GE Consumer & Industrial
Electrical Distribution

IBC-2003 Seismic Rating

What's Shakin'?

The IBC and IEEE seismic standards and the seismic qualification process

BACKGROUND

International Building Code 2003 (IBC-2003)

For the past several decades, three regional organizations promulgated model building codes for the United States: The Building Officials and Code Administrators International, Inc. (BOCA) wrote the National Building Code (NBC) for the Northeast US; the International Conference of Building Officials (ICBO) wrote the Uniform Building Code (UBC) for the Western US; the Southern Building Code Congress International (SBCCI) wrote the Standard Building Code for the Southeastern US. Each of these included a unique set of seismic requirements.

In 1994, these organizations formed the International Code Council (ICC) to develop a single set of model codes for the entire country. By 1999, the last versions of the NBC, UBC, and SBC were published; in 2000 the ICC released the first International Building Code (IBC), obsolescing the earlier three. The ICC releases revisions to the IBC every three years.

The 2003 version of the International Building Code applies to

> "the construction, alteration, movement, enlargement, replacement, repair, equipment, use and occupancy, location, maintenance, removal and demolition of every building or structure or any appurtenances connected or attached to such buildings or structures."

The following exceptions, however, are made:

> "Detached one- and two-family dwellings and multiple single-family dwellings (town houses) not more than three stories above grade plane in height with a separate means of egress and their accessory structures shall comply with the *International Residential Code.*" and
>
> "Existing buildings undergoing repair, alterations or additions and change of occupancy shall be permitted to comply with the *International Existing Building Code*."[1]

The IBC-2003 contains seismic design requirements for both buildings and electrical equipment installed therein. The standard incorporates, by reference, the design requirements of The American Society of Civil Engineers' (ASCE) *Minimum Design Loads for Buildings and Other Structures* standard, referred to as SEI/ASCE 7-02.

Though they contain comprehensive instructions for seismic design, the IBC and ASCE codes offer little guidance for seismic testing. To clarify the seismic qualification requirements of nonstructural (e.g. electrical) equipment in accordance with IBC-2003, the ICC Evaluation Service (ICC-ES) issued a clarifying instruction entitled *Acceptance Criteria for Seismic Qualification by Shake-Table Testing of Nonstructural Components and Systems* (ICC-ES-AC156) in July, 2004. GE's shake-table testing procedures incorporate the requirements set forth in this instruction.

Institute of Electrical and Electronics Engineers Standard 693-1997 (IEEE Std 693-1997)

The 1997 version of the Institute of Electrical and Electronics Engineers Standard 693 is applicable to power distribution utilities and commercial and industrial electrical equipment. It specifies seismic test procedures, shake test levels, and acceptance criteria. IEEE Std 693-1997 utilizes broad response spectra that inherently account for site-specific effects, such as soil type. Seismic design recommendations for substations, including qualification of each equipment type, are discussed.

Vibration Fundamentals

Understanding seismic engineering requires a basic knowledge of vibrations and oscillating systems. Figure 1 illustrates a simple oscillator composed of a flexible, cantilever beam with a mass on its end. Though highly simplified, this provides an apt representation of an electrical cabinet firmly mounted to the ground.

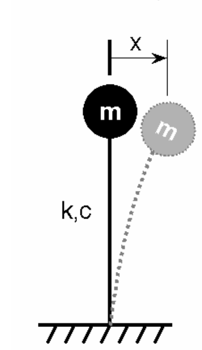

Figure 1

Assuming small, linear deflections, the displacement, velocity, and acceleration of the mass are sinusoidal and are dependent upon time and maximum displacement amplitude.

Resonance and Damping

After an initial impulse, a spring-mounted mass oscillates back and forth at its system resonance frequency, given by

$$\omega_n = (k / m)^{1/2}$$

where k is the spring constant and m is the mass. In theory, once the system begins oscillating, it continues infinitely. In real mechanical systems, however, the motion of the mass slows and eventually stops. This slowdown is due to damping, which dissipates some of the spring energy during each cycle. In the case of a cantilever beam, friction internal to the material and air resistance during motion are the primary sources of damping. In a building or electrical equipment

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[1] International Building Code, 2003 Edition

cabinet, damping also results from sliding material interfaces, such as bolted joints.

