P7.101 Performance of residences and shelters in the Oklahoma tornadoes of 24 May 2011

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1. INTRODUCTION

On 24 May 2011 a total of 22 tornadoes struck central Oklahoma (Fig. 1). Fortunately, these tornadoes missed towns and metropolitan areas. The next day, the Oklahoma City National Weather Service Forecast Office (OUN NWSFO) dispatched several survey teams to determine the characteristics of the tornado paths and assign damage ratings. Survey team members included the authors of this paper. Three of the 22 tornadoes were found to have been violent with complete destruction of residences, debarked trees, and lofted vehicles. The longest and most violent tornado traveled from near Hinton to El Reno to Piedmont to Guthrie, a distance of 104 km, and caused nine fatalities with 181 injuries (Storm Data, 2011). Team members rated this tornado EF-5 on the Enhanced Fujita (EF) scale. Another violent tornado traveled from Chickasha to Newcastle, a distance of 52 km, killing one and injuring 48 people. Team members rated this tornado at the upper end of EF-4. The third violent tornado traveled from near Bradley to Goldsby, a distance of 37 km, ending just southwest of Norman. Team members rated this tornado at the upper end of EF-4.

This paper will present the results of the damage surveys for the three violent tornadoes. Excellent advanced warnings, people reacting properly to those warnings, and people using tornado shelters had minimized the number of fatalities. Examples will be presented where people survived in above-ground and below-ground shelters.

However, tornado shelters were not without problems. Some doors were damaged or blocked with debris trapping people inside. Also, flying debris struck and damaged some of the shelter doors and/or locks. None of the inspected shelters were approved by the NSSA (National Storm Shelter Association) but still performed well enough to protect occupants. This paper will also highlight some of the new shelter design criteria adopted recently by the ICC (International Code Council, 2008).

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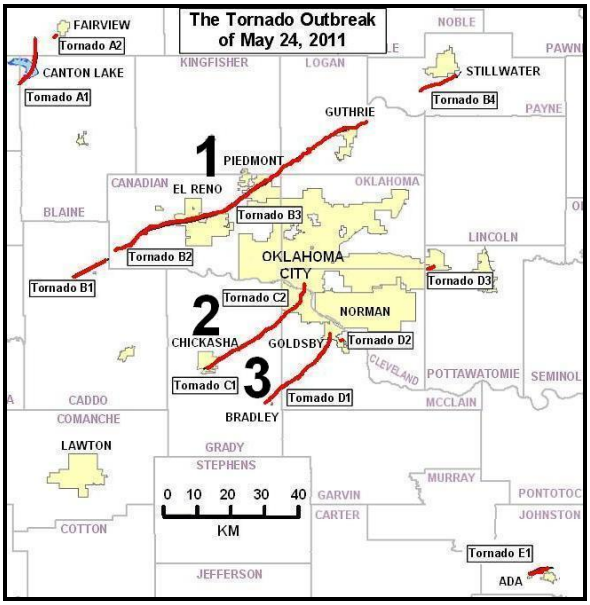

Figure 1. Tornado tracks on 24 May 2011 in central Oklahoma. Violent tornado tracks by town are: 1) Hinton-El Reno-Piedmont-Guthrie, 2) Chickasha-Newcastle, and 3) Bradley-Goldsby. Courtesy of the OUN NWSFO. More detailed maps are appended.

2. DAMAGE SURVEY

The degree of damage (DOD) to residences was determined using the Enhanced Fujita scale developed by the Wind Science and Engineering Research Center (WISE, 2006). This scale involves the use of 28 damage indicators (DIs). However, only five building types have expected values of 200 mph or more to receive an EF-5 rating. In this event, residences were the only building type where EF-5 ratings could be assigned. All three violent tornadoes destroyed homes on concrete slab foundations, and team members assigned a DOD of 9 where all walls were down and slabs were swept clean. However, a DOD of 10 must involve the destruction of an engineered or well-constructed residence on concrete slab foundations.

The definition of a well-constructed house can vary among individual damage surveyors. In this paper, we define a well-constructed residence as one that has a continuous load path of straps and anchors, without weak connections in horizontal or vertical

planes. Straight-nailed connections (typically between wall studs and bottom plates) are weak, and we found them in every destroyed home. Thus, we used a number of non-traditional DIs to help delineate between EF-4 and EF-5 damage in an effort to determine associated failure wind speeds. Such non-traditional DIs included an overturned oil derrick, extreme car lofting, ground/pavement scouring, mobile radar measurements, and mesonet measurements. The presence of any one of these non-traditional DIs did not automatically determine the EF- rating; however they were studied in conjunction with traditional DIs. Survey teams still encountered a number of difficulties in delineating between EF-4 or EF-5 damage. For example, the tornado tracks were in rural areas where there were few DIs or non-traditional DIs and a general lack of substantial or well-constructed buildings.

