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Contents

PERFORMANCE-BASED BUILDING REGULATORY SYSTEMS: STRUCTURE, HIERARCHY AND LINKAGES

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ABSTRACT

Performance-based building regulatory systems are in use or under development in numerous counties worldwide. Within each of these regulatory systems there exists a structure, which includes enabling legislation, a regulatory instrument (regulation or code), and various types of supporting infrastructure, which combine to provide a system aimed at producing buildings that meet societal expectations in terms of safety, health and welfare. However, the structure is not always explicit, and in some cases may be incomplete. This is important, as, in order for the regulatory system to function as intended, the interdependencies between the various components must be understood. Otherwise, there may exist significant gaps in the regulatory system that could inadvertently lead to an incomplete understanding of the performance of a building. This paper explores the issue of performance regulatory system structure and the linkages that are needed to assure that pertinent interdependencies are addressed.

Keywords: *Performance-based; building regulation; regulatory structure; building design; performance levels; criteria; risk.*

1.0 INTRODUCTION

For performance-based regulations and design methods to be effective, there must be a logical and transparent relationship between top level societal and policy level goals, and the bottom level specification solutions, or performance verification methods. Until now, many performance-based building regulations have followed the five-tiered hierarchy first suggested by the Nordic Committee on Building Regulations in 1976 (NKB, 1976; NKB, 1978). In recent years, however, it has become apparent that more detail is required to describe the levels of performance (or risk) that a category of buildings is intended to achieve over a wide range of hazard events, and to better describe the criteria or measures against which successful performance will be evaluated (e.g., Traw, 1999; Meacham, 1999). As a result, an eight-tiered performance-based hierarchy has been developed by the author, in collaboration with the members of the Inter-jurisdictional Regulatory Collaboration Committee (www.ircc.gov.au).

The fundamental difference between the IRCC performance hierarchy and the NKB hierarchy is the inclusion of tiers for *performance or risk group*, *performance or risk level*, and *performance or risk criteria* (measures) within the IRCC model. These tiers were added to the hierarchy to illustrate how factors such as levels of tolerable building performance or risk, and importance of a building category to the community, are reflected in goals, functional requirements, and operative (performance) requirements. With these added tiers, the IRCC hierarchy is also better able to illustrate how test methods and standards, evaluation methods, design guides, and other verification methods can be used to demonstrate compliance. It should be noted that eight tiers are used in part to introduce and discuss concepts important to a performance-based regulatory system. In practice, there may be more or less than eight tiers in a regulatory system, depending on local or national needs, legal structure or other such influences.

2.0 THE EIGHT-TIERED HIERARCHY

2.1 General

The hierarchy can be viewed as "top-down" or "bottom-up," meaning that one can go from an overarching goal to the specific requirements necessary to achieve that goal (top-down), or start with a specific requirement and understand the goal(s) it supports. For the purpose of this discussion, the top-down approach will be followed.

Societal and policy level goals, and to some extent each of the lower levels, embody value statements regarding acceptable performance of buildings in terms of health, safety, welfare, amenity, mission and/or other goals for buildings of various uses. This means that acceptable performance (and acceptable risk) should not necessarily be driven solely by the current state of scientific and engineering knowledge, but also by what

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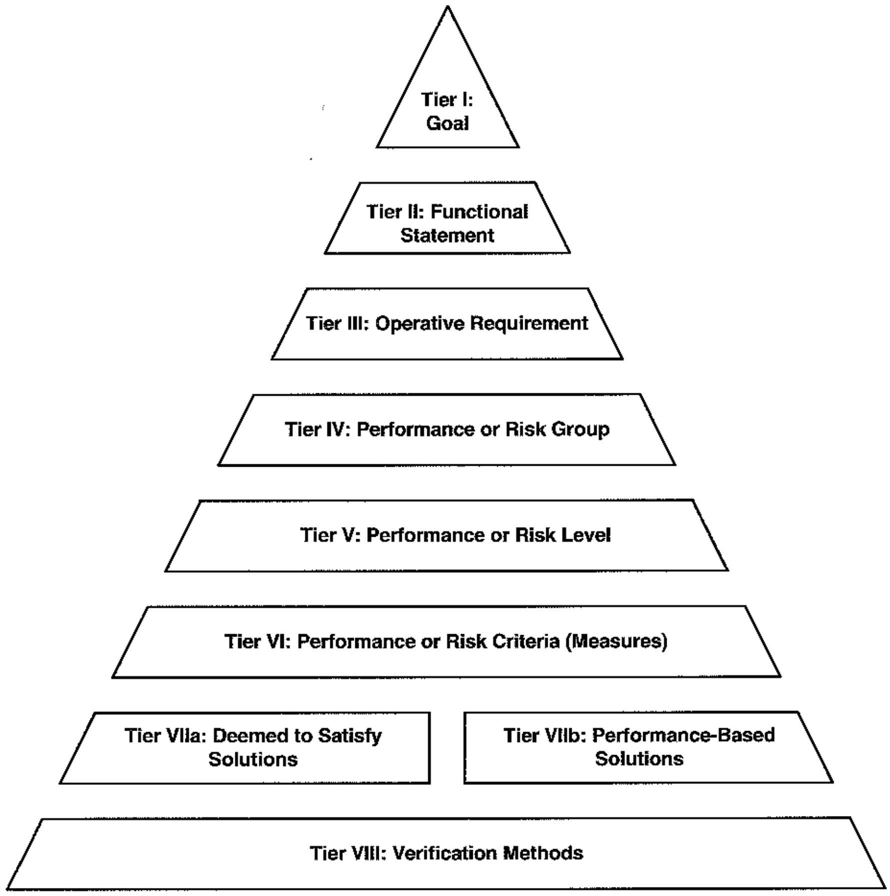

Figure 1. Eight-Tiered IRCC Performance-Based Building Code Hierarchy

society deems to be acceptable or tolerable. In the case of government occupancies, goals may also be driven by such factors as terrorism mitigation and national security, which may result in higher levels of required performance for specific structures or for certain categories of structures.

Once goals for acceptable (tolerable) levels of performance and risk have been established, and related functional and operative requirements have been developed, scientists and engineers can translate these goals and functional and operative requirements into criteria for design and design assessment. This translation occurs predominantly between Tiers III and VIII: Operative (Performance) Requirements and Verification Methods. A common structure in existing building regulations is to have all general goals in a single section, functional and operational requirements grouped together by building system, such as Structural, Mechanical, Electrical, Fire Protection, Egress, and so forth. However, a potential drawback of this approach is that it treats each building system in isolation, instead of as part of an overall building performance.

As part of establishing goals and functional and operative requirements, it is helpful to consider whether and how different classes of buildings may be expected to perform under a variety of normal and emergency conditions (thus resulting in categorization into different performance groups with differing performance levels). Once the categorization is complete, *and* a building or a building element can be described in terms of how it performs under normal and emergency conditions with respect to appropriate load effects, *and* methods are available to evaluate and to verify this performance, a design solution that complies with the regulation can be engineered.

