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Seismic Isolation of Semiconductor Production Facilities

Hal Amick, P.E., and Ahmad Bayat, P.E.

Colin Gordon & Associates
San Mateo, CA

Zoltan A. Kemeny, S.E.

Tekton Inc.,[1]
Tempe, AZ

ABSTRACT

Semiconductor facilities engaged in development, production, and mask-making for computer chips are extremely expensive, often with unit costs exceeding $3,000 per sq ft of cleanroom. The total cost—including both building and equipment—might exceed $1 billion, of which 3/4 might be the cost of the delicate equipment used to make the products (chips, masks, etc.). Much of this equipment is vibration-sensitive, and building designers go to great lengths to minimize the vibrations to which the equipment is exposed. The structures themselves are generally designed to meet or exceed seismic code requirements. However, the fragile, vibration-sensitive equipment—sometimes equipped with internal pneumatic isolation but without additional seismic provisions—is typically "hard-mounted" to the structure, exposing it to the full lateral loads of a seismic event. A major earthquake could leave one or more of these facilities standing but non-functional for quite some time, posing disastrous economic consequences for an industry center like Silicon Valley. The authors present a conceptual approach in which the design objective for the facility would be that its contents remain operational following an earthquake. The structure and mechanical systems would be designed for strength and rigidity, but the most costly portion of a semiconductor facility—the cleanroom and the expensive production tools—would be designed to be decoupled from the building shell using low-compliance isolation and/or dissipative systems. This concept will be compared and contrasted with base isolation approaches which might be considered for the building shell by itself.

INTRODUCTION

Microchip fabrication facilities (called "fabs" within the semiconductor industry) are among the most expensive buildings on earth. The costs of these buildings often exceed one billion dollars. Many U.S. fabs are concentrated in seismically active areas: Silicon Valley and Southern California, both seismic zone 4; Utah and coastal Oregon and Washington, all zone 3; Idaho, zones 2B and 3; Albuquerque, zone 2B;

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and New York and New England, zone 2A.[2] Many are also in high-risk countries such as Japan, China, Malaysia, Korea and Taiwan.

They are generally built in accordance with the seismic provisions of local building codes, but the emphasis typically is on survival of the building and its inhabitants, with attention limited to egress and containment of hazardous materials. Little if any attention is devoted to the operability of the contents, to ensure that the facility as a whole can remain operational after a major earthquake. However, if a Northridge-sized or larger earthquake were to strike close to an area like Silicon Valley, the economic consequences would be enormous. If the facilities or their contents were a total loss, the economic impact to the region could be an order of magnitude greater than that of Northridge or Loma Prieta.

An additional complication is that much of the work carried out in fabs is highly vibration-sensitive. Over the last quarter-century of this industry's evolution, the requirements for a low-vibration environment have been in conflict with those for a sound seismic environment. Rotating mechanical equipment (i.e., motors, pumps and fans), ducting and piping are considered to be vibration sources and must be isolated on springs, and many items of production equipment (called "tools") are also supported on "soft" isolation systems.

This paper addresses three topics:

- The nature of fabs, their cost, and a methodology directed toward seismic protection for their contents,
- SEAOC's *VISION 2000* document and its relevance to fabs, and
- A scheme by which the most critical components of a fab can be seismically isolated without compromising the vibration control that is mandatory in a fab.

SEMICONDUCTOR FACILITIES

The inner workings of computer chips must be produced in cleanrooms—factories in which environmental conditions are stringently controlled. It is necessary to maintain tight control over airborne particles, contaminants in liquids and gases, microvibrations, temperature, and humidity. The typical fab contains production equipment which actually fabricate the chips; a cleanroom, the controlled environment in which the tools are housed; hazardous process materials such as acids and pyrophoric gases; the mechanical equipment which maintains the controlled environment; support areas (such as labs, offices and maintenance areas); and the building shell, which encloses all of the above.

The Semiconductor Industry Association (SIA) defines a fab in terms of four systems which, conveniently, represent four groupings of design disciplines which must consider seismic design in one form or another.[3] Figure 1 shows a simplistic schematic diagram of a cleanroom system, incorporating several of these systems.

- **Building Systems**—This is the building shell and the physical components of the cleanroom. It is generally the responsibility of an Architect and a Structural Engineer. Seismic code compliance issues are primarily addressed by this team.

- **Factory Environment**—This refers to everything which contacts the product apart from the process equipment. During design, it generally falls within the purview of an HVAC Mechanical Engineer and a Piping Engineer, with input from Process Engineers and Control Systems Engineers. Together they are responsible for air moving equipment (including multiple exhaust systems) as well as delivery and processing of water for temperature and humidity control. Seismic issues are addressed for these

[2] Zones after Uniform Building Code™ Figure 16-2, Seismic Zone Map.
[3] "The National Technology Roadmap for Semiconductors," Semiconductor Industry Association (SIA), 1994.

systems, but not necessarily by the project's Structural Engineer; the focus is generally on safety, not operability.

- **Specialty Gas Systems**—This refers to the safe, efficient, contamination-free, and consistent delivery of toxic, corrosive, and pyrophoric gases to the process tools, and involves a specialized Mechanical Engineer. Seismic issues are addressed with a focus on preventing leakage.
- **Fluid Delivery Systems**—Generation, purification, and distribution of chemicals, solvents, and ultrapure water (UPW) to the process tools is the responsibility of specialized Mechanical Engineer. Seismic issues are addressed with regard to preventing leakage of hazardous materials.