The level of damping in a spring-mass-damper system determines the amplitude of the oscillations over time. Time history plots of spring-mass-damper systems with various damping levels are shown in Figure 2. The amplitude of an oscillator without any damping does not decrease over time as an underdamped oscillator does. The masses in critically damped and overdamped systems do not oscillate back and forth. Instead, they return to their starting points at different amounts of time. The critical damping level, or c_c, of the system provides the fastest asymptotic approach to zero. The ratio of the actual system damping, c, to the critical damping is called the damping coefficient. After an initial impulse, buildings and electrical equipment cabinets settle back to their initial positions in different amounts of time based upon their damping ratios.

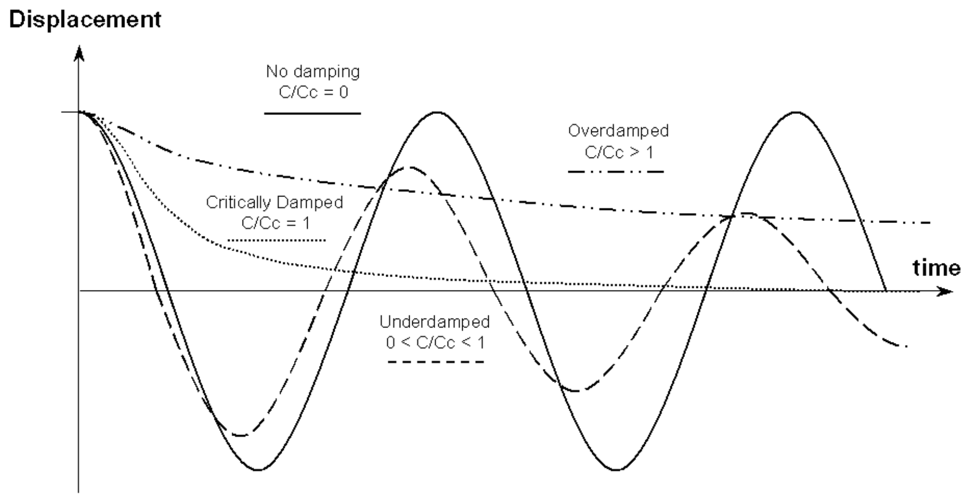

Figure 2

Forced Oscillation

When the base of a spring-mass-damper system is subject to a cyclical force or displacement, the behavior of the mass becomes more complex. This situation is referred to as forced oscillation, as opposed to the free oscillation previously described. The ratio between the motion of the base and center of mass is called the transmissibility, and it measures the structural amplification of the input motion. Transmissibility, as shown in Figure 3, changes based upon damping ratio and the ratio of the input and resonance frequencies.

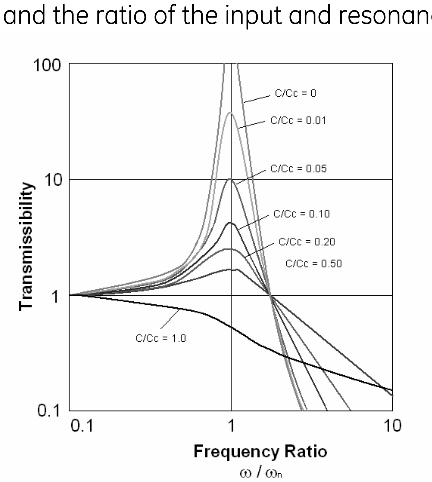

Figure 3

Every building and electrical equipment cabinet has at least one resonance frequency. When the input frequency, ω, is substantially less than the resonance frequency ω_n, the frequency ratio is less than one and the mass generally follows the motion of the base. When the input frequency is greater than the resonance frequency, the system attenuates the input, and the mass moves less than the base. A frequency ratio of one indicates that the base of the structure is being moved at its resonance frequency. In this situation, significant amplification results, as shown in Figure 3. Without damping, oscillation amplitude increases without bound. That significant amplification occurs at resonance frequencies indicates that structures are especially vulnerable to damage in certain frequency ranges.