2.2 Tier I: Establishing Goals

The top tier of the hierarchy is policy level (societal) goals. In general, goals should reflect the essential interests of the community at large, as well as those of specific stakeholders, with regard to the built environment. Goals for general building codes are often limited to health, safety, welfare, amenity, and accessibility, and in some cases include property protection, affordability and durability. For some occupancies, such as hospitals, utilities and other such critical infrastructure, additional goals may be needed, such as mission continuity. To be most effective, goals should reflect the values of society and the affected stakeholders, should be stated using clear, unambiguous and easily comprehensible language, and should not be described in terms of technical requirements. Policy level goals are typically most appropriate when established by governmental (or quasi-governmental) bodies that have knowledge of building construction and regulatory issues, and have responsibility for the health and safety of those in the regulated buildings. In many regulatory systems, policy level goals will ultimately become part of the law(s) or act(s) regulating buildings.

Establishment of goals should consider the above factors, as well as any facility-specific factors. For government occupancies, such additional factors include symbolic importance, criticality, consequence and threats, and these factors may change in relative importance based on the location and use of the facility, as well as its proximity to other facilities with similar concerns.

In general, a section on policy level goals might include statements such as the following (as adapted with modifications from ICC, 2001):

- The purpose of this Code is to provide appropriate levels of health, safety, welfare, and social and economic value, while promoting innovative, flexible and responsive solutions that optimize the expenditure and consumption of resources.
- The primary goals for facilities constructed using this Code are to provide acceptable levels of health, safety and welfare, and to limit damage resulting from events that are reasonably expected to impact on buildings and structures. Accordingly, this Code intends that facilities constructed using these guidelines provide for:

    1. An environment free of unreasonable risk of death and injury from natural and technological hazard events.
    2. A structure that will reasonably withstand those loads that can be expected to impact on the facility throughout its intended lifetime.
    3. Means of egress and access for normal and emergency circumstances.
    4. Limits to the unreasonable spread of fire, products of combustion, and airborne contaminants both within the building and to adjacent properties.
    5. Ventilation and sanitation facilities to maintain a reasonably healthy environment for the occupants.
    6. Natural light, heating, cooking and other amenities necessary for the well-being of the occupants.
    7. Efficient use of energy.

Such goal statements clearly identify aims for health, safety and welfare, as well as other policy-level goals that a government may deem appropriate for building regulation. Once such a set of clear, unambiguous and easily comprehensible goal statements has been developed, more detailed functional and operative (performance) statements can then be established.

2.3 Tier II: Establishing Functional Statements

For each policy level goal, functional statements provide qualitative requirements for buildings or specific building elements (features) that describe how the goal can be met. To meet the goal for "acceptable level of safety," functional statements might reflect such individual factors as fire safety and structural stability.

Functional statements provide more specific guidance than the general goal statement, and should contain or reference an appropriate measure (qualitative or quantitative) of the level(s) of performance and/or risk tolerable/acceptable to the community (agency/stakeholders). This may be done, for example, by inclusion of specific criteria (Tier VI), by reference to "deemed to satisfy" solutions (Tier VIIa), or by reference to criteria and methods/standards developed by others (Tiers VIIb and VIII). As noted above, eight tiers are used in this paper to introduce and discuss concepts important to a performance-based regulatory system. In practice, there may be more or less than eight tiers in a regulatory system, depending on local or national needs, legal structure or other such influences.

Establishment of tolerable/acceptable performance and/or risk levels can be difficult, and will likely result from a policy decision that is informed by a variety of input, including from elected or appointed government officials; building and fire officials; architects and engineers; owners and tenants; and the public (consumers). Further discussion of the relationship of functional statements to risk and performance levels, and to associated criteria, can be found in discussion on Tiers V and VI.

To illustrate how functional statements might be developed, consider the following goal statement, as previously suggested:

- The primary goals for facilities constructed using this Code are to provide acceptable levels of health, safety and welfare, and to limit damage resulting from events that are reasonably expected to impact on buildings and structures.

This goal statement speaks to the issues of health, safety and welfare, but gives no specific guidance as to functional expectations related to these goals. Associated functional statements are therefore needed, and might be as simple as the following:

- <u>Life safety and injury prevention</u>: Structures shall be designed and constructed so as to minimize injury to occupants due to events expected to impact on the building over its intended life, and as appropriate to the associated design performance level, considering the facility's use, occupancy, construction, geographic location, symbolic importance, and criticality to the community.

- Property and amenity protection: Structures shall be designed and constructed so as to minimize damage to property and loss of amenities due to events expected to impact on the building over its intended life, and as appropriate to the associated design performance level, considering the facility's use, occupancy, construction, geographic location, symbolic importance, and criticality to the community.

Although there is still little detail, connections are being made hierarchically downward, drawing into the structure the concepts of risk assessments, performance levels, and other considerations. Not yet addressed are the loads. There are various loads that can be expected to impact on all facilities, including live and dead loads associated with construction materials, contents and people, and loads associated with natural and technological hazards, such as earthquakes, hurricanes, flooding, fire and explosion. For each load that is identified, specific performance requirements may be needed (in some cases, one performance requirement can be applicable to more than one load).

2.4 Tier III: Establishing Operative (Performance) Requirements

Operative (performance) requirements provide actual requirements in terms of performance criteria or expanded functional descriptions. As with the above discussion of functional statements, operative requirements also require some reference to the levels of acceptable/tolerable performance and/or risk. As noted above, there is considerable flexibility in how this is accomplished. Some operative requirements may simply be detailed qualitative statements, while others might include quantitative performance criteria. In some cases, the choice is dependent upon the level of flexibility desired, while in other cases, limitations on applicable solutions may be the driver.

Following are examples of operative requirements:

- Stability. Structures, or portions thereof, shall remain stable and not collapse during construction or alteration and throughout their lives.

- Disproportionate failure: Structures shall be designed to sustain local damage, and the structural system as a whole shall remain stable and not be damaged to an extent disproportionate to the original local damage.

- Progressive failure: Structures shall be designed to prevent progressive collapse due to the loss of one primary column, or it shall be acceptably demonstrable that the proposed design precludes such a failure.

- Exterior walls: Exterior walls shall be designed to resist the actual pressures and impulses acting on the exterior wall surfaces from the impacts defined for the facility. Exterior walls shall be capable of withstanding the dynamic reactions from the windows.

- Loss of amenity: Structures, or portions thereof, shall have a low probability of causing loss of amenity through excessive deformation, vibration or degradation during construction or alteration and throughout their lives.

The following examples illustrate how performance criteria may be integrated into the operative requirements. These examples illustrate both risk-based (frequency-based) and deterministic criteria.