Figure 2 shows a cross-section of a typical fab. The grillage (or waffle slab) floor and the columns supporting it make up a table-like structure-within-a-structure. We find either a single-level subfab (shown) or double-level subfab or subfab-and-basement configuration. The outer shell of the structure generally consists of a long-span truss spanning over the cleanroom and supporting mechanical equipment at the mezzanine level and the adjacent spaces.

The shell and the grillage structure of the fab are often separated by a structural isolation break (SIB) around the perimeter of the cleanroom, including a double-column-line to support the structure on both sides of the joint. This section shows one of several schemes for recirculating air, the use of vertical fan towers along the sides of the fab. Another scheme places recirculation fans in the mezzanine. The primary purpose of the SIB is to prevent vibrations from propagating from the shell to the cleanroom floor at fab level.

There is a vast quantity of mechanical equipment associated with a fab, on the order of 100 to 150 watts/sq ft of cleanroom. (For example, a fab with a 100,000 sq ft cleanroom would have between 10,000 and 20,000 hp of motor-driven equipment such as pumps, fans and chillers.) The clean and climate-controlled environment is maintained by high-volume air flow: about 600 air changes per hour in a Class 1 cleanroom, as compared to about 6 air changes per hour in a normal office building. Traditionally, all rotating mechanical equipment of 3 hp or greater is placed on vibration isolation of some sort. Fans are internally isolated on springs, pumps are placed on concrete inertia bases with springs. Seismic protection for isolated equipment is provided in the form of seismic snubbers, which limit the dynamic displacement of the isolated device during an earthquake.

Independent lateral resisting elements such as shear walls, diagonals, etc., are provided for the shell and fab structure. The fab grillage floor generally requires the presence of shear walls to provide horizontal stiffness to reduce vibrations, so these same shear walls provide lateral seismic resistance. The fundamental horizontal frequency of a fab grillage structure is on the order of 3-6 Hz, corresponding to a period of about 0.3 sec or less. The form of the lateral load-resisting mechanism of the shell is at the discretion of the structural engineer, but generally must be kept independent of the grillage structure if there is a SIB.

The economics of fabs are rather dramatic. The newest "superfabs" cost $1 - $1.5 billion fully equipped. Though the actual amounts vary widely, one of these fabs is capable of generating $1 - $2 billion revenue per year (around $3 million per day). The unit cost to build and equip a fab is generally between $2000 and $4500 per sq ft of cleanroom. The total cost generally breaks down roughly along the following lines:

- 75 percent for equipment
- 5 percent for building shell
- 11 percent for mechanical and delivery systems.[4]

[4] Cost data courtesy M. Fitzpatrick, McCarthy Construction, private communication.

Building codes such as *Uniform Building Code* (UBC-97) assume—but do not mandate—good engineer-owner communication. As a result, owners seldom understand the level of seismic damage they accept by not designing beyond code-prescribed minimum provisions. On occasion, additional importance factors beyond code requirements are included in the design of the fab structure, but a building owner who accepts nominal code level design is accepting a high probability of critical structural and non-structural damage. Semiconductor facility owners cannot afford this risk. The potential dollar loss of fab contents—which are generally <u>not</u> covered by code-prescribed provisions—far exceeds that of the building structure to which the code <u>does</u> apply. Furthermore, the cost of business interruption is simply prohibitive.

The current approach to seismic protection of fab contents is usually limited to preventing the overturning of tools. This is based upon the assumptions that an overturned tool poses an egress hazard and that a tool can leak hazardous materials. The support structures for tools are designed to provide rigid attachment to the cleanroom floor, itself a very rigid structure. Thus, the tools themselves are exposed to the full base accelerations of the earthquake.

VISION 2000 APPROACH

The Structural Engineers Association of California (SEAOC) has prepared *VISION 2000: Performance Based Seismic Engineering of Buildings*, which proposes a systematic approach to seismic engineering that is based upon the concepts of *performance objective* and *performance level*. It also defines categories of facilities, which in turn, dictate the seismic requirements to be implemented for each category.

Terminology of *VISION 2000*. The SEAOC document *VISION 2000* introduces a number of new terms and concepts. The ones germane to our position are reviewed below:

- A design *performance objective* is an expression of the desired performance level for the building for each earthquake design level.
- A *performance level* is an expression of the maximum desired extent of damage to a building, given that a specific earthquake design level affects it.

Performance Levels. Four individual performance levels are defined. Each specific performance level defines the limit to a range of damage states which meet basic user needs such as continuity of function, suitability for repair, safety, etc. The four performance levels are:

- **<u>Fully Operational</u>** — Essentially no damage has occurred. The consequences to the building user community are negligible. *The building is occupiable and <u>all equipment and services related to the building's basic occupancy and function are available for use.</u>*
- **<u>Operational</u>** — Moderate damage to nonstructural elements and contents, and light damage to structural elements has occurred. *It would be available for occupancy for its normal intended function … however, damage to some contents, utilities and non-structural components <u>may partially disrupt some normal functions. Back-up systems and procedures may be required to permit continued use</u>.*
- **<u>Life-safe</u>** — Moderate damage to structural and nonstructural elements, and contents has occurred. Egress from the building is not substantially impaired … and *<u>mechanical devices may not function.</u>* The building would not be available for immediate post-earthquake occupancy. The building would probably be repairable, although it may not be economically practical to do so.
- **<u>Near Collapse</u>** — An extreme damage state in which the lateral and vertical load resistance of the building have been substantially compromised. *The building will likely be unsafe for occupancy and repair may not be technically or economically feasible.*

The first two conditions are ones for which "green tags" would be issued after an earthquake. The third would generally warrant a "yellow tag", and the last would be granted a "red tag".