TRS and RRS

Time History

A seismic event consists of an irregular time history of ground displacements, unlike the single-frequency oscillation shown in Figure 2. Figure 4 shows the acceleration time history of a typical shake-table test to which electrical equipment could be subjected. Such time histories contain frequency ranges and acceleration amplitudes analogous to those encountered in actual seismic events.

Time history plots provide the relationship between the shake-table acceleration and time. A frequency analysis of a time history, however, charts the more important relationship between acceleration and input frequency. Figure 5 is the frequency analysis, or test response spectrum, for the time history shown in Figure 4. During a seismic shake-table test, the table time history is measured and converted to a test response spectrum, or TRS, based upon an assumed damping ratio for the equipment.

Test Response Spectra (TRS)

Seismic test response spectra are not simply frequency transforms of the input time history. They are instead plots of the calculated center of gravity acceleration as a function of resonance frequency. In other words, the acceleration at a specific frequency in a response spectrum is that which the mass in an oscillator would undergo if that were its resonance frequency. For example, assume the simple oscillator of Figure 1 has a natural frequency of 4 Hz and a damping ratio of 5%. If that system were mounted to a shake-table with the time history response spectrum shown in Figure 5, the acceleration of the mass would be 5g. Since a response spectrum is a plot of acceleration versus resonance frequency, it is a concise method for expressing the damage potential of a given time history.

Required Response Spectra (RRS)

Figure 5 plots a TRS against a required response spectrum, or RRS. The RRS constitutes a requirement to be met by the shake-table time history, and thus by the test sample. Seismic standards provide RRS or the calculations required to construct them. The TRS generated by the shake-table must exceed, or envelope, the RRS to qualify a test sample to a specific qualification level.

Peak and ZPA

Seismic standards provide required response spectra parameters at various frequencies. A peak acceleration value is established over a range of lower frequencies where, historically, most seismic damage has been known to occur. Since most electrical equipment structures have resonance frequencies in this range, test samples typically amplify the table motion. Indeed, as Figure 4 indicates, the table experiences significantly lower accelerations than the TRS plots for the equipment center of mass. The RRS shown in Figure 5 has a peak of 3.2g between 1.1 Hz and 8.3 Hz. At the end of the peak range, the RRS slopes downward and plateaus at a zero period acceleration, or ZPA, value. Seismic ZPA values typically begin at 33 Hz. In this frequency range, most equipment attenuates the table motion.