- Expected loads: Structures, or portions thereof, shall be designed and constructed taking into account all expected loads, and combination of loads, associated with the events and associated magnitudes that would affect their performance, including, but not limited to:

  1. Dead loads

  2. Live loads

  3. Impact loads

  4. Soil and hydrostatic pressure loads

  5. Flood loads (mean return period)
     Small: 100 years
     Medium: 500 years
     Large: (Floods of greater mean return periods shall be determined on a site specific basis)
     Very Large: (Floods of greater mean return periods shall be determined on a site specific basis)

  6. Wind loads (mean return period)
     Small: 50 years
     Medium: 75 years
     Large: 100 years
     Very Large: 125 years

  7. Wind-borne debris loads

  8. Snow loads (mean return period)
     Small: 25 years
     Medium: 30 years
     Large: 50 years
     Very Large: 100 years

9. Earthquake loads (mean return period)
   Small: 25 years
   Medium: 72 years
   Large: 475 years (Need not exceed 2/3 of the intensity of Very Large loads)
   Very Large: 2,475 years (At sites where the 2,475 year, 5 percent damped spectral response acceleration at a period of 0.3 second period exceeds 1.5 g and at 1 second period exceeds 0.6 g, Very Large ground shaking demands need not exceed a 5 percent damped response spectrum that at each period, is 150 percent of the median spectral response acceleration ordinate resulting from a characteristic earthquake on any known active fault in the region.)

A caution when incorporating performance criteria into operative requirements: *all steps should be taken to ensure uniformity of metrics for like components, and appropriateness of multiple criteria in relation to a complete design.* Likewise, clear and unambiguous guidance is needed with respect to risk acceptance/tolerance levels and building performance. Unless appropriate guidance is provided, either in the regulations/ guidelines or in referenced documents, vastly different solutions may be proposed and accepted, some of which may be less than desirable. For example, for the above criteria to be meaningful, low, medium and higher risk, and low, medium and higher level performance need to be clearly defined. Furthermore, the assessment and quantification of risk for the same facility needs to be reproducible by different parties, and the estimation, calculation or measurement of performance needs to be reproducible from one engineer to another. If this is not done, vastly different levels of risk and performance could result.

Reference to risk characteristics, tolerance levels, and/or specific performance criteria are also needed for manufacturers and testing laboratories. Without this information, it will be difficult for manufacturers to know if their products will be suitable for a specific use until late in the design process (e.g., if not cross-tested, a window treatment may adequately resist a target hurricane atmospheric pressure, but may restrict fire-fighter access in a fire emergency). This argues for a clear understanding of all performance measures, and a clear connection between the regulation-defined acceptable level of performance and the tools and methods required to verify performance (e.g., test methods, models, standards).

Likewise, although performance (acceptance) criteria may be provided, there may still be issues such as the actual hazard that will impact on the building (compared with a laboratory test or engineering analysis), and how closely the scenarios used to estimate the threats and vulnerabilities approximate reality. Although criteria embodied in operative requirements may provide manufacturers and testing facilities more guidance than if no criteria are provided in the regulation, care needs to be taken that the criteria are appropriate for the level of safety or risk desired. If not appropriate, a product that complies with appropriate verification methods could be selected, yet the overall performance could be less than desired, because the verification methods are not tied to the levels of risk and performance contemplated by the regulation.

To address the above concerns, there needs to be a clear connection between Tiers I-III and Tier VIII; verification methods must be clearly tied to goals, functional statements and operative requirements. This is required whether the operative requirements are in the form of detailed functional statements or include performance criteria. Furthermore, this connection must reflect the tolerable levels of performance and/ or risk. Tiers IV-VII help to address the required connection, providing reference to the tie between hazards, risk factors, levels of tolerable risk, levels of tolerable performance and the criteria used to assess compliance.

A representation of these linkages is provided later in this document in Figure 4.

2.5 Tier IV: Performance or Risk Groups

In concept, a Performance Group is a set of building use groups or occupancy types for which similar performance is desired or required. Likewise, a Risk Group is a set of building use groups or occupancy types for which similar levels of risk exist. The primary intent of establishing such groupings is to simplify a performance-based regulation or guideline. If a specific jurisdiction chooses not to group buildings or facilities for ease of use, Performance Groups are not required, and performance requirements and criteria can be defined on an individual building-use category basis.

As described here, performance groups are composed of buildings and structures for which a similar level of importance, *performance, and/or risk tolerable to society has been identified, given such factors as expected* loads associated with normal use and natural and technological hazards likely to impact on the building or structure.[1] For example, small, unoccupied low-hazard storage buildings, and remote, non-essential transformer substations, which generally do not have a high level of symbolic importance, criticality, consequence or threats associated with them, can be grouped together for the purpose of describing desired performance. Likewise, facilities where large groups of people may work or can assemble, where sensitive work is undertaken, where critical equipment resides, or where the facility may have significant symbolic importance, criticality, consequence or threat importance can be grouped. Because these two groups of facilities have different performance expectations, they would form different Performance Groups (or Risk Groups).

Although there are no strict rules for determining the number of performance or risk groups that are needed for any given

[1] *Performance groups may also be defined based on goals such as amenity and accessibility, but in many cases, the performance requirements for these goals will be more building-use specific and not as easily grouped.*

regulatory system, there should at least be a sufficient number of groups to provide distinguishable differences in desired performance or assessed risk. In the ICC Performance Code for Buildings and Facilities, four performance groups are used (ICC, 2001; 2003). Establishment of these performance groups was accomplished through consideration of building uses, building risk factors, and the importance of specific structures to a community (Meacham, 2000).

2.6 Tier V: Performance or Risk Levels

In concept, a Performance Level (or Risk Level) should describe the desired, required, and/or expected performance of a building or structure in terms of a specified measure of performance (or risk). For example, when describing Performance Levels for safety, the definition may describe the required performance of a building or facility when subjected to a particular magnitude of event that has been designated within a regulation or guide for design purposes. In such a case, the Performance Levels may be described by defining a set of maximum tolerable impacts (design performance levels) or a set of tolerable risk levels for a set of specified design loads. When describing Performance Levels for amenity and/or health, the definition may refer to whether the building is occupied or unoccupied and to the characteristics of the people expected to occupy the building.

As with establishing performance groups, there are no hard-and-fast rules for the number of performance levels that are required, other than providing a sufficient number of levels to provide distinguishable differences in desired performance.

For the *ICC Performance Code for Buildings and Facilities* (ICC, 2001; 2003), Performance Levels are defined strictly in terms of safety, for which there are four design performance levels defined in terms of tolerable limits of impact to the structure, its contents, and its occupants. As the intent is to describe performance in terms of variables that can be measured or calculated, the tolerable limits of impact reflect various limit states of damage, injury, or loss.

Establishment of these levels requires a balance of technical knowledge and ability and societal values. The term tolerable is used to reflect the fact that absolute protection is not possible, and that some damage, injury, or loss is currently tolerated in structures, especially after a hazard event. The term impact is used as a broad descriptor of loss. The four design performance levels are provided to bound the expected performance when subjected to various design loads, and are described as Mild, Moderate, High, and Severe Impact (ICC, 2001; 2003).