Earthquake Severity. The document rates earthquake severity in a probabilistic manner using terms that can be understood by a layperson but also have geophysical significance, as shown in the Table 1.

Table 1. Earthquake design levels[5]

Earthquake Design Level	Mean Recurrence Interval	Probability of Exceedance
Frequent	43 years	50% in 30 years
Occasional	72 years	50% in 50 years
Rare	475 years	10% in 50 years
Very Rare	970 years	10% in 100 years

VISION 2000 defines "recurrence interval" as the average period of time, expressed in years, between the occurrence of earthquakes which produce the effects of the same, or greater, severity. It defines the "probability of exceedance" as a statistical representation of the chance that earthquake effects exceeding a given severity will be experienced at the site within a specified number of years. The Uniform Building Code specifies the use of a design basis earthquake having a 10 percent probability of being exceeded in 50 years and a recurrence interval of 475 years—that which *VISION 2000* categorizes as "rare."

This can be put into perspective by means of applying *VISION 2000* terms to a hypothetical location in Silicon Valley. Table 2 lists the five closest faults, their distance, estimated recurrence intervals, estimated maximum magnitude, and estimated maximum acceleration. We can see that the two faults which can produce "occasional" earthquakes—Hayward and Calaveras—are at a great enough distance that the estimated maximum accelerations are 0.2 to 0.5 g. The one fault that can produce "rare" earthquakes—the San Andreas, which theoretically could produce a magnitude 8.5 earthquake—can produce a 1g maximum acceleration.

Table 2. Faults affecting Silicon Valley[6]

Fault	Approx. Dist., km	Estimated Recurrence, years	Est. Max. Magnitude	Est. Max. Acceleration, g	Design Level
San Andreas	8	100-1000	8.5	1	Rare
Hayward	15	10-100	7.0	0.5	Occasional
Calaveras	30	10-100	7.3	0.2	Occasional
Black Mtn.	6	—	6.7	1	Very Rare
Silver Creek	30	—	6.2	0.1	Very Rare

Performance Objectives by Facility Type. Recommendations are provided in *VISION 2000* for minimum design performance objectives for buildings of three different occupancies and uses:

- **Safety Critical Facilities** — Facilities which contain large quantities of hazardous materials, the release of which would result in an unacceptable hazard to wide segments of the public.

[5] After Table 2-1 in *VISION 2000.*
[6] After maps and data in "Studies for Seismic Zonation of the San Francisco Bay Region," *US Geological Survey Professional Paper 941-A*, edited by R. D. Borcherdt, 1975.

- **<u>Essential / Hazardous Facilities</u>** — ***Essential*** Facilities are those which are critical to post-earthquake operations, such as hospitals, police stations, fire stations, etc. ***Hazardous*** Facilities are those which contain large quantities of hazardous materials, but where the release of those materials would be contained within the boundaries of the facility and the impact to the public would be minimal.
- **<u>Basic Facilities</u>** — Buildings not classified as Safety Critical or Essential / Hazardous facilities.

The relationship between earthquake severity, performance level and occupancy type is defined in Tables 2-3, 2-4, and 2-5 in *VISION 2000*. The document defines "microchip facilities" (fabs) as ***Hazardous*** facilities. This performance level is intended to remain **Fully Operational** only after an "occasional" earthquake. It is only to remain **Operational** (moderate damage to non-structural elements) after a "rare" earthquake (the UBC design basis earthquake). For comparison, the *Basic* facilities are to remain **Fully Operational** following "frequent" earthquakes, **Operational** following "occasional" earthquakes and **Life-safe** following "rare" earthquakes. This is the approach most commonly taken at this time for fab design.

VISION 2000 would call for our hypothetical Silicon Valley fab to remain "operational," but not "<u>fully</u> operational" after an earthquake. Under this classification of *VISION 2000*, the structure and mechanical systems should remain operational (though not without minor damage) but there is a significant risk that the tools in the fab might not survive 1g accelerations without major damage. We now turn our focus to these costly—and generally overlooked—nonstructural components.

Non-structural Components. Most of the differences between a facility remaining **Fully Operational**, **Operational**, or merely **Life-safe** lie with non-structural components. *VISION 2000* defines four categories of non-structural components, only one of which is expected to function after "moderate" or "rare" earthquakes: performance category D.

A number of categories of fab support equipment fall within the category *"Structurally Rugged Equipment"*, which, if fabricated in accordance with industry standard practice for the component, have been demonstrated to be able to withstand very strong levels of seismic excitation without structural failure. However, *structurally rugged components may not necessarily function following severe shaking.* Air handlers and fans which are internally vibration isolated—which includes virtually all those found in a fab—are <u>not</u> structurally rugged.

Other equipment which falls within the category *"Functionally Rugged Equipment"* includes those classes of components that have been demonstrated in past earthquakes to be capable of surviving very strong seismic excitation, without failure, if fabricated and installed in accordance with industry standard practice. We will make use of industry experience that fab tools have been known to survive moderate earthquakes, making them functionally rugged to a limited extent.

PROPOSED OBJECTIVE FOR FAB SEISMIC DESIGN

A significant portion of fab equipment is fragile, but its fragility must be examined in two contexts. During production, this equipment is <u>highly</u> sensitive to vibration, which if excessive, will cause faulty circuits to be created. We must design the long-term, operational environment to limit vibrations to extremely small amplitudes, using units on the order of microinches/sec or micro-g. However, during and immediately following an earthquake, production would probably be suspended, so our concern is with maintaining the operability and internal alignment of the tools. Ideally, one would like to see the equipment in a state in which it can be re-started with a minimum of setup protocol and re-calibration. If this is to have practical value, then it is important that the mechanical and process support systems remain in working order, so that they too can be re-started.