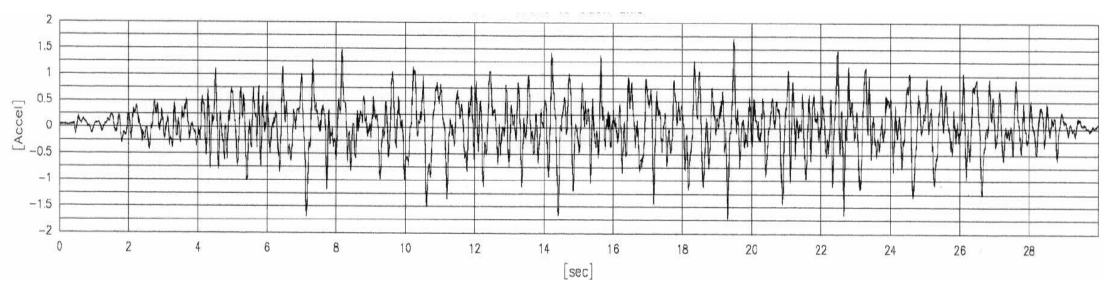

Figure 4

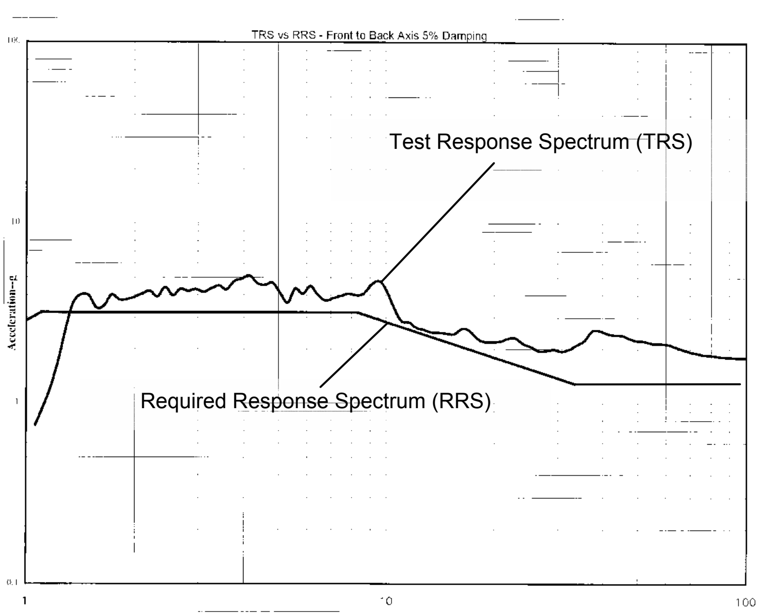

Figure 5

CODE REQUIREMENTS

IBC-2003

S_S

Despite its name, the International Building Code sets forth seismic requirements for the United States. In its pages, the code provides contour maps of the maximum considered earthquake ground motion for the entire country. The contour lines on these maps connect contiguous points of the same 0.2 second spectral response acceleration, or S_S. S_S values are assigned based upon geographic location, probability, and severity of seismic activity. S_S ranges from 0% to 300% and represents a percentage of gravitational acceleration.

S_{DS}

S_S does not address site-specific characteristics, such as differences in soil type, which can have an effect on the seismic response of a building. To address this, the code establishes a design spectral response acceleration, or S_{DS}, according to

$$S_{DS} = 2/3 * F_a * S_S$$

where F_a is an acceleration-based site coefficient with a maximum value of 1. Thus, S_{DS} ranges from 0g to 2g and, similarly to S_S, is a multiple of gravitational acceleration.

S_{DS} is the key input parameter for determining shake test levels. Customers also frequently specify S_{DS} as a requirement that electrical equipment must meet if it is to be suitable for a specific installation location.

z/h

The IBC accounts for the equipment mounting height above ground using a ratio of mounting height, z, to the total building height, h, as shown in Figure 6. The z/h ratio, for example, equals zero for ground-level equipment mounting and equals one for roof-level mounting. During a seismic event, the acceleration inside a building increases as a function of height above grade due to structural amplification. This means that equipment mounted at the top floor of a building will experience higher forces than similar equipment mounted at ground level.

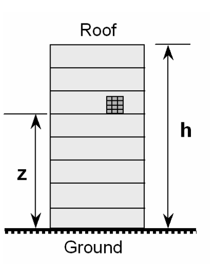

Figure 6

I_P

The IBC-2003 standard establishes an importance factor, I_P, to describe the nature and usage of the electrical equipment of interest. I_P is equal to 1.0 for non-critical electrical equipment. After a seismic event, such equipment does not need to function properly. However, the equipment must remain sufficiently intact so as not to pose a safety hazard due to collapse or the separation of major parts. For life-safety equipment, for equipment required for the continued operation of a facility, or for equipment containing hazardous substances, the I_P value increases to 1.5. This equipment must meet all the I_P=1.0 requirements and function properly during and after a seismic event.

RRS

In its discussion of seismic requirements, the IBC-2003 references SEI/ASCE 7-02. These two standards provide detailed instructions and formulas for the design of seismic structures. The force equations in these standards, however, are not used to specify required response spectra for shake-table testing. To clarify the seismic qualification requirements of nonstructural equipment in accordance with IBC-2003, the ICC Evaluation Service issued a clarifying instruction entitled *Acceptance Criteria for Seismic Qualification by Shake-Table Testing of Nonstructural Components and Systems* (ICC-ES-AC156) in July, 2004.