2.1 Hinton-ElReno-Piedmont-Guthrie Tornado

This tornado began near the Caddo-Canadian County border, about 23 km west-southwest of the town of Calumet. The tornado quickly became a large tornado and destroyed numerous trees, many of which were debarked, before crossing Interstate 40. Three people died in vehicles near the Calumet exit, and two other fatalities occurred just northeast of that location. Winds tossed the cars more than 1 km.

According to Bluestein et al. (2012), a Rapid-Scan X-band Polarimetric (RAXPOL) mobile Doppler Radar was located on a section line road a few kilometers south of the Calumet exit on Interstate 40. They scanned the tornado and obtained maximum instantaneous radial velocities of 125 m s^{-1} at a location 4 km southeast of the radar with beam heights between 60 and 70 m above ground. Radial velocities remained greater than 120 m s^{-1} for several minutes. When the tornado crossed Interstate 40, maximum radial velocities were just over 100 m s^{-1} at a range of about 10 km and height of approximately 170 m.

The Cactus 117 oil rig site was struck by the tornado just north of Interstate 40. The rig reportedly weighed 862 metric tons and toppled onto its side (Fig. 2). At the time of the tornado, the drill head and pipes extended deep into the well bore. According to Baker (2011), twelve workers sought shelter in a shipping container called the "change house" that was anchored by four, 2.56 cm diameter steel cables hooked to steel augers extending 1.7 m into the ground (Fig. 3). One of the cables broke and flying debris dented the change house. The workers escaped serious injuries. Nearby, the blowout preventer was bent at a 30 degree angle toward the north. A number of vehicles and unanchored cargo containers were rolled and lofted on the site. One cargo container was dropped onto two vehicles.

According to Bowen (2011), a mesonet station located 8 km west of El Reno measured a wind gust of 56 m s^{-1} at 1920 UTC from the south and a gust of 68 m s^{-1} at 1925 UTC from the northwest as the tornado passed.

Ten wood-framed houses were leveled on Northridge Lane, 5 km north of Piedmont. These houses had concrete slab foundations (Fig. 4). Close inspection revealed that cut nails had fastened wall bottom plates to the slab perimeters. In these instances, the plates had pulled away from the slabs leaving divots or broken portions of the slabs where nails had been driven (Fig. 5). Other homes had bottom plates properly bolted to their slabs but failed where the wall studs were straight nailed into the bottom plates. Such homes were deemed not well constructed and were assigned a maximum DOD rating of 9.

Figure 2. Overturned oil rig at the Cactus 117 drilling site.

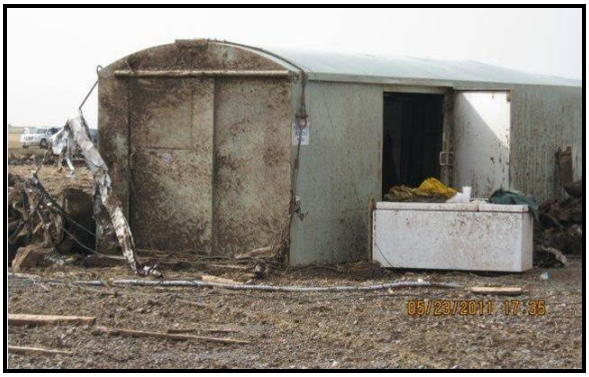

Figure 3. Steel container at the Cactus 117 drilling site where 12 workers survived the tornado.

Each home surveyed also had a steel bathtub. Some tubs remained in place and contained debris while other tubs were removed from their slab foundations (Fig. 6). Regardless, none of the steel bathtubs would have provided adequate shelter from the tornado. Also, several vehicles were rolled or lofted into an adjacent farm field and would not have been safe places of refuge.

Each of the ten destroyed homes surveyed had an exterior, pre-cast concrete storm shelter installed partially below grade. Each shelter had a single steel door that swung outward with pivoting latch. A few shelter doors also contained pairs of spring loaded locks. In each instance, the doors remained attached to their hinges, although one door was bent. A number of people survived in these shelters (Fig. 7).