Suppose we wished for the hypothetical Silicon Valley fab to remain operational after the maximum credible earthquake—a magnitude 8.5 earthquake on the San Andreas fault. What would this require? The cleanroom must remain clean, and the tools and their support systems (vacuum systems, chilled water, specialty gases, etc.) must remain fully operational—and within calibration. Since the inevitable infrastructure problems[7] following an earthquake of this magnitude would make actual production impossible (or at least difficult) for a few days, the facility could remain under conditions of reduced air flow, using emergency power, while a skeleton crew systematically shut down the plant.[8]

Tools might be considered <u>functionally rugged</u>—to an extent—but the seismic limits of tools have never been quantified. They have been shown to survive medium-sized earthquakes, such as the Loma Prieta earthquake, so we know that tools can withstand accelerations on the order of 0.1 to 0.25 g. (One stepper manufacturer reports that none of its tools produced a single error during the shaking of Loma Prieta. Several fab operators report being back in production within one to two hours after the earthquake, following safety inspections of the hazardous materials containment systems.)

The following conditions would have to be met, and would have to be anticipated during design:

- The shell structure must be safe for occupancy immediately after the earthquake
- The cleanroom must be safe for occupancy immediately after the earthquake
- The cleanroom tools, control systems and robotics must remain operational and within calibration following the earthquake.
- The emergency power generator must survive the earthquake and come on immediately. It must have enough fuel reserve to last until a tool and mechanical system shutdown protocol can be executed.
- The exhaust and make-up air systems must remain operational through the system shutdown period.
- Hazardous material containment must remain fully intact.

In order for these conditions to be met, all components in the systems defined above must either be rated as Class D or isolated in some manner that reduces the peak accelerations to amplitudes for which the components can be considered functionally rugged. (From past experience, this would suggest that this condition might be met for typical fab production equipment if the cleanroom accelerations were less than about 0.2 g.) Virtually all of the fragile and expensive production systems (tools, environmental enclosures, robotics, and product) are contained within the cleanroom.

From the preceding discussion, it is clear that a thorough economic analysis must be performed to determine the extent to which the operability requirements should be extended to all components and systems in a fab. Obviously, beyond the safety requirements to protect the occupants, the economic factors (i.e., the extent of damage in dollars, the extent of down time and loss of revenue) will dictate performance-based design of a fab. Much thought and study should be carried out in this regard to determine the boundaries of such classifications and design approaches.

However, from the cost breakdown given earlier, one can easily see that protection of fab cleanroom contents—primarily the critical and expensive tools such as those used for photolithography and metrology—is very important in terms of cost. For instance, a fan or a pump can easily be repaired or replaced in a timely manner with small costs, while a stepper (which costs over $5 million) may be very

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[7] As pointed out by *VISION 2000* (and can be confirmed by anyone who has experienced a major earthquake), several days may pass before resumption of basic city utilities such as electricity, water, and natural gas. It might not be possible for a fab to continue <u>producing</u> immediately after an 8.5 earthquake on the San Andreas, simply because these utilities may not be available. It may be necessary to achieve a consensus within the fab community regarding the definition of "fully operational" in this context.

[8] A more all-encompassing (and expensive) approach would be to ensure that the facility remained "fully operational" and operate on emergency power until utilities become available.

difficult to replace in a timely manner, resulting in additional loss of revenue. It is upon this latter issue—the protection of these expensive tools—that the authors will focus in subsequent sections.

PROPOSED CONCEPT FOR SEISMIC PROTECTION OF CLEANROOMS

Available Options. An engineer designing seismic isolation for a fab has several options:

1) base isolate an entire building or a portion of the building,
2) isolate essential flooring systems (raised access floors or slab-on-grade floors),
3) isolate individual semiconductor tools and other critical pieces of equipment by placement on separate isolation bearing systems,
4) protect the structure with dissipative bracing employing supplemental dampers, and/or
5) locate tuned mass dampers on the building roof to cancel out earthquake induced vibrations.

By combining one or more of these options with conventional seismic design, an engineer can deliver the highest performance with the lowest acceptable seismic risk and at the lowest cost.

Isolated Access Floor. Figure 3 illustrates a concept by which the cleanroom in its entirety could be equipped with seismic isolation hardware and the remainder of the facility is all supported from the shell. The cleanroom walls, filter ceiling and access floor are all supported on a framework resting on seismic isolators. The fab tools are supported either on the RAF or on separately isolated steel pedestals. Perhaps the most critical key to the success of this system is the "isolation break" around the cleanroom. This consists of resilient joints in all piping, ducting and conduit that crosses from the shell to the cleanroom.

We propose that the seismic isolation of the cleanroom be accomplished by placement of seismic isolators beneath a structural framework which would support the access floor, as shown in a plan drawing in Figure 6. A prototype is shown in Figure 7. This has the added benefit of placing the access floor, which is manufactured with a 2 ft x 2 ft tile grid, on a framework which could have columns at some multiple of 2 ft, such as 4, 6 or 8 ft. The larger spacing would address the interference problem routinely faced by those designing piping and ducting runs between the access floor and the structural floor.