IBC shake-table required response spectra are functions of site S_{DS} level and installation z/h ratio. ICC-ES-AC156 details the calculation of the peak and ZPA levels and the frequencies that delineate them. The RRS peak acceleration level, or A_{FLX}, is given by

$$A_{FLX} = S_{DS} (1 + 2 z/h).$$

but is limited to a maximum of 1.6 times the S_{DS}.[2] The ZPA level of the RRS, or A_{RIG} is then given by

$$A_{RIG} = 0.4 S_{DS} (1 + 2 z/h)$$

The peak acceleration extends from 1.3Hz to 8.3Hz and decreases logarithmically to the ZPA at 33.3Hz.

The RRS described above is used for the two horizontal dimensions. The vertical RRS is two-thirds the amplitude of the horizontal RRS. All IBC-2003 RRS assume an equipment damping level of 5% of critical damping.

IEEE Std 693-1997

Levels and Amplification Multipliers

The IEEE standard prescribes Moderate and High RRS levels to which equipment is qualified. Like ICC-ES-AC156, the standard provides formulas for the RRS peak and ZPA values and specifies the frequency ranges for each. The 1997

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[2] ICC-ES-AC156 Section 6.5.1.2.1

version of the standard, however, does account for the effects of equipment mounting at heights other than ground level. To account for this, GE includes an amplification multiplier M in the peak and ZPA formulas provided in the IEEE Std 693-1997 standard. M ranges from 1.0 for ground level mounting to 2.5 for roof-level mounting.

RRS

The IEEE peak acceleration, or A_{FLX}, is calculated using

$A_{FLX} = 0.625\ B\ M$

for the Moderate level and

$A_{FLX} = 1.25\ B\ M$

for the High level

where $B = (3.21 - 0.68 \ln(D)) / 2.1156$.

The peak acceleration extends between 1.1Hz and 8.0Hz and decreases logarithmically to the ZPA at 33.3Hz.[3]

The RRS formulas above are used for the two horizontal dimensions. The vertical RRS is created by simply multiplying the peak and zero period acceleration values by 0.80. For consistency with IBC-2003, GE assumes an equipment damping level of 5% of critical damping.

GE Required Response Spectra

It is acceptable by both the IBC and IEEE standards to test at levels exceeding the specified RRS. GE defines RRS levels by selecting the highest accelerations and widest frequency ranges given in comparable IEEE and IBC spectra. This allows for simultaneous testing to both standards. Figure 7 shows three RRS to which GE equipment is tested that simultaneously satisfy both standards.

The lower RRS shown in Figure 7 is used to qualify equipment to the following levels:

- IBC-2003 S_{DS} = 1.0g, S_S = 150%
- IEEE Std 693-1997 Moderate with 2.5 multiplier
- IEEE Std 693-1997 High with 1.3 multiplier

The middle RRS shown in Figure 7 is used to qualify equipment to IBC-2003 S_{DS} = 1.33g, S_S = 200%.

The highest RRS shown in Figure 7 is used to qualify equipment to the following levels:

- IBC-2003 S_{DS} = 2.0g, S_S = 300%
- IEEE Std 693-1997 High with 2.5 multiplier