Figure 4. A home nearly swept clean from its concrete slab foundation on Northridge Lane northwest of Piedmont, OK.

Figure 5. Broken edge of the concrete slab foundation where a perimeter wall plate had been secured with a cut nail.

Figure 6. Example of a steel bathtub removed from house foundation. This tub would not have provided adequate shelter during the tornado.

Figure 7. Storm shelter adjacent to a destroyed house. Note the steel door swung outward and had a single, pivoting latch.

The tornado leveled two more homes on Axeman Street off Moffat Road, 6.5 km northeast of Piedmont. However, workers had cleared debris from the concrete slab foundations prior to our arrival. Given the descriptions of the DOD by the owners, the team assigned EF-4 ratings to the houses. Both houses had wall bottom plates attached to their foundations with steel anchor bolts and cut nails installed in an alternating manner. Failure commonly occurred where the wall studs were straight nailed to the bottom plates.

One home had a pre-cast exterior shelter installed partially below grade. The door remained intact but the handle had broken off where struck by flying debris (Fig. 8). A red-colored Chevrolet Avalanche vehicle, initially parked in the garage, was blown to the northeast 650 m and impacted a tree in a ravine. The engine block and axles were located nearby (Fig. 9). Trees in the ravine were debarked, and branches were removed.

The other home had a poured-in-place, steel-reinforced above-ground shelter that was installed at the southeast corner of the concrete slab. Flying debris had penetrated the outer panel of the inward swinging steel door but the interior panel of the door remained intact. The door had three deadbolt locks, and one lock had been pushed into the hollow door by debris impact. As a result, the door lock was jammed and could not be opened (Fig. 10).

Four houses were examined in the Falcon Lakes subdivision off Azalea Street, 8 km northeast of Piedmont. These homes had walls removed from their concrete slab foundations. Several wall bottom plates were secured to the slab perimeters using cut nails. In these instances, the wall plates had been pulled loose leaving divots or broken portions of the slab where the nails had been driven. One home had an above ground, steel shelter that remained intact. The inward opening steel door had three locks (Fig. 11). The home across the street to the west did not have a shelter, and two occupants died. The tornado tossed some vehicles into the adjacent lake.

Figure 9. Metal skin of Chevrolet Avalanche vehicle that traveled 650 m and impacted a tree.

Figure 8. A partially below grade storm shelter had lost its door handle. A wrench was used to open the door.

Figure 10. A cast-in-place, steel reinforced concrete shelter survived the tornado but had a damaged door: a) outer panel penetration, and b) damaged deadbolt lock mechanism.

Figure 11. An above ground steel shelter with a steel door survived the tornado.

The tornado continued through the extreme southeast corner of Kingfisher County and into rural portions of Logan County, but was not as intense as in Canadian County. Houses sustained occasional EF-2 to EF-3 damage and the tornado destroyed several manufactured homes (both single and double-wide) after entering Logan County. Two additional fatalities occurred when persons were caught outside during the tornado near Cashion. The tornado finally dissipated near Guthrie.

2.2 Chickasha-Newcastle Tornado

This tornado developed on the south side of Chickasha in Grady County and destroyed several mobile homes killing one person. A mesonet station in Chickasha measured a gust of 24 m s^{-1} just outside the vortex. The tornado moved northeast of town and gained significant strength as it traveled through rural areas. Many trees were debarked and/or broken with only stumps remaining. The most intense damage occurred at the intersection of Kitty Hawk Road and Meadowlark Lane, just across the McClain County line, about 8 km north of Blanchard. Three homes were leveled on their concrete slab foundations (Fig. 12). Wall bottom plates were secured to the slabs with steel anchor bolts. However, some bolts were missing their nuts and washers. Several wall bottom plates remained anchored to the concrete slab foundations. However, wall studs had pulled apart from their straight-nailed connections to the bottom plates (Fig. 13).

One home had an exterior, below grade, steel storm shelter. The steel door opened outward and had two sliding latches; the door remained undamaged (Fig. 14).

Several cars were thrown more than 100 m. A silver-colored Dodge Ram pickup truck, initially parked in a driveway, traveled 300 m to the northeast where it impacted the ground leaving the frame and axles. The engine block was found just northwest of the frame, and the cab continued another 150 m to the northwest (Fig. 15). A 1.2 x 20 m section of asphalt pavement was removed by the tornado from the east side of Meadowlark Lane.