The vibration amplitudes in raised access floors are quite high, mostly due to personnel activity. In current design, many vibration-sensitive tools are supported on stiff pedestals, which in turn are supported directly on the structural floor. This serves to extend the "quiet" vibration environment of the structural floor up to the elevation of the access floor and protect the tool from the high amplitudes present in the access floor. In addition, some heavier tools are supported in the same manner, simply because the access floor does not have adequate strength. Under the proposed scheme, those frames would also be supported by their own seismic isolators, and connected to the RAF frame in a manner that ensures that those frames and the RAF frame move in phase, but avoid transferring vibratory energy from the access floor to the vibration-sensitive tool pedestals.

Ball-bearing Isolators. For the isolators themselves, we present a cleanroom seismic isolation scheme based upon the "ball in a spherical cup" principle, used in a nearly-literal implementation of Figure 4.[9] The concept is a variation of a pendulum, and the system has the horizontal resonance frequency defined by Equation (1) and associated with the radius l (or length of the equivalent pendulum) in Figure 4, after Haskell.[10]

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[9] In theory, a similar scheme could be implemented using rubber isolation bearings. That technology has been covered in other sources.

$$f = \frac{1}{2p}\sqrt{\frac{g}{l}} \quad \text{Hz} \qquad (1)$$

Haskell presented experimental results of a similar approach for seismic isolation of equipment on rollers.[10] Resonance frequency is dependent only upon the geometry of the cup and ball, and is independent of surcharge weight or location of the center of gravity.[11] He derived an expression for resonance frequency of this system, given here as Equation (2).

$$f = 0.225\sqrt{\frac{gh}{R^2 - 2hr}} \quad \text{Hz} \qquad (2)$$

The displacement x can reach a maximum value of D when the total bearing rise becomes $h = jD$, where j is the cone angle (see Figure 4).

The Ball-N-Cone® (BNC) bearing system—an exploded view of which is shown in Figure 5—introduces two modifications: (1) a conical surface is substituted for the spherical one, and (2) the ball bearing is sandwiched between two facing concave surfaces, rather than one concave and one flat surface. Both of these changes cause significant changes in the isolator's behavior. If the spherical surface is changed to a conical one, the inclined surface changes from a curve to a ramp, and the ratio of vertical motion to horizontal motion becomes constant. This prevents resonance at a discrete frequency, though there is still a predisposition to a particular range of frequencies of motion. When this happens, the sharp, high-Q resonance associated with a ball on a spherical surface is eliminated. When the isolator is converted from one using a single concave surface (Figure 4) to one in which the sphere is sandwiched between two facing concave surfaces, the equivalent pendulum length doubles. This reduces the predominant frequency (<u>resonance</u> frequency in the case of spherical surfaces) and improves the performance of the isolator.

Several of the available options (see above) combinations were studied in depth and compared. One such comparison for a hypothetical fab floor in Silicon Valley is abstracted here for reference. The cleanroom is described as:

- 30,000 ft^2 plan area
- 12' main column spacing
- location: San Jose, CA, seismic zone 4, importance factor 1.25
- limit the cleanroom floor acceleration to 0.15 g max

We will examine two options. Option "A" is configured around the use of conventional resilient base isolation bearings beneath the columns supporting the cleanroom, otherwise a conventional design is used. Since the spacing of fab columns is smaller than in a typical building (on the order of 12 to 15 ft), a 30,000 ft^2 cleanroom would have about 500 isolators, as opposed to about 50 for a conventional building of the same size. Option "B" is configured around implementing the other approaches (given above) in a single design: friction dampers, isolated cleanroom flooring, and isolated tools.

The seismic floor isolation system of Option "B" physically limits acceleration to 0.18g, based upon the laws of physics. Floor acceleration is limited, regardless of the characteristics of the input force, by the cone angle of the Ball-N-Cone® bearings and the factory calibrated yield force of the Seismic Brake®

[10] Richard C. Haskell, "Protecting Caster Mounted Equipment from Earthquake Damage, ATC-29, pp 417-427.
[11] For this reason, we can disregard torsion, bi-directionality and plan irregularity.

friction dampers used in the system.[12] The restoring force of a ball rolling down a ramp (a conical surface) is constant and therefore so is the level of acceleration forces transferred into the isolated structure. The yield force of the Seismic Brake®, a Coulomb friction damper, is also constant. These two devices working together in a system physically limit the acceleration forces transferred into the raised access floor or other isolated structure. On the other hand, state-of-the-art conventional seismic base isolators for building columns at best would reduce floor acceleration on the 2nd floor to approximately 0.25g. This neglects the problems posed by making the base isolators—essentially "point" loadbearing—compatible with the shear walls normally required for vibration control.

Figures 6, 7 and 8 illustrate the main components of the access floor isolation system:

- Stringers — steel or aluminum channels @ 2'-0" c/c
- Beams — steel or aluminum channels @ 8'-0" c/c (range is 8' max., 2' min.)
- Ball-N-Cone® bearings—10" round x 3", 1 ± 0.5g load, , +/- 8" stroke
- Seismic Brake® dampers— ½" x 2 ½" x 5'-8", ± 0.05 g yield, ± 10" stroke
- diagonal ties or braces—steel or aluminum channels
- columns—steel or aluminum T's.

Note that the beams and stringers support the short, access floor panel pedestals. The height of this particular isolation system is 12"; the access floor panel pedestals provide the additional clearance. Isolation systems with different heights are possible. The piping, cable and duct work is more conveniently located under an isolated access floor system with 8' x 8', 6' x 6', or 4' x 4' supports than under a conventional system with 2' x 2' supports. The larger spans will require larger members.

