accordance with JIS E 4031 [ref 11]. The setup used followed ASTM F1387 [ref 8], the same shown in Figure 1. The length "F" and the test pressures, both initially and after vibration testing, for each size tube fitting were specified as shown in **Table 5**. The tube fitting assemblies were not pressurized during vibration testing.

Table 5: Vibration Test Tube Fitting Assembly Set-up [Part 2]

Tube OD mm	**Tube Wall Thickness** mm (in.)	**Tube Support Spacing "F"** mm	**Internal Hydraulic Test Pressure** MPa (psig)	**Internal Nitrogen Test Pressure** MPa (psig)
10	1.0 (0.039)	600	1.00 (145)	1.00 (145)
15	1.5 (0.059)	600	1.00 (145)	1.00 (145)
18	1.5 (0.059)	600	1.00 (145)	1.00 (145)
22	2.0 (0.079)	600	1.00 (145)	1.00 (145)
28	2.0 (0.079)	600	1.00 (145)	1.00 (145)

The test fittings were assembled following Swagelok tube fitting installation instructions [ref 9], pneumatically and hydraulically pressure tested, then fastened to a vibration table with accelerometers positioned on the tube fittings and on the vibration table. Frequency sweeps were applied continuously, raised and lowered twice over ranges spanning 5 to 190 Hz. The single amplitude displacement of the table was also varied such that the calculated and measured acceleration at the table simulated a constant equivalent PGA of 0.50 G.

These frequency sweeps were conducted in sequence three times for each tube fitting, each time varying the direction of input vibration displacement in each rectilinear axis of tube fitting assembly, longitudinal with the tube axis, and "x" and "y" perpendicular to the tube axis. The rate of frequency sweep was conducted such that each tube fittings was subjected to a total of five hours of vibration in each axis, 15 hours total.

Resonance responses were found with all sizes. For each tube fitting size, **Table 6** shows the greatest amplified transmitted acceleration ratio and frequency where each greatest response was found. These responses all represented resonance peak maximums.

Table 6: Vibration Resonance Response Findings [Part 2]

Tube OD mm	**Greatest Transmitted Acceleration Ratio, Frequency Where Found**
10	5.5 at 170 Hz
15	3.1 at 141 Hz
18	4.0 at 133 Hz

Tube OD mm	**Greatest Transmitted Acceleration Ratio, Frequency Where Found**
22	5.5 at 139 Hz
28	7.4 at 139 Hz

No tube fitting leakage was detected, both before and after vibration. For all sizes of tube fittings the driving vibration at the table simulated an equivalent PGA of 0.50 G. This magnitude corresponds to an **8** seismic intensity on the **Modified Mercalli** scale, a **7** on the **Omori** scale, and an **8** on the **Richter** scale, and would correspond to tubing systems that do encounter resonance induced PGA amplification at installed Swagelok tube fittings during an earthquake event.

(c) **High Impact Shock Tests—**To apply an extreme vibratory acceleration test, various sizes of installed stainless steel Swagelok tube fittings were subjected to repeated high impact shock testing according to MIL-S-901D (Grade A, Class 1, Type A, hull mounted) [ref 12]. As stated in the standard, "The purpose of these requirements is to verify the ability of shipboard installations to withstand shock loadings which may occur during wartime service due to the effects of nuclear or conventional weapons."

Swagelok tube fitting unions pull assembled on two opposing lengths of tubing. For shock test A, each test assembly was cantilever suspended by a single tube support on one of the lengths of tubing clamped to the anvil table of a shock machine. The union tube fittings were all positioned 51 mm (2 in.) from the tube support. On the other tube length a specified free weight was clamped on the tube at specified tube spacing from the union tube fitting as shown in **Table 7**. For shock test B, each test assembly was mounted with two tube supports as shown in Figure 1 with an "F" spacing of 417 mm (16.4 in.).