The tornado directly struck a fiber and steel reinforced concrete domed home. The concrete walls varied in thickness from 7 to 14 cm and the exterior surface was covered with 20 – 25 cm of sprayed-in-place polyurethane foam (SPF) coated with a white elastomeric sealant. Occupants were sitting at the kitchen table when the tornado struck. Windows blew in and a skylight at the top of the dome blew off. A long crack reportedly developed in the dome when impacted by a large object, but the shell remained intact. The occupants survived without serious injury (Fig. 16).

The tornado crossed the intersection of Highway 9 and Highway 76 then began to weaken in southern portions of Cleveland County. A few barns and outbuilding also sustained minor damage east of I-44. The tornado dissipated just north of the South Canadian River.

Figure 12. This house was swept clean from its concrete foundation at the intersection of Kitty Hawk Road and Meadowlark Lane.

Figure 13. Close up view of southwest corner of concrete slab foundation. Anchor bolts were missing nuts and washers.

Figure 14. A below-grade steel shelter. The steel door was not damaged.

Figure 15. Portions of a Dodge Ram pickup truck deposited 300 m from its original location.

Figure16. A fiber and steel-reinforced concrete dome home survived a direct hit by the tornado.

2.3 Bradley-Goldsby Tornado

This tornado developed west of Bradley in Grady County and increased in intensity as it approached the McClain County line. Damage was confined mostly to trees. Some trees were broken at their bases or debarked. Just across the McClain County line, a single-story, wood-framed house was swept clean from its concrete slab foundation at the intersection of Rockwell Road and Highway 76. Close examination revealed that anchor bolts (with nuts and washers) alternated with cut nails had secured the perimeter walls (Fig. 17). A wire fence remained intact in the backyard, but it was bent slightly where impacted by flying debris. Given the less than adequate attachment of the home to its foundation (use of cut nails) and limited damage to the adjacent fence, the home was rated EF-4. The home was equipped with a below grade storm shelter that had a sliding steel door. The door was not damaged (Fig. 18).

The tornado continued northeast shredding trees along Criner Creek. The tornado then crossed Highway 39 and leveled a one- and two-story, wood-framed house at 212th Street and Cedar Lane. The second story was deposited in a heap in the backyard. Bottom wall plates were 2 x 6's anchored to the concrete slab foundation with closely spaced anchor bolts (with nuts and washers). However, wall studs were straight-nailed to the plates. The second story wall plates also were straight-nailed into the floor. Failure occurred when the straight-nailed connections were pulled apart (Fig. 19). Although the rafters were secured to wall top plates with metal straps, the inherently weak straight-nailed connections caused the house to collapse in the tornado. A metal frame of a nearby mobile home found in the debris may have also contributed to the collapse of all walls, so the authors rated the damage at EF-4. Significant ground scouring was noted just south of the house and nearby vehicles had been thrown and wrapped around trees.

An exterior, pre-cast concrete storm shelter was located adjacent to the house. The shelter had a steel door that opened outward. The door contained a swinging bar latch and two spring-loaded steel dowel locks. The shelter and door remained undamaged (Fig. 20).

A large, two-story, wood-framed house was leveled on Highway 74B and just west of High Road. Close examination revealed perimeter wall bottom plates had been secured with anchor bolts (with nuts and washers) alternated with cut nails (Fig. 21). Vehicles were moved, rolled, or tossed into the back yard; a pickup truck was found in a creek bed 50 m behind the house. Given the less than adequate attachment of the house framing to its foundation (use of cut nails), the home was rated EF-4.

The house had a below ground, pre-cast concrete storm shelter in the garage. The shelter had a steel door with swing latch and two spring-loaded dowels. Occupants sought refuge in the shelter but became trapped when a vehicle moved on top of the door (Fig. 22). The tornado lifted west of Goldsby with EF-3 damage occurring just prior to dissipating.

Figure 17. A single-story house at Rockwell Road and Highway 76 was swept clean from its concrete slab foundation. Perimeter wall plates were secured with alternating: a) cut nails and b) anchor bolts.

Figure 18. This house had a below ground storm shelter with sliding steel door that was not damaged.

Figure 19. A leveled one- and two-story home at 212th Street and Cedar Lane: a) wall failure occurred when straight-nailed connections pulled apart.

Figure 20. This house had an exterior, below grade storm shelter with steel door that was not damaged.