ANALYSIS AND CODE COMPLIANCE

Innovative techniques, such as base isolation and the use of energy dissipative bracing at critical junctions of structural and nonstructural elements, are covered by the building codes. Specifically, UBC-97 Sect. 1624 covers the seismic design of structures and its components in general. This section makes reference to other sections covering innovative design, such as Sect. 1650 for seismic-isolated structures and its components and Sect. 1630 for non-structural components such as access floors and equipment (pumps, chillers, etc.). Most of the innovative designs are not spelled out in great detail, and some code interpretation is required by the engineer and by the building officials.

The essence of the seismic floor isolation system incorporated into the access floor system is the Ball-N-Cone® (BNC) isolation bearing. The constitutive laws of the BNC's restoring force *F* and dissipative (damping) force *Q* are defined as given in Equations (3) and (4), respectively.

$$F = j\,W\,\mathrm{sgn}(x) \tag{3}$$

where *x* is the design displacement and φ is the cone angle in radians.

$$Q = a W \,\mathrm{sgn}\frac{dx}{dt}\text{, where } \frac{dx}{dt} \text{ is the velocity associated with } x \tag{4}$$

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[12] "A Seismic Isolation Bearing with Nonlinear Gravity Restoring," by Zoltan A. Kemeny and Ferenc Szidarovszky. (Copies available from Tekton Inc., Tempe, Arizona). See also "Experimental Study of Ball-In-Cone Isolation System," Kasalanati, Reinhorn, Constantinou, and Sanders, *Proceedings of Structures Congress XV*, Structural Engineering Institute / ASCE, April 13-16, 1997, Portland, Oregon.

and the design displacement is $D = x_{\max}$. Since F and Q are constant under all dynamic or static circumstances, C can be defined by Equation (5).

$$C = a + j \tag{5}$$

The BNC bearing can be shown to meet the requirements of UBC-97. The following UBC terms are used in the analysis of systems involving BNC isolation systems:

- D = design displacement, in inches, at the center of rigidity of the isolation system as prescribed by Formula (54-1), but replaced by Equation (6) below.
- D_T = total design displacement, in inches, of an element of the isolation system including both translational displacement at the center of rigidity, D, and the component of torsional displacement in the direction under consideration, as specified in Section 1654.3.3
- T_I = period of seismic-isolated structure, in seconds, Formula (54-2), but replaced by Equation (7) below.
- Z = seismic zone factor, Table 16-I
- N_I = numerical coefficient related to fault proximity and potential magnitude, Table A-16-D
- S_I = numerical coefficient for site-soil profile, Table A-16-C
- B = numerical coefficient related to the effective damping of the isolation system, Table A-16-E, [Note: $B \approx \left(\frac{8}{p}\right) b^{1/3}$ can be used in computer programs.]
- W = total seismic dead load above the isolation interface, as defined in Sec. 1628.1
- β = effective damping of the isolation system, Formula (61-2)

The additional terminology introduced by the use of BNC isolators includes:

- F = Restoring force proportional to displacement
- Q = Dissipative force proportional to velocity
- φ = Ratio of restoring force to total seismic dead load = F / W = constant
- α = Ratio of friction damper force to total seismic dead load = Q / W = constant
- C = Ratio of total force (F+Q) to total seismic dead load = φ+α = (F+Q) / W = constant

The displacement and period are defined in UBC by the following equations.

$$D = \frac{10ZS_I T_I}{B} \tag{UBC 54-1}$$

$$T_I = 2p\sqrt{\frac{W}{k_{\min} g}} \tag{UBC 54-2}$$

The dynamic stiffness of the isolator is defined by Equation (6)

$$k_{\min} = k_{\max} = k = \frac{CW}{D} = \frac{CW4p^2}{gCT_I^2} = mw_I^2, \tag{6}$$

where $m = \frac{W}{g}$ and $w_I = \frac{2p}{T_I}$.

UBC Formulas (54-1) and (54-2) are modified for BNC isolators such that we obtain Equations (7) and (8).

$$D = \frac{gCT_I^{\ 2}}{4p^{\ 2}} \tag{7}$$

$$T_I = \frac{ZN_I S_I}{BC} \tag{8}$$

The damping term β used to obtain B is calculated with Equation (9).

$$b = \frac{2a}{p(a + j)} = \frac{2a}{pC} \tag{9}$$

Cost Implications: We have examined two options: Option “A” is configured around the use of conventional resilient base isolation bearings beneath the columns supporting the cleanroom; Option “B” is configured around implementing several other approaches in a single design: friction dampers, isolated cleanroom flooring, and isolated tools. The cost of implementing the Ball-N-Cone® system shown in Figure 6 is about $15/ft^2, excluding the cost of the floor tiles and pedestals. We have estimated that it would cost between $15,000,000 and $20,000,000 to install a conventional system (Option “A”) and around $1,000,000 to install the Option B system. The Option 'B' design is significantly less expensive than the Option 'A' design. Furthermore, Option 'B' is easier to execute under the fast track construction schedules typical for wafer fab facilities. It can be installed as part of a renovation (with some compromises on headroom), and it is itself amenable to renovation. On the other hand, retrofit of base isolators beneath building columns is possible, but extremely complex.

SUMMARY

The *VISION 2000* document provides a framework by which performance based engineering can be applied to the seismic design of facilities. The goal is to control the seismic risk associated with a building to pre-determined levels of acceptability. This approach represents a significant improvement over current building codes, yet it does not address buildings in which the loss of functionality for any period of time might pose catastrophic economic consequences.