Mild Impact. The tolerable impacts of the design loads are assumed as follows:

- <u>Structural damage</u>. There is no structural damage and the building or facility is safe to occupy.
- <u>Nonstructural systems</u>. Nonstructural systems needed for normal building or facility use and emergency operations are fully operational.
- <u>Occupant hazards</u>. Injuries to building or facility occupants are minimal in numbers and minor in nature. There is a very low likelihood of single- or multiple life loss.[2]
- <u>Overall extent of damage</u>. Damage to building or facility contents is minimal in extent and minor in cost.[2]
- <u>Hazardous materials</u>. Minimal hazardous materials are released to the environment.

Moderate Impact. The tolerable impacts of the design loads are assumed as follows:

- <u>Structural damage</u>. There is moderate structural damage, which is repairable; some delay in re-occupancy can be expected.
- <u>Nonstructural systems</u>. Nonstructural systems needed for normal building or facility use are fully operational, although some cleanup and repair may be needed. Emergency systems remain fully operational.
- <u>Occupant hazards</u>. Injuries to building or facility occupants may be locally significant, but generally moderate in numbers and in nature. There is a low likelihood of single life loss, very low likelihood of multiple life loss.[2]
- <u>Overall extent of damage</u>. Damage to building or facility contents may be locally significant, but is generally moderate in extent and cost.[2]
- <u>Hazardous materials</u>. Some hazardous materials are released to the environment, but the risk to the community is minimal. No emergency relocation is necessary.

High Impact. The tolerable impacts of the design loads are assumed as follows:

- <u>Structural damage</u>. There is significant damage to structural elements but no large falling debris; repair is possible. Significant delays in re-occupancy can be expected.
- <u>Nonstructural systems</u>. Nonstructural systems needed for normal building or facility use are significantly damaged and inoperable; egress routes may be impaired by light debris; emergency systems may be significantly damaged, but remain operational.

[2] *Applies only to hazard-related applied loads. The nature of the applied load (i.e., fire hazard) may result in higher levels of expected injuries and damage in localized areas, whereas the balance of the areas may sustain fewer injuries and less damage.*

The types of prescriptive codes and standards that may be 'approved documents' for developing deemed to satisfy solutions can include installation standards, prescriptive design standards (guidelines, codes of practice), and prescriptive codes (i.e., building, fire, plumbing, electrical, and mechanical).

Most performance-based regulations allow for a mix of prescriptive- and performance-based solutions to be applied. This is necessary for several reasons, including: performance-based solutions are not always needed for the entire building, but often only for specific components; prescriptive solutions can be easier to apply; and the combination of prescriptive and performance solutions can provide optimal flexibility and cost effectiveness.

2.9 Tier VIIb: Performance-Based Solutions

Performance-based solutions are those solutions that are demonstrated to meet the performance (operative) requirements and associated performance criteria, typically by employing performance-based analysis and design standards, guidelines, or practices generally accepted in their associated professional discipline. In the broadest sense, performance-based analysis and design is a process of engineering a solution to meet specific levels of performance, where performance may be stated in terms of qualitative or quantitative objectives, criteria, or limiting states of damage or injury (Meacham, 1998). In structural engineering, for example, performance levels are often defined in terms of specific limiting damage states against which a structure's performance can be objectively measured (Hamburger *et al.*, 1995). This concept has been adopted by the fire safety engineering community, where performance-based fire safety design has been defined as (Custer and Meacham, 1997):

> *"an engineering approach to fire protection design based on (1) agreed upon fire safety goals, loss objectives, and design objectives; (2) deterministic and probabilistic evaluation of fire initiation, growth, and development; (3) the physical and chemical properties of fire and fire effluents; and (4) quantitative assessment of the effectiveness of design alternatives against loss objectives and performance objectives."*

Although this definition is not universal, research conducted into the evolution of performance-based codes and performance-based fire safety analysis and design methods determined that the concepts are entrenched in more than a dozen performance-based fire safety analysis and design approaches under development or in use around the world (Meacham, 1998a). Furthermore, many of these approaches contain seven interrelated steps of the following form (Meacham, 1998):

1. Identification of site or project information,

2. Identification of goals and objectives,

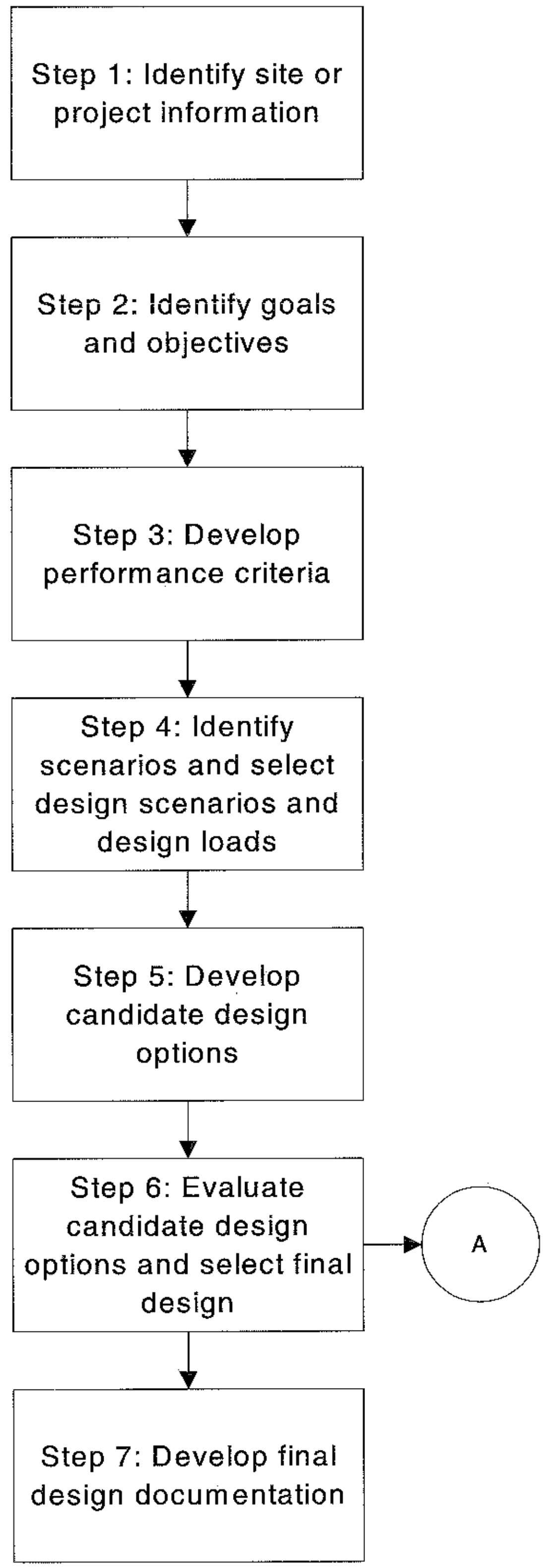

Figure 2. Seven Steps in a Performance-Based Analysis and Design Process

Table 1. Maximum Level of Damage to be Tolerated based on Performance Groups and Design Event Magnitudes