Figure 21. This house was swept clean from its concrete foundation on Highway 74B just west of High Road: a) wall failure occurred at straight nailed connections, and b) not all anchor bolts had nuts and washers.

Figure 22. Occupants survived in this below ground storm shelter but were trapped when a vehicle slid over the door during the tornado.

3. RESIDENTIAL STORM SHELTERS

In May 2002, the International Code Council (ICC) and the National Storm Shelter Association (NSSA) initiated a joint project to write a standard for the design and construction of storm shelters. The purpose of the standard was to provide minimum design and construction requirements that provide a safe refuge from storms that produce high winds and debris impacts. The document entitled *ICC/NSSA Standard for the Design and Construction of Storm Shelters,* was published in 2008 and includes four design wind speed regions in the United States (ICC, 2008) for tornadoes (Fig. 23). Shelter design wind speeds are for three-second gusts at 10 m in open terrain (Exposure C).

The highest shelter design wind speeds are in the Midwest and Ohio Valley where the most violent tornadoes typically occur. The design wind speed is 116 m s^{-1} (250 mph). The southeast and northern plains have lower design wind speeds of 89 m s^{-1} (200 mph). Remaining regions east of the Rocky Mountains, including New England states and Hawaii, have design wind speeds of 72 m s^{-1} (160 mph) while the western U.S. and most of Alaska have shelter design wind speeds of 58 m s^{-1} (130 mph).

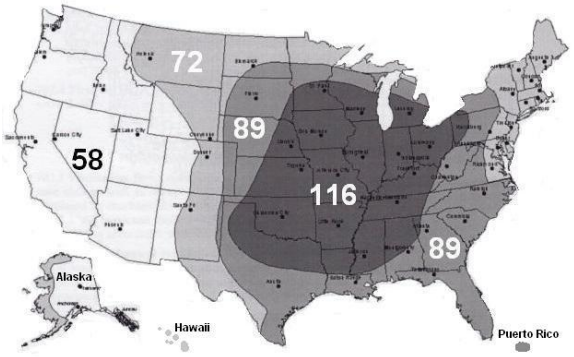

Figure 23. Storm shelter design wind speeds for tornadoes per the ICC-500 standard. Wind speeds shown are 3-second gusts in meters per second at 10m in open terrain.

Above ground shelters must be anchored properly to their foundations. The standard also addresses shelter ventilation, flood zone locations, and proximity requirements. The missile criteria for tornado shelters involves passing a series of impact tests by using a 6.8 kg (15 lb.) 2 x 4 traveling at velocities that are dependent on the design wind speed zone. Shelter components, including the doors, must pass the impact tests. Community shelters have additional requirements including lighting, sanitation, and an emergency escape opening.

4. SUMMARY

Three violent tornadoes occurred in the central Oklahoma outbreak on 24 May 2011. Fortunately, the tornadoes traveled through rural areas avoiding towns and cities. However, a number of rural homes were completely destroyed including several that were swept clean from their concrete slab foundations. Close examination revealed poor attachment of walls which resulted in the homes failing prior to EF-5 winds. Thus, non-traditional DIs, such as a toppled oil rig, had to be utilized to better delineate EF-4 from EF-5 damage. In addition, mobile radar measurements and mesonet observations were utilized. We believe that all available information needs to be considered for determining a damage rating. This includes traditional DIs as well as non-traditional DIs, whether damaged or not.

Some of the destroyed rural homes had storm shelters. All but two shelters were pre-cast, steel-reinforced concrete structures and were installed below grade. One shelter was an above ground, steel-reinforced concrete structure and the other was an above ground steel enclosure. All shelters had steel doors and performed well even in the most intense portion of the tornadoes. The storm shelters saved many lives. However, some shelters did have problems. In one instance, a steel door was bent. Another door had its lock broken, preventing the door from opening. In another instance, a vehicle was shifted over the door trapping the occupants inside.

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Pablo Santos (NWS/FO Miami)
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Craig Schwer (OU/CIMMS NOAA/NSSL)
Steve Martinatis (OU/CIMMS NWS/WDTB)
Clark Payne(OU/CIMMS NWS/WDTB)
Andy Wood(OU/CIMMS NWS/WDTB)
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References

Baker, K., 2011: Twelve lives saved in F5 tornado proves value of Cactus Drilling emergency plan. Available online at: http://www.drillingcontractor.org/12-lives-saved-in-f5-tornado-proves-value-of-cactus-drilling-emergency-plan-13665

Bluestein, H., J. C. Snyder, J. B. Houser, and A. L. Pazmany, 2012: Rapid-scan, polarimetric, Doppler-radar observations of an EF-5 tornado in Oklahoma on 24 May 2011, 26th Conf. on Severe Local Storms, Amer. Meteor. Soc., Nashville, TN.