Based upon an argument of economic impact, we have proposed that fabs <u>and their contents</u> be classified as *Essential Facilities*. We have presented a scheme by which the contents and operational integrity of a fab can be seismically protected. The important aspects of that scheme are summarized below:

- A design basis earthquake is selected through which the facility is to remain operational.
- The building shell is built to withstand this earthquake and remain occupiable immediately following the earthquake.
- The structural floor beneath the cleanroom is designed to be vertically and laterally stiff (as it generally is now).
- The individual components of critical systems (power, HVAC, exhaust and distribution) and their supports are designed and/or selected to satisfy—to the extent practical—the requirements of Performance Category D. Vibration isolation of machinery, ducting and piping must not be compromised by seismic restraints, but restraints must be adequate to ensure complete operability immediately following the earthquake.
- The cleanroom as a whole is seismically isolated:
    - The cleanroom walls, HEPA filters, process tools and a portion of the distribution system are supported on a framed system, which also supports the raised access floor. The framing system is in turn is supported on base shear isolation.
    - Individual heavy or vibration-sensitive tools would be supported from independent steel frames, as they are now, but those frames would also be supported by seismic isolators.

- All connections spanning between the building shell and the isolated cleanroom must have adequate compliance to accommodate the travel of the isolation system.

We have presented a scheme in which this isolation takes the form of ball-and-cone isolators, but the concept would also work with resilient base shear isolators which are capable of large lateral displacements and are sufficiently shallow.