[3] IEEE Std 693-1997 Annex A

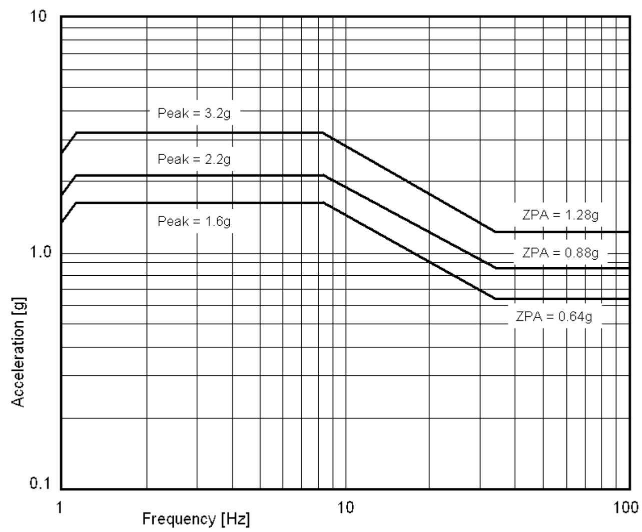

Figure 7

Structural Requirements

In addition to response spectra, seismic standards also specify structural and functional requirements that shake-table tested equipment must meet. The structural acceptance criteria, which apply to equipment after each shake-table test, are similar for both IBC and IEEE standards.

Both standards require the structural integrity of the equipment to be maintained throughout the test. Thus, test units may not pose an immediate safety hazard to personnel due to collapse or separation of major assemblies. Yielding or breakage of the equipment anchorage system, such as the mounting bolts, are not permitted. Insulation damage is also prohibited. Localized yielding or minor fractures of the structure are permitted to some extent, however, as long as their presence does not affect the function of the equipment. Structural requirements for IBC equipment with I_P values of 1.0 and 1.5 are generally the same.

Functional Requirements

The functional requirements of equipment under test differ slightly between the IBC and IEEE standards and significantly between the IBC I_P ratings. IBC equipment with an I_P value of 1.0 does not require functionality to be proven after a seismic shake test; meeting the structural acceptance criteria are sufficient for qualification.[4]

Equipment certified to IEEE Std 693-1997 must demonstrate functionality after an event.[5] The standard contains annexes for different types of electrical equipment that specify functional tests to be performed. IBC-2003 equipment with an I_P value of 1.5 must demonstrate functionality during and after the event.[6] Unlike the IEEE standard, however, neither the IBC nor the clarifying ICC-ES-

[4] ICC-ES-AC156 Section 6.7
[5] IEEE Std 693-1997 Section A.2.5
[6] SEI/ASCE 7-02 Section 9.1.3.1.2

AC156 provides specific tests to perform. Thus, experts in the product line and its technology make the selection of during- and post-test acceptance criteria and document them in a functional test plan. These criteria are based on product manufacturing test plans, corresponding IEEE criteria, and suspected seismic failure modes of the equipment.

There are several functional acceptance criteria that apply to most electrical equipment. To ensure the integrity of the electrical insulation, dielectric testing is performed according to factory specifications. Circuit breaker opening, closing, charging, and removal, as well as safety interlocking are also typically checked. When applicable, circuit breaker operation timing and calibration are checked to confirm the performance of the protective functions.

TEST PROCESS

1. Baseline

Shake-table testing begins with a baseline check of the structural and functional requirements of the equipment. This is typically done after the equipment has been mounted to the shake-table. The structure and mounting of the test sample is thoroughly inspected and photographed to ensure it represents properly manufactured, shipped, and installed equipment. The functionality of the sample and its subcomponents is then tested using the same procedure and acceptance criteria that are applied to the equipment after the shake test.

2. Instrumentation

After the baseline testing, the test sample is fitted with at least one triaxial accelerometer assembly. This is typically placed at an upper corner of the sample, as close as possible to a structural joint. This ensures that the accelerometer monitors the motion of the equipment structure and not extraneous vibrational modes. Other accelerometers are sometimes added to the equipment near the estimated center of gravity. Triaxial accelerometers on the shake-table, not those mounted on the test sample, are used to calculate the test response spectra.

3. Resonance Frequency Search

After initial testing and instrumentation, uniaxial resonance frequency searches are performed on the test sample in each of the three dimensions. The resonance frequencies of a structure can help predict its behavior, and they are important for the interpretation of the test response spectra after the shake test. Each search consists of a low-level time history shake test in which the table and equipment accelerometer responses are compared. The response of the test sample is significantly greater than that of the table at the resonance frequencies. Either a white noise or frequency sweep time history may be used to drive the table motion during a resonance frequency search.