Bowen, S., 2011: Tornado strikes at mesonet sites. MESONET, Vol. 2, Issue 10. Available online at: http://www.mesonet.org.

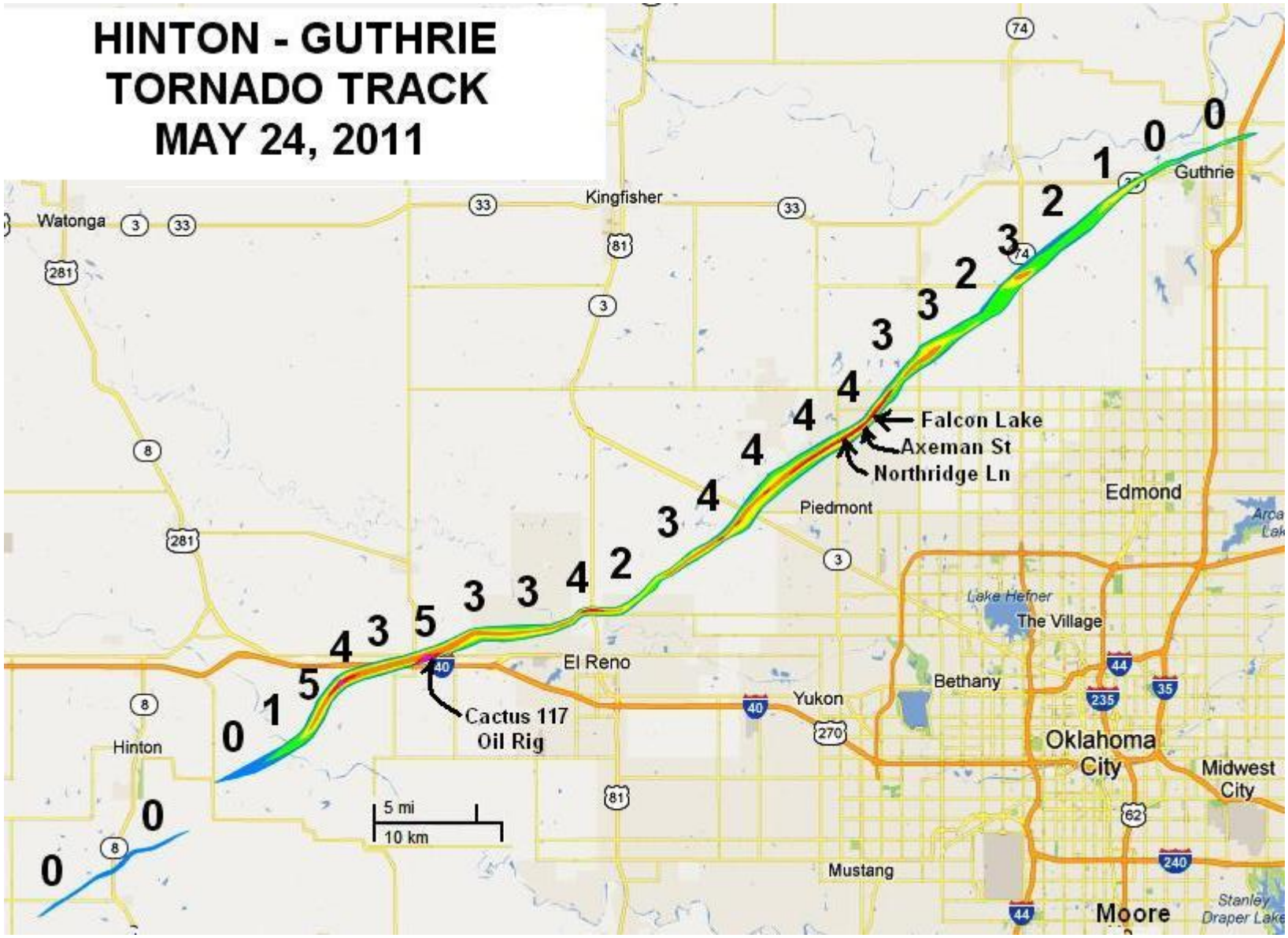
International Code Council (ICC), 2008: ICC/NSSA Standard for the Design and Construction of Storm Shelters, 42pp. (Available for purchase at http://www.iccsafe.org/store)