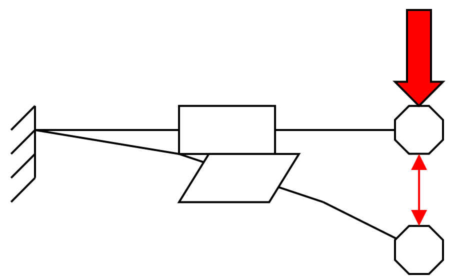
Table 7: Tube Fitting Assembly High Impact Shock Test Set-up

Tube OD in.	**Free Weight** kg	**Free Weight Tube Spacing** mm	**Internal Hydraulic Test Pressure** MPa (psig)	**Post Shock Hydraulic Test Pressure** MPa (psig)
1/4 (test A)	1.3	190	25.9 (3750)	38.8 (5625)
1/4 (test A)	1.5	190	25.9 (3750)	38.8 (5625)
1 (test A)	32	370	25.9 (3750)	38.8 (5625)
1 (test B)	N/A	370	25.9 (3750)	38.8 (5625)

High impact shock tests A were performed at room temperature in laboratory conditions at the Southwest Research Institute facilities [ref 7]. Test fittings were assembled according to Swagelok tube fitting installation instructions [ref 9] and hydraulically pressurized to a specified pressure during shock testing and again for a 10 minutes period for the post shock testing as shown in **Table 7**. High impact shock tests B were performed at Aero Nav Labs facilities [ref 13] where the test fittings were additionally subjected to a final 1 minute hydraulic pressure at 103 MPa (15000 psig) after the shock and post shock hydraulic pressure tests.

While under test pressure each Swagelok tube fitting union was subjected to high impact shocks as shown in Figure 2 for test A, and as shown in Figure 1 for test B. The high impact shock testing comprised a sequence of specified 1, 3, and 5 ft (0.30, 0.91, 1.5 m) hammer drops against the anvil table to which the test assemblies were mounted and were repeated again in each rectilinear axis of the table.

Figure 2: High Impact Shock Test Setup



Computing an equivalent PGA seismic driver that could induce these elevated levels of shock acceleration starts with Equation 3 which relates the system resonance amplification of vibratory acceleration at an installed tube fitting as a function of driving frequency and tube system harmonic properties [ref 14].

$$\frac{\text{Maximum Acceleration at the test fitting}}{\text{Peak Ground Acceleration}} = \left[\frac{1+(2\zeta r)^2}{(1-r^2)^2+(2\zeta r)^2}\right]^{1/2} \quad (3)$$

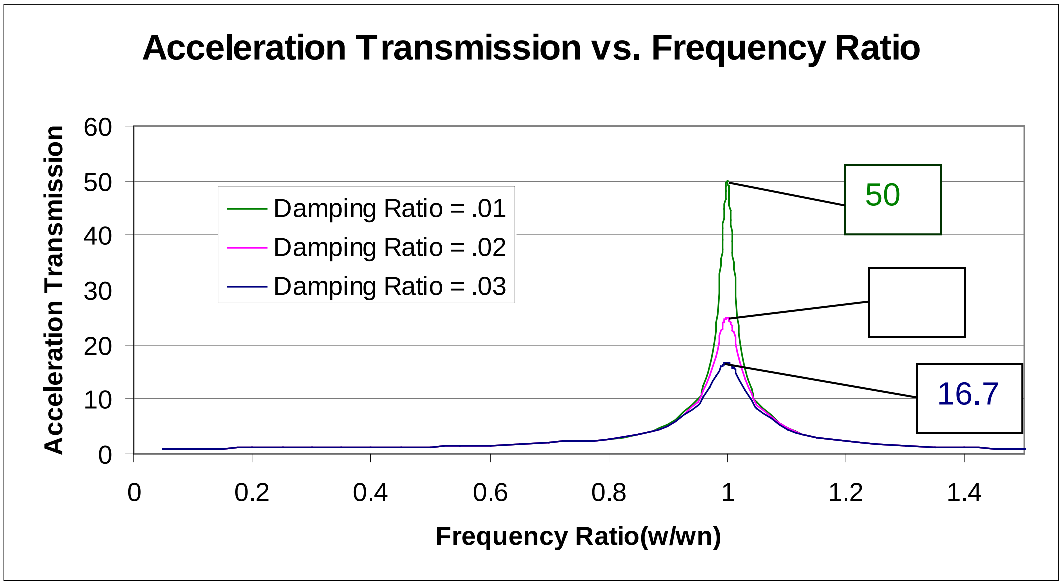
ξ = Damping Ratio
r = Frequency Ratio (ω/ωn)