MAGNITUDE OF DESIGN EVENT	Performance Group I	Performance Group II	Performance Group III	Performance Group IV
	INCREASING LEVEL OF PERFORMANCE →→→→→→→→→→→→→→→→ PERFORMANCE GROUPS			
VERY LARGE (Very Rare)	SEVERE	SEVERE	HIGH	MODERATE
LARGE (Rare)	SEVERE	HIGH	MODERATE	MILD
MEDIUM (Less Frequent)	HIGH	MODERATE	MILD	MILD
SMALL (Frequent)	MODERATE	MILD	MILD	MILD

In general, design loads may be defined, quantified, and expressed deterministically or probabilistically. They may be point values with confidence limits or safety factors, or distributions. How these loads are expressed may also vary by type. For example, a current approach to earthquake loads involves a probability of exceedence in a defined time period (SEAOC, 1998). A very rare earthquake, or "very large" design load earthquake, would be a very large magnitude event. This is a probabilistic approach. For design against snow, however, the design load may be expressed in terms of a ground snow load, based on historical data, modified by exposure and importance factors. This is a deterministic approach.

Definition of design loads is also dependent on the measurement of performance. In the current ICC approach, performance is expressed in terms of tolerable impacts (consequences) on structures, occupants, and contents (ICC, 2001; 2003). Thus, a "mild" fire impact to contents of an office may be different than a "mild" impact in a clean-room. As a result, a "small" design load fire for an office may be different than a "small" design load fire for a clean-room. Limitations on the extent of impacts are provided through *performance levels* to which the structure must conform when subjected to design loads of various magnitudes.

Once the trinity of Performance/Risk Groups (Tier IV), Performance Levels (Tier V), and Design Loads/Design Event Magnitudes has been developed and agreed, they can be visualized in tabular form. This provides designers, authorities and stakeholders with a simple visual representation of how the proposed facility is categorized, what magnitudes of threats are anticipated, and how the building is expected to perform. This relationship is illustrated in Table 1, as can be found in the *International Performance Code for Buildings and Facilities* (ICC, 2001).

2.8 Tier VIIa: Deemed to Satisfy Solutions

One way to demonstrate compliance with a performance-based regulation is through strict application of prescriptive codes and standards (sometimes called 'approved documents' or 'approved methods') that have been 'deemed to satisfy' the goals, functional statements, and operative (performance) requirements of the regulation. Deemed to satisfy solutions may be used for technical, political, and/or practical reasons (e.g., ease of use and enforcement).

In many cases, deemed to satisfy solutions are derived from the prescriptive requirements in place before a performance-based code was introduced. Although taking this approach provides some performance criteria and a built-in 'comfort level,' there is the chance that the prescriptive requirements (and associated criteria) do not, in fact, comply with the goals, functional statements, and/or performance objectives of the performance-based code. In some cases, this may be due to new requirements in the performance-based code. In other cases, it may be a result of unavailable or incompatible metrics for assessing performance. (This is where the linkage between goals, functional statements, performance objectives, and criteria are essential.)

- Occupant hazards. Injuries to building or facility occupants may be locally significant with a high risk to life, but are generally moderate in numbers and nature. There is a moderate likelihood of single life loss, with a low probability of multiple life loss.[2]

- Overall extent of damage. Damage to building or facility contents may be locally total and generally significant.[2]

- Hazardous materials. Hazardous materials are released to the environment with localized relocation needed for buildings and facilities in the immediate vicinity.

Severe Impact. The tolerable impacts of the design loads are assumed as follows:

- Structural damage. There is substantial structural damage, but all significant components continue to carry gravity load demands. Repair may not be technically possible. The building or facility is not safe for re–occupancy, as re–occupancy could cause collapse.

- Nonstructural systems. Nonstructural systems for normal building or facility use may be completely nonfunctional. Egress routes may be impaired; emergency systems may be substantially damaged and nonfunctional.

- Occupant hazards. Injuries to building or facility occupants may be high in numbers and significant in nature. Significant risk to life may exist. There is a high likelihood of single life loss and a moderate likelihood of multiple life loss.[2]

- Overall extent of damage. Damage to building or facility contents may be total.[2]

- Hazardous materials. Significant hazardous materials are released to the environment, with relocation needed beyond the immediate vicinity.

2.7 Tier VI: Performance/Risk Criteria

Performance Criteria (or Risk Criteria) are the metrics against which performance should be measured, calculated, predicted, evaluated, and/or assessed to demonstrate compliance with goals, functional objectives, and performance (operative) requirements. Although these criteria do not have to reside in the performance-based code, they must, as discussed under Tier III above, be an integral part of a performance-based system.

From the perspective of the goals Safety and Health, prescriptive building codes deal with structural loads, natural hazards, and technological hazards (e.g., fire, explosion, contamination, infection and other safety and health hazards). As long as these hazards are protected against to some tolerable level of performance or risk, and no other goals and objectives are violated, the intent of the codes will be met. In a prescriptive building code, the criteria against which tolerable levels of performance or risk are measured are stated in a variety of forms, from applied loads, to air changes per hour, to maximum travel distances. Unfortunately, the prescribed criteria often reflect outcomes of idealized formulae or standardized tests, and may not reflect actual performance under load, especially during a hazard event.

In a performance-based regulatory system, there must be ways to define, assess, design and evaluate the desired/expected performance of building components, systems and assemblies and of the building or structure itself. In order to define, assess, design and evaluate the desired/expected performance of building components, systems and assemblies, there need to be performance (or risk) criteria (measures) that serve as metrics for determining compliance. Such criteria may be presented qualitatively or quantitatively in the code, but ultimately, quantitative values are required for design and evaluation.

However, it is not easy to readily determine tolerable levels of performance. In assessing safety, for example, a primary reason is the difficulty in determining the "load" against which appropriate "resistance" is required. This is the current situation with prescriptive fire protection requirements. Almost every fire test of building materials, elements, and systems are against different, and sometimes incompatible or unrealistic loads. Thus, prior to assembly in a building, it is difficult to predict, and after assembly in a building, it is difficult to determine, what level of performance is being provided.

In an attempt to address these concerns in the development of the *International Performance Code for Buildings and Facilities*, the concepts of *magnitude of design load* and *performance levels* have been adopted (Meacham, 2000; ICC, 2001; 2003). The term "design load" is used as one cannot guarantee the maximum load that a structure will be subjected to (especially hazard induced loads); however, one can design a structure to resist loads that are representative of probable loads that can be reasonably expected. Design loads are characterized by four classes: Small, Medium, Large, and Very Large, indicating increasing magnitudes where "small" loads are indicative of high probability, limited consequence events,and "very large" loads are indicative of low probability, significant consequence events. The establishment of the design loads requires the expertise of appropriate technical communities and the value judgments of society. At this juncture, attempts are being made to incorporate design loads that have already been deemed tolerable (or acceptable) through use in existing regulation or practice. Understandably, this intersection of risk tolerability, design loads, and performance levels is critical, and can benefit from further research, data, tools and methods (Meacham, 2003).