Storm Data, 2011: May issue. NOAA. Available online at: http://www7.ncdc.noaa.gov/IPS/sd/sd.html;jsessionid=277C8116A5D92E2FD8852C2839054D9F

Wind Science and Research Engineering Center (WISE), 2006: A recommendation for an enhanced Fujita scale, 111 pp. Available at: http://www.depts.ttu.edu/weweb/efscale.pdf

MAP ATTACHMENTS

We have attached damage maps developed from our analysis of the Oklahoma tornadoes. Contours range from EF-0 to EF-4 or EF-5 depending on the tornado and are color coded: EF-0 is blue, EF-1 is green, EF-2 is yellow, EF-3 is orange, EF-4 is red, and EF-5 is pink. Interactive maps are available at: http://goo.gl/maps/YrkdD.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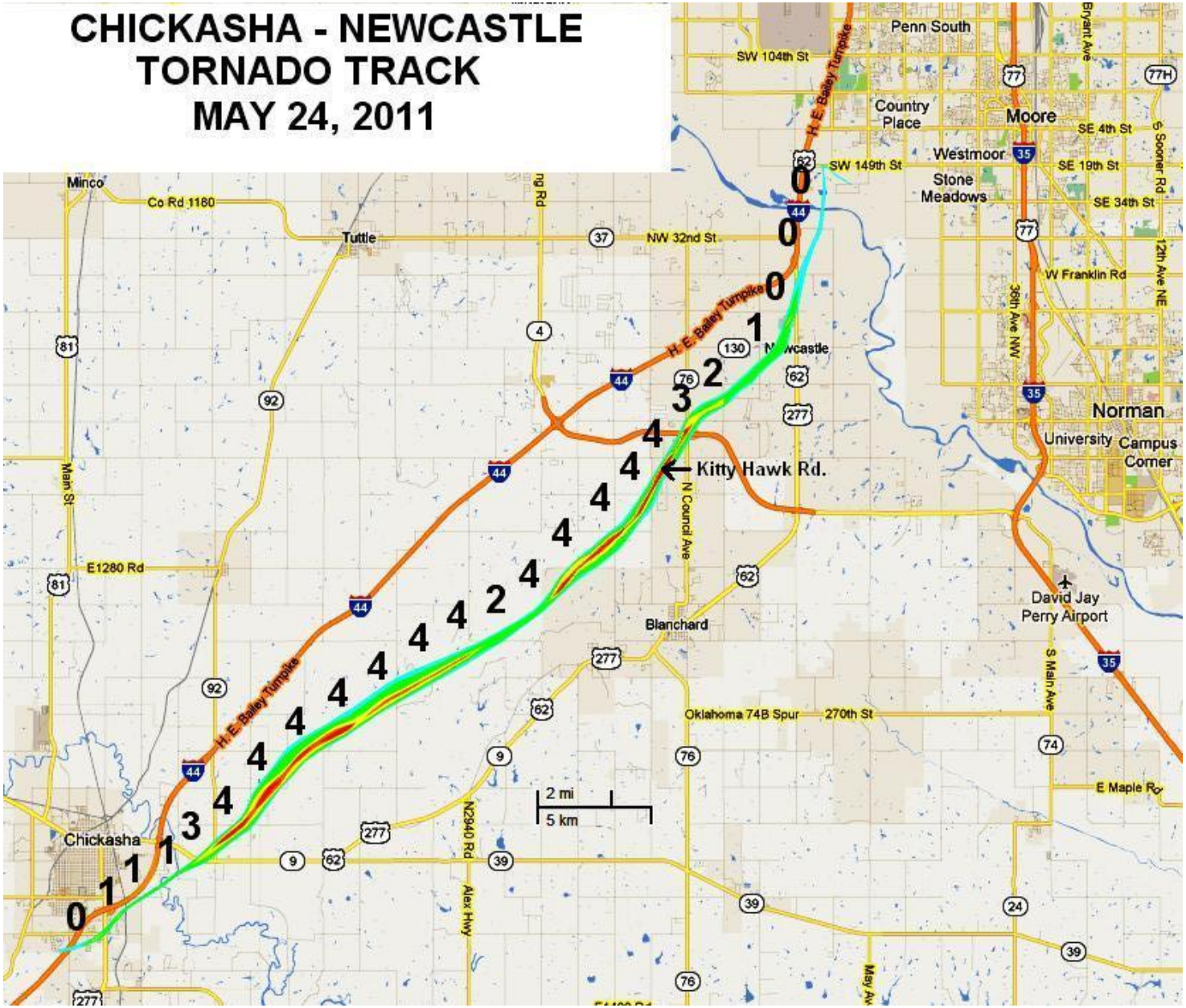
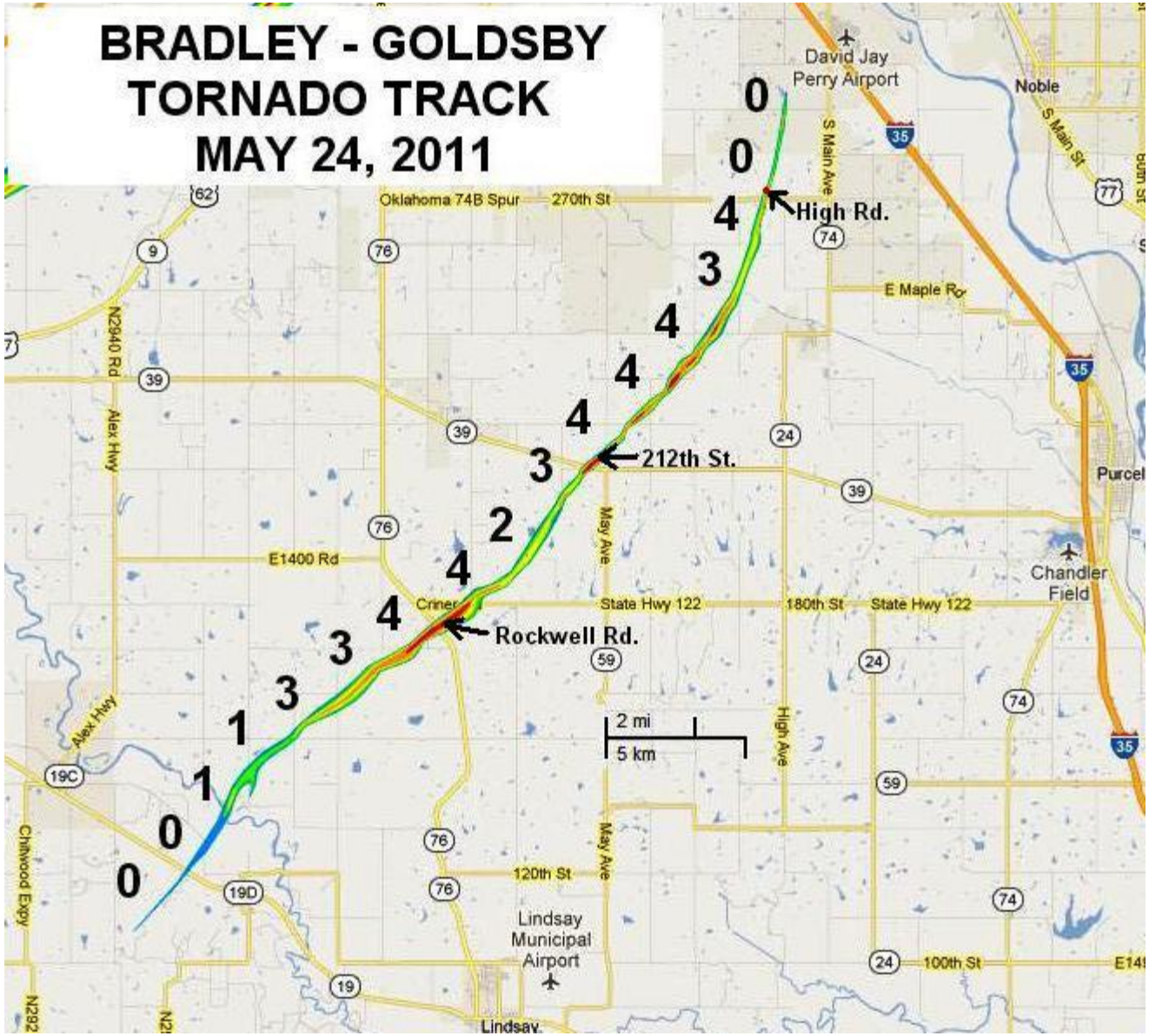
CHICKASHA - NEWCASTLE TORNADO TRACK MAY 24, 2011

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