The damping ratio (ξ) is defined as the ratio of damping (internal or material) in a system over the critical damping of the system. Critical damping is defined as the level of damping at which a vibrating system will not overshoot its equilibrium position, returning to equilibrium in the minimum amount of time [ref 14].

The damping in tube and tube fitting system would be considered hysteresis damping which is energy lost within a moving structure. “In hysteresis damping, some of the energy involved in the repetitive internal deformation and restoration to original shape is dissipated in the form of random vibrations of the crystal lattice in solids and random kinetic energy of the molecules in a fluid”[ref 15]. For a typical tube fitting and tube system the damping ratio is in the range of 0.01 to 0.03 [ref 16].

The frequency ratio (r) is the ratio of the frequency (w) of the driving ground (or seismic) vibration over the natural frequency (wn) of a tube run system comprising installed tube fittings and other components. The natural frequency of the system is based on the installed component masses and spring constants of tubing. The maximum transmission of acceleration occurs at resonance or at r =1. This value was used to find the maximum ratio or amplification of fitting acceleration from a PGA seismic driver. Applying equation (3), the amplified acceleration transmission can range from 16.7 to 50, as shown in Figure 3.

Figure 3: Acceleration Transmission



Finally, the high impact shock testing was literature researched for acceleration imparted during impacts. Peak values of acceleration measured in the 250 to 550g range [ref 17]. The lowest value of this range shock induced G equivalent acceleration (250), divided by the maximum amplification of tube fitting acceleration from a PGA seismic driver (50 in Figure 3) computes to a lowest equivalent PGA of 5.0, which is still well above the greatest seismic PGA (2.04) listed in the **Appendix One** major seismic intensity scales. In all cases the tube fittings sustained these elevated levels of shock acceleration without leakage.

While this test result demonstrates the robust performance of the Swagelok tube fitting, high impact shock testing should not alone constitute a seismic intensity scale comparison. Rather, this result serves to reinforce the comparisons derived from the table vibration testing as reported in the Abstract of this report and in the following summary of Test Results.

TEST RESULTS

Table Vibration Tests [Part 1]—With durations of exposure well exceeding those of major seismic events, based on driving peak accelerations of table vibration, presuming no tubing system resonance based amplification of peak acceleration at installed test fittings, Swagelok tube fittings were subjected to peak table vibration accelerations that compare to Peak Ground Accelerations corresponding to earthquake events up to a **10** on the **Modified Mercalli** scale, **7** on the **Omori** scale, and **9** on the **Richter** scale.

No tube fitting leakage was detected throughout any of the vibration exposure, nor during the 150% of test pressure exposure subsequent to vibration exposure.

Table Vibration Tests [Part 2]—With durations of exposure well exceeding those of major seismic events, based on the driving peak acceleration of table vibration, specifically at vibration frequencies of tubing system resonance with measured 3.1 to 7.4 amplification of peak acceleration at installed test fittings, Swagelok tube fitting were subjected to peak table vibration acceleration that compares to Peak Ground Accelerations corresponding to earthquake events up to an **8** on the **Modified Mercalli** scale, **7** on the **Omori** scale, and **8** on the **Richter** scale.

No tube fitting leakage was detected both before and after any vibration exposure.

High Impact Shock Tests—With repeated exposure to a series of high acceleration inducing hammer blows on installed test fittings, based on prior study and measurement of shock induced acceleration with this laboratory set-up, Swagelok tube fittings were subjected to minimum calculated peak driving accelerations, presuming a worse case tubing system resonance, that are still over twice the Peak Ground Accelerations corresponding to the highest level on all the three major seismic intensity scales.