[2] *Applies only to hazard-related applied loads. The nature of the applied load (i.e., fire hazard) may result in higher levels of expected injuries and damage in localized areas, whereas the balance of the areas may sustain fewer injuries and less damage.*

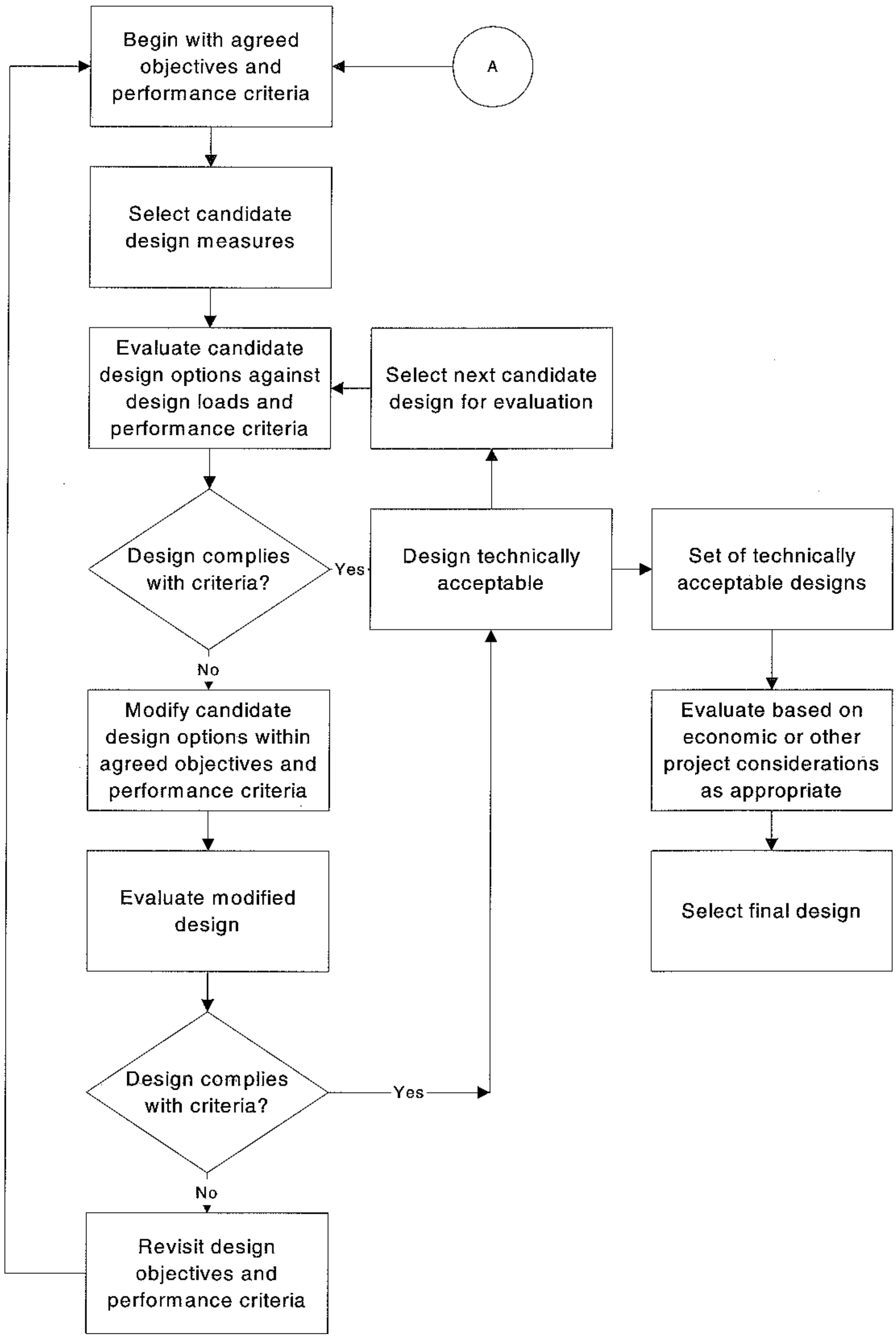

Figure 3. Iterative Nature of the Performance-Based Design Evaluation Process

3. Development and selection of performance criteria,

4. Development of possible scenarios, design scenarios and design loads,

5. Development of candidate design options,

6. Evaluation of candidate design options and selection of a final design, and

7. Development of final design documentation.

The basic flow of the above steps is outlined in Figures 2 and 3 (adapted from Meacham, 1998). In Figure 2, the process is outlined as a sequential process. In reality, however, there will be several iterations, especially during the evaluation stage (Step 6). The iterative nature of the evaluation, including the possibility of revisiting selection of performance criteria, is illustrated in Figure 3. The figures illustrate the process without reference to fire, indicating the applicability to any engineering problem.

The advantage of a performance-based analysis and design approach lies in the flexibility that can be achieved, while not compromising on safety, cost, or other important factors. It allows all parties involved to agree on the goals, objectives, criteria, and analysis and evaluation methods, resulting in a design that best fits all parameters – a performance-based design solution. The following provides a brief summary of the various steps in the process. It should be noted that a performance-based analysis and design approach can be used in conjunction with a performance-based regulation or on its own. Where a performance-based regulation exists, issues such as goals, objectives, criteria and performance requirements may already exist, and will not necessarily require development as part of the analysis.

Step 1: Identify Site or Project Information

The first step in the process is to gather information about the site, structure, facility or process. This includes building characteristics, such as size, layout, use, and construction, with particular attention paid to the facility's use, occupancy, construction, geographic location, symbolic importance, criticality, consequence and threats. Operational characteristics relate to specific functions of a facility, building or process, or to needs specific to the mission of the facility or its occupants. This category should address facilities or areas of facilities that are very important because they contain areas of high value equipment or areas where down-time needs to be effectively zero. This is especially important where the facility serves a community, such as a hospital or a utility. Finally, it is important to characterize the occupants at this stage. Occupant characterization will vary by use of the building, and should include such factors as ages, abilities, whether people sleep in the building, and whether any or all of the occupants might be considered targets (where terrorism is a concern). Obtaining this information is extremely important, especially where performance-based codes are lacking in specifics on the populations being protected and the levels of risk or safety that are desired.

Step 2: Identify Goals and Objectives

In general, *goals* are non-controversial statements that reflect a common aim. They are often easy to agree with and are measured qualitatively, if measured at all. In a performance-based regulatory system, goal statements are normally provided in the regulation (Tier I of the IRCC hierarchy).

Objectives are used to provide more direction as to how a goal might be met, and are normally stated in quantifiable terms. In performance-based design, one could find an objective expressed as a *stakeholder objective* or as a *client loss objective* (some indication of the level of loss that the client can tolerate). An example of this might be to "protect the piece of equipment in Room X against the effects of a fire such that a return to full operation can occur within 2 hours." Here, in order to meet the goal of maintaining continuity of operations, the objective is to ensure that the equipment is not out of service for more than 2 hours. (Design objectives relate to IRCC Tier II, functional statements.)