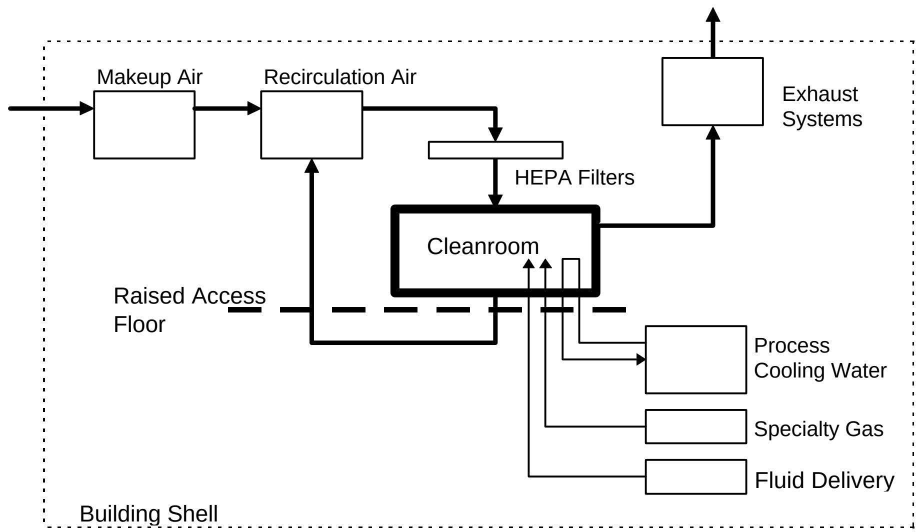

Figure 1. Schematic Diagram of a Cleanroom

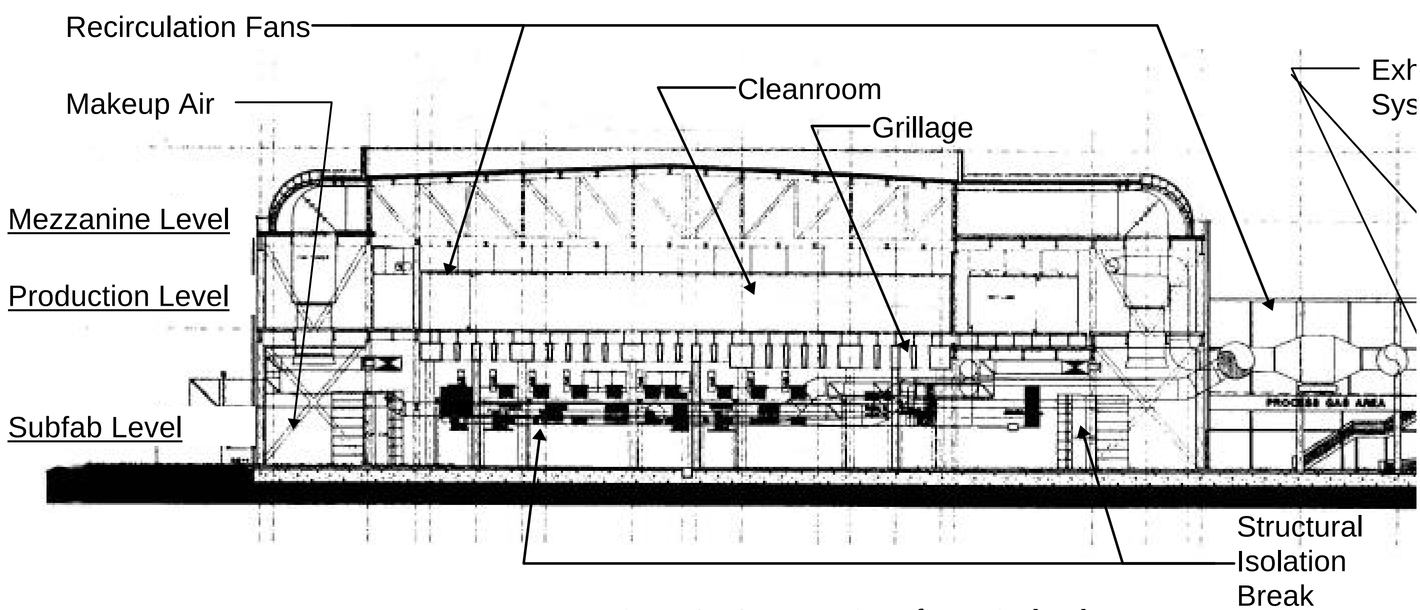

Figure 2. Cross-section of a Typical Fab

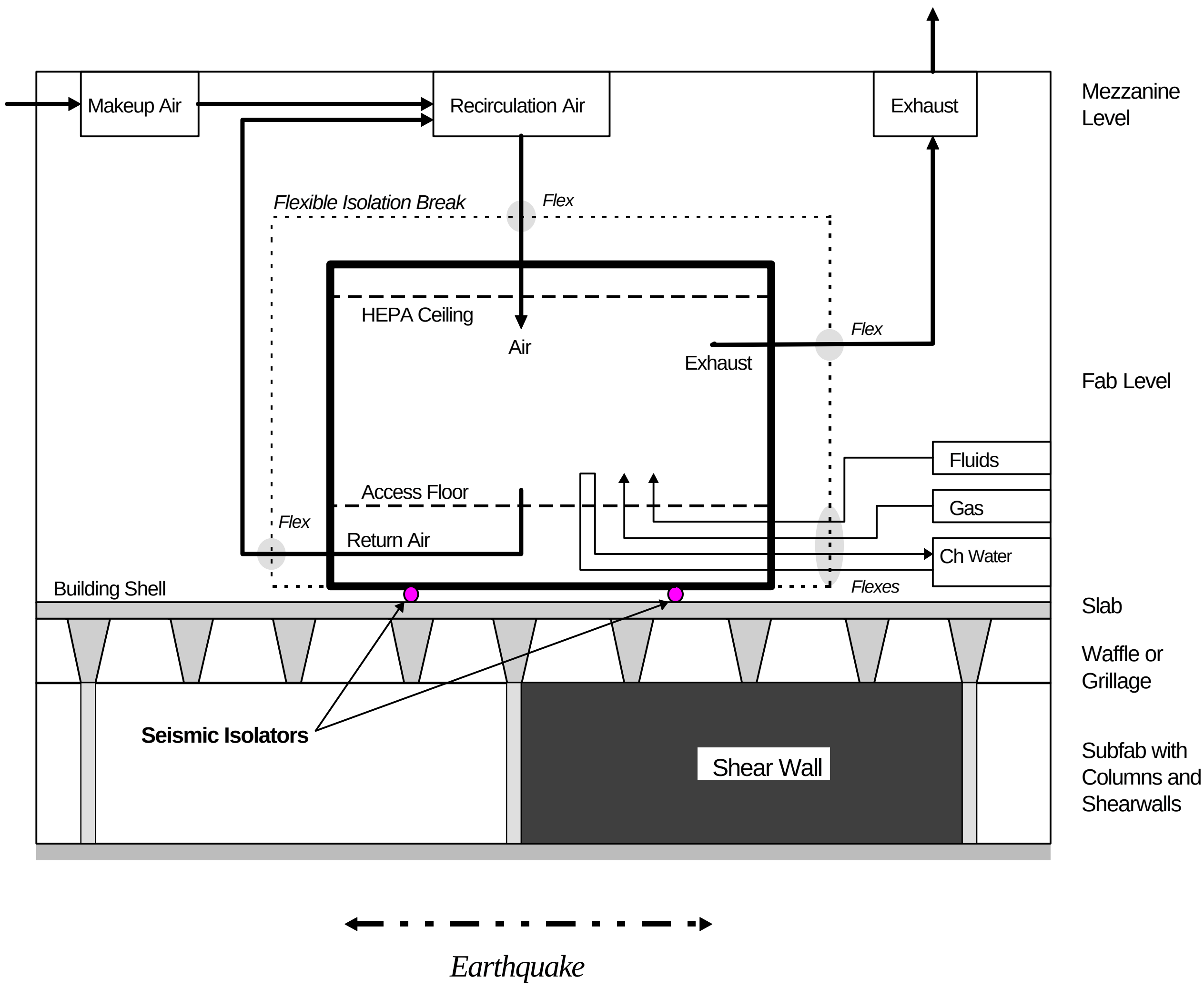

Figure 3. Proposed Isolation Scheme for Cleanroom

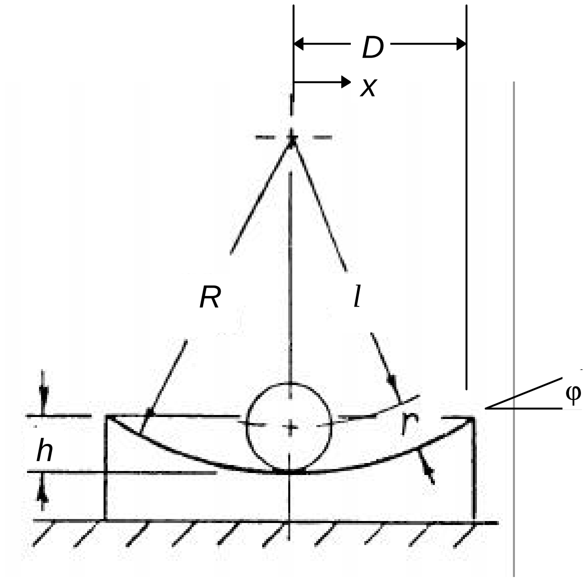

Figure 4. Ball in Spherical Cup — Coordinate System