4. Time History Shake-table Test

After the resonance frequencies are identified, three independent time histories are used to simultaneously drive each axis of the shake-table. The entire triaxial shake test lasts approximately thirty seconds. Data sampled from the three table accelerometers are converted from the time domain to the frequency domain, and a test response spectrum is created. The TRS from each dimension must envelope the required response spectra of the seismic level to which qualification is sought. Figure 5 shows an example of a TRS and RRS overlay.

During the shake-table test, devices are usually monitored or actuated to prove their functionality. For example, circuit breaker primary and auxiliary contacts are monitored electronically for state changes. Several circuit breakers may also be tripped to validate the operability of the tripping mechanisms. Since the test lasts only thirty seconds, however, it is impractical to test every function of a complex piece of equipment.

5. Structural and Functional Testing

After the shake test, the structure of the test sample is inspected and the unit is functionally tested to ensure the acceptance criteria are met. If the test sample meets these requirements, the equipment is considered to have passed the test level. If there are higher levels to which qualification is desired, another test sequence may be performed.

TEST SAMPLES

Since it is impractical to test every configuration of a particular product line, representative test samples are carefully chosen to qualify a broad range of product constructions. Worst-case test samples are selected based on several criteria, including overall weight, height to width ratio, mounting type and geometry, and subcomponent content. Where possible, several different worst-case product configurations are tested.

The following is a listing of product lines, test sample quantities, and test dates for the seismic qualification of GE equipment:

A-Series™ Lighting Panels
12 samples; Wyle Laboratories: Nov 2005

AKD-10™ Low Voltage Switchgear
2 samples; Wyle Laboratories: Nov 2005

BreakMaster™ Load Interrupter Switches
1 sample; Clark Dynamic Testing Labs: Oct 2000

Entellisys™ Low Voltage Switchgear
2 samples; Clark Dynamic Testing Labs:
Sept 2005 & Jan 2006

Evolution™ Low Voltage Motor Control Centers
2 samples; Wyle Laboratories: Nov 2005

IP, QB, QL, QMS, and TransforMore™, Low Voltage Transformers
7 samples; Clark Dynamic Testing Labs:
Dec 2005, Jan 2006, Mar 2006

LimitAmp™ Medium Voltage Motor Control Centers
7 samples; Wyle Laboratories: Aug 1997, Dec 2002;
Clark Dynamic Testing Labs: Jan 2006

PowerBreak II™ Switchboards
1 sample; Clark Dynamic Testing Labs:
May 2006

PowerVac™ Medium Voltage Distribution Breakers
3 samples; Clark Dynamic Testing Labs:
Jan & Mar 2006

PowerVac™ Medium Voltage Switchgear
2 samples; Wyle Laboratories: Nov 2005

Spectra™ Series Busway
2 samples; Wyle Laboratories: Aug 1992

Spectra™ Series Power Panels
4 samples; Wyle Laboratories: May 1998

Spectra™ & Jiffy™ Series Switchboards
7 samples; Wyle Laboratories; May 1998, July 1998,
Mar 2001

CERTIFICATION

The IBC-2003 and IEEE Std 693-1997 are standards to which equipment manufacturers self-certify through test or analysis. GE has taken a number of measures to ensure objective adherence to industry-accepted practices during its seismic qualification program. An independent seismic consultant who was a Registered Professional Engineer in the State of California reviewed all equipment sample selections, acceptance criteria, and test plans. Third party test laboratories performed all seismic testing and documentation thereof. After testing, the seismic consultant performed the requisite results and data review, analysis, and interpretation with respect to the IEEE and IBC standards. A seismic certification report for each product line documents test sample details, test results and interpretation, and the maximum levels to which equipment is qualified.

At the onset of GE's seismic certification program, the IEEE, IBC, and ASCE standards described were the most recently published. However, each code agency has since released an updated edition. There are very few differences in the new editions that impact seismic testing and certification as described herein.

Adoption of the International Building Code throughout the United States is increasing as the UBC, NBC, and SBC are being phased out. Furthermore, it is anticipated that the California Building Code (CBC) will incorporate the seismic requirements of the IBC in the next few years.

REFERENCES

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