Once the stakeholder objectives or functional requirements are clearly defined and agreed to by those involved in the design process, one must have a means of identifying the level at which the building and its systems should perform in order to meet these objectives. This is done through statements called *design objectives* or *performance requirements*. For example, a design objective for mission protection might be: "limit the temperatures in the room to less than that which would cause irreversible or unrecoverable damage to the target equipment." In this case, if one can estimate the fire size that will cause the damage, one can design appropriate structural and other systems to meet this requirement.

In performance-based codes, one typically finds *performance requirements*, which are statements of the level of performance that must be met by building materials, assemblies, systems, components, and construction methods in order for the fire safety goals and objectives to be met (IRCC Tier III, operative requirements, as well as Tier V, performance or risk level). Not only should one be able to quantify these parameters, one should be able to measure, calculate and/or predict them as well.

Step 3: Develop Performance Criteria

Performance criteria are the metrics against which design objectives or performance requirements are assessed (see IRCC Tier VI). Unlike design objectives or performance requirements, which are often stated qualitatively, performance criteria must be stated in such a manner that they can be directly measured or calculated (e.g., gas temperature), as these become the criteria on which a design will be based. This is one area where performance-based design differs significantly from many performance-based regulations: not all performance-based regulations include quantitative criteria, but a performance-based design cannot be undertaken or evaluated without quantitative criteria. This need for quantitative criteria can be illustrated using a simplified example based on a goal aimed at life safety:

- The *life safety goal* is to protect those people not intimate with the initial fire from loss of life. (This is easy to agree with, yet difficult to quantify.)
- To meet this goal, one *stakeholder objective (functional requirement)* might be to provide people not in the room of fire origin with adequate protection from the effects of the fire. (This provides a little more detail: one could infer that fire protection systems must be provided.)
- To meet this requirement, one *design objective* (*operative requirement* or *performance requirement*) might be to limit the effects of the fire to the room of origin. (If the fire effects are contained to the room of origin, the people outside of the room will not be exposed to the threat under most conditions.)
- To meet the *design objective*, an engineer (or some document within the regulatory system) needs to establish a *performance criterion* (or set of *performance criteria*), such as a maximum expected heat release rate or fire growth rate for the room of fire origin.

In most cases, several design criteria will be needed to demonstrate that a performance requirement has been met. Demonstrating this may be difficult, as the interrelations between requirements and criteria may be complex.

Step 4: Develop Event Scenarios, Design Scenarios, and Design Loads

An *event scenario* is a set of conditions that defines an initiating event and its subsequent impact throughout a building or part of a building. There is an infinite number of event scenarios possible for any given building. As this range of event scenarios includes situations that may be considered highly unlikely, it is possible to pare the scenarios down into a smaller group of scenarios that can be used as part of the design process. These are called *design scenarios*. The range of design scenarios selected for consideration should reflect both probabilistic and deterministic considerations; that is, how likely it is that the event will occur, and if it does occur, how it is expected to impact the building. There are many factors that one must consider when developing event scenarios and paring them down into design scenarios, including:

- *Pre-event situation*: building, compartment, conditions.
- *Extension potential*: beyond compartment, structure, area or origin (including subsequent events, such as fire).
- *Occupant characteristics*: alert, asleep, self-mobile, disabled, infant, elderly, etc.
- *Available relevant data.*

Risk assessment is often the most appropriate tool for identifying event scenarios and paring them down to design scenarios.

Once a set of design scenarios has been developed, a set of corresponding design loads needs to be developed. Design loads are used to evaluate the candidate design options, much the same as design loads will be used in structural design to ensure that the strength of a structure is adequate. Design loads need to be developed for every design scenario considered for a compartment, building, structure, or process.

Step 5: Development of Candidate Design Options (Design Alternatives)

After the design scenarios and design loads have been developed, the next step is to develop candidate design options (design alternatives). Candidate designs should be selected from components, systems, and strategies that will ensure the design objectives are met. In most cases, a number of candidate design options should be considered, including applicable prescriptive code requirements.

Step 6: Evaluate Candidate Design Options and Select Final Design

After the candidate design options have been developed, the next step is to evaluate them for compliance with the design objectives and performance criteria, and select a suitable option as the final design. The evaluation process is an iterative one wherein a variety of mitigation measures are evaluated against the design loads and the design objectives. Factors such as modifications to the ventilation systems, and variations to construction materials, interior finish and contents are evaluated here. In many cases, code-prescribed requirements will serve as a baseline for evaluation and review, and it is important to know if the code requirements meet the performance criteria, exceed them, or fall short of them.

Step 7: Developing Final Design Documentation

The final step in the process is documenting the analysis and design and preparing equipment and installation specifications. The analysis and design report will be a critical factor in gaining the acceptance of a performance-based design. It needs to outline all of the steps taken during the analysis and design, and present the results in a format and manner acceptable to the authorities and to the client (stakeholder). At a minimum, the report should include:

Intent of the analysis or design: the reasons it was undertaken.

Statement of design approach (philosophy): the approach taken, why it was taken, what assumptions were made, and what engineering tools and methodologies were applied.

Site or project information: hazard and risk analysis, building characteristics, occupant characteristics, etc.

Statement of client goals and objectives: the agreed upon goals and objectives of the performance-based analysis or design, who agreed and when.

Performance criteria: the performance criteria and the performance requirements (design objectives) to which they relate, including any safety or reliability factors applied, and support for safety or reliability factors where necessary.

Event and design scenarios: the event scenarios considered and the design scenarios used, the bases for selecting and rejecting event scenarios not used as design scenarios, and assumptions and design restrictions (conditions).

Design load(s): the design load(s) used, the bases for selecting and rejecting design load(s), and assumptions, limitations, and design restrictions (conditions).

Candidate designs: the design alternative(s) selected, bases for selecting and rejecting design alternative(s) (deterministic, probabilistic), assumptions, conditions, limitations and uncertainties. This should include comparison of results with the performance criteria and design objectives and a discussion of the sensitivity of the selected design alternative to changes in the building use, contents, occupants, etc.

Uncertainty factors: any uncertainty (safety, reliability) factors, how they were derived, and/or appropriate references.

Cost-benefit analyses: where cost is a factor in the decision-making process, cost-benefit analyses should be included as well.

Design tools and methods used: the engineering tools and methods used in the analysis or design, including appropriate references (literature, date, software version, etc.), assumptions, limitations, uncertainties, engineering judgments, input data, validation data or procedures, and sensitivity analyses.

Test, inspection and maintenance requirements: test procedures, maintenance schedules, etc.

Emergency management concerns: discussion on changes in use, contents or materials, training and education for building staff and occupants, etc.

References: software documentation, journal reports, handbook references, technical data sheets, fire test results, etc.