No tube fitting leakage was detected throughout the repeated shock test exposure. In some cases the tubing attached to the Swagelok tube fittings became permanently damaged, but nevertheless with no leakage detected.

This analysis comprises a seismic intensity scale comparison with Vibration Table and High Impact Shock laboratory tests and does not represent a seismic intensity product rating.

These tests where conducted beyond the product's recommended operating parameters and do not modify the published product ratings.

These tests were performed to consider a specific set of conditions and should not be considered valid outside those conditions. Swagelok Company makes no representation or warranties regarding these selected conditions or the results attained. Laboratory tests cannot duplicate the variety of actual operating conditions. Test results are not offered as statistically significant. See the product catalog for technical data.

SAFE PRODUCT SELECTION

When selecting a product, the total system design must be considered to ensure safe, trouble-free operation. Function, material compatibility, adequate ratings, proper installation, operation, and maintenance are the responsibilities of the system designer and user.

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Appendix One:
Peak Ground Acceleration (PGA) Comparison of Three Major Seismic Intensity Scales

Modified Mercalli		Omori(JMA)		Richter	
Nominal PGA cm/s^2 (G equivalent)	Scale Description	Nominal PGA cm/s^2 (G equivalent)	Scale Description	Nominal PGA cm/s^2 (G equvalent)	Scale Description
				0.05 (4.89E-6)	**1.** Micro earthquake, not felt
<1.67 (≤0.002)	**1.** Felt by very few under favorable conditions			0.258 (2.63E-4)	**2.** Generally not felt, but recorded
1.67 (0.002)	**2.** Felt by few at rest, especially in higher floors			1.22 (0.001)	**3.** Often felt, but rarely causes damage
7.7 (0.008)	**3.** Felt noticeably indoors, vibration similar to passing truck			5.1 (0.005)	**4.** Noticeable shaking of indoor items, rattling noises, significant damage unlikely
				18.8 (0.019)	**5.** Major damage to poorly constructed buildings. Slight damage to well designed buildings
26 (0.027)	**4.** Felt indoors and outdoors, walls cracking, similar to truck striking building	30 (0.031)	**1.** Shock strong, walls crack slightly, furniture overturned, trees shaken		
64.3 (0.065)	**5.** Felt by almost everyone, unstable objects overturned	60 (0.061)	**2.** Wooden walls crack, small stone structures overturned	61.4 (0.063)	**6.** Destructive in areas about 160 km across in populated areas
		105 (0.107)	**3.** 1/4 of factory chimneys destroyed, brick partially or totally destroyed		
133 (0.136)	**6.** Felt by everyone, heavy furniture moved, damage slight				
		160 (0.163)	**4.** All factory chimneys ruined, most brick and some wood houses destroyed, crevices in ground	177 (0.180)	**7.** Serious damage over large areas

255 (0.260)	**7.** Negligible to considerable damage to buildings based on quality of construction	225 (0.229)	**5.** All brick houses seriously damaged, 3% of wooden houses destroyed		
		325 (0.331)	**6.** 50 to 80% of wooden houses destroyed, iron bridges destroyed, wooden bridges partially or totally damaged		
485 (0.494)	**8.** Considerable structure damage, partial collapse, heavy furniture overturned	≥400 (≥0.408)	**7.** All buildings destroyed except a few wooden structures	449 (0.458)	**8.** Serious damage in areas hundreds of kilometers across
927 (0.945)	**9.** Damage considerable to all buildings. Buildings shifted off of foundation			1000 (1.02)	**9.** Devastating in areas several thousand kilometers across
1220 (1.24)	**10.** Well built wooden structures destroyed, most masonry structures destroyed, rails bent				
>1220 (>1.24)	**11.** Few, if any structures remain standing, bridges destroyed, rails bent greatly				
>1220 (>1.24)	**12.** Lines of sight and level are distorted, objects thrown in air			2000 (2.04)	**10.** Widespread devastation over very large areas. Never recorded