With regard to both the design and the emergency management aspects, it is important to consider the expected use of the building, throughout its lifetime, when designing the mitigation measures. There should be clear indicators, in the design documentation, as to the limits of the design and to any specific factors that will warrant a re-evaluation or re-design. These may include change of occupancy, significant change of mission, or significant modifications to the building or its systems. Concerning equipment installation specifications, although one may undertake a performance-based analysis and design, at the end of the day, the installation of the equipment, systems and features will have to be specified in exactly the way it is done today.

2.9 Tier VIII: Verification Methods

In the NKB hierarchy, verification methods are simply defined as instructions or guidelines for verification of compliance. In the IRCC hierarchy, the definition is broadened to include such items as test standards, test methods, analytical methods (including computational models), and the like. In short, verification methods include any suitable document, system, test, method or tool that is needed to verify a design, and its components, with respect to goals, functional statements, operational requirements and performance criteria.

In a performance-based system, verification methods are often computer-based analytical tools, which require a combination of data and judgment. This is because it may not be cost-effective or socially acceptable to physically test every possible mitigation solution (e.g., it is not acceptable to test the fire performance of a building by starting a fire in the building). In these cases, care should be taken that the tools and the data needed for the analysis are suitably verified and validated, and that sources of uncertainty, variability and unknowns are appropriately treated. Also, care should be taken that appropriately qualified personnel who understand the totality of a risk-informed performance-based approach use such tools and methods. Otherwise, there is a risk that a disproportionate level of analysis may be focussed in one area to the detriment of the overall safety of the facility.

3.0 INTERRELATIONSHIP OF IRCC PERFORMANCE-BASED BUILDING REGULATORY SYSTEM HIERARCHY COMPONENTS

As discussed above, several design criteria may be needed to demonstrate that a performance requirement has been met. This may be difficult, as the interrelations between requirements, criteria, and verification and design tools and methods can be complex. This interaction between requirements, criteria, and verification and design tools and methods is illustrated in Figure 4 (Meacham, 1999; ICC, 2001).

In Figure 4, each level corresponds directly to the IRCC hierarchy. The figure is meant to illustrate that, in addition to

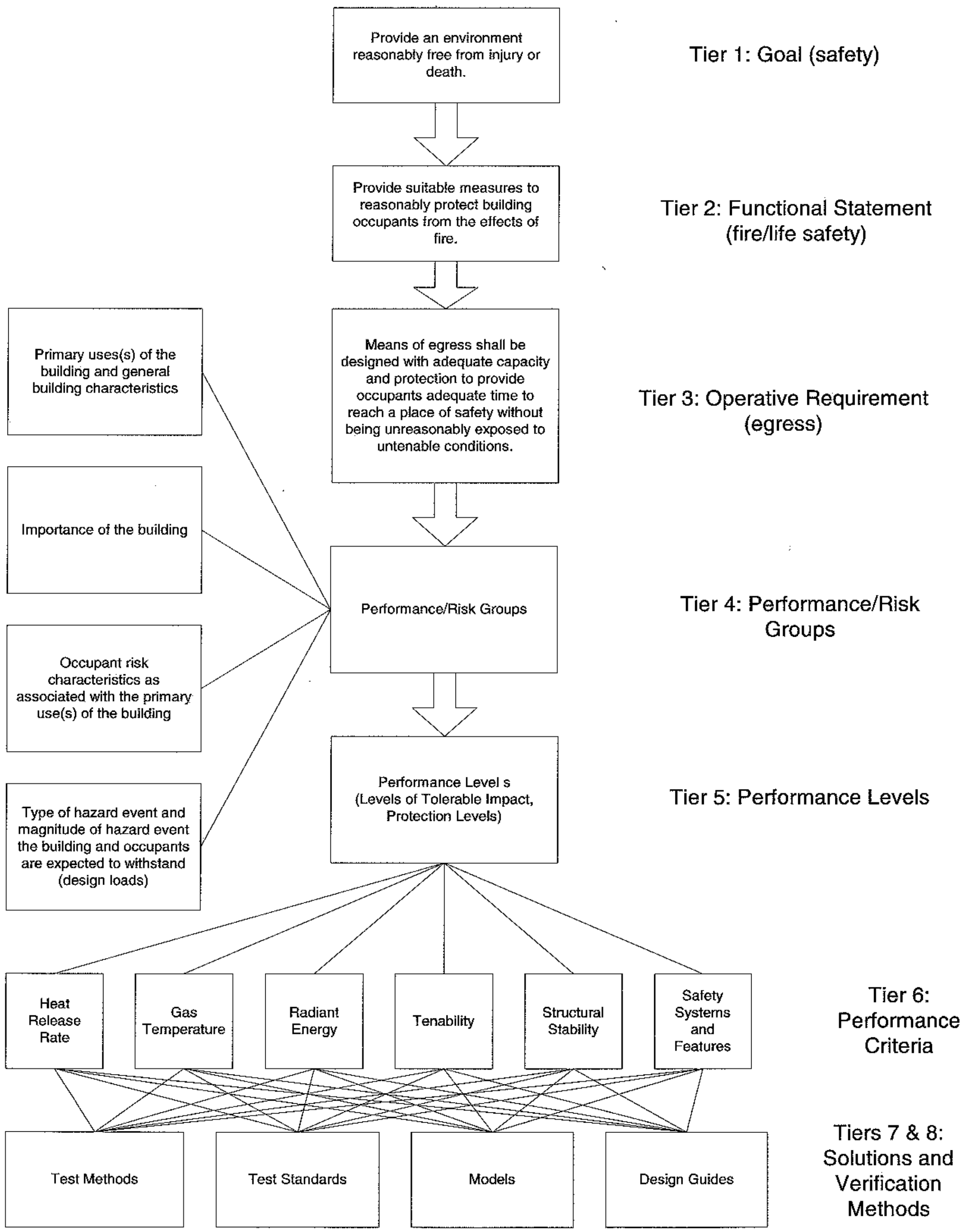

Figure 4. Interaction of Goals, Objectives and Criteria in the IRCC Performance-Based Building Regulatory System Hierarchy

having qualitative statements of performance (Tiers I - III), one needs to know who is being protected and to what level (Tiers IV and V) in order to select performance criteria (Tier VI). Figure 4 also illustrates that one needs to know the form of the performance criteria in order to select appropriate design tools and methods, and that the form of the performance criteria is dependent on test methods and standards.

The interactions illustrated in Figure 4 are extremely important in both performance-based design and in the performance-based regulatory system as a whole. One cannot go directly from Tier III to Tier VII or VIII, or the reverse, without clear linkages between the levels of performance desired, the criteria to be used to verify performance, and the standards, methods, models, and guides used to measure, estimate, or calculate performance. Any component of the hierarchy that is developed without consideration of the other components runs the risk of being incompatible, and it will be difficult to support linkages between components developed in isolation.

4.0 SUMMARY

This paper has outlined considerations for enhancing the fundamental structure of performance-based regulations, which have been implemented or are under development in many countries worldwide. This paper represents current thinking of the author and members of the IRCC in relation to the components of a performance building regulatory system that should be considered by regulatory developers, and provides insight into the importance of properly linking policy goals down to specific criteria, standards, guides and methods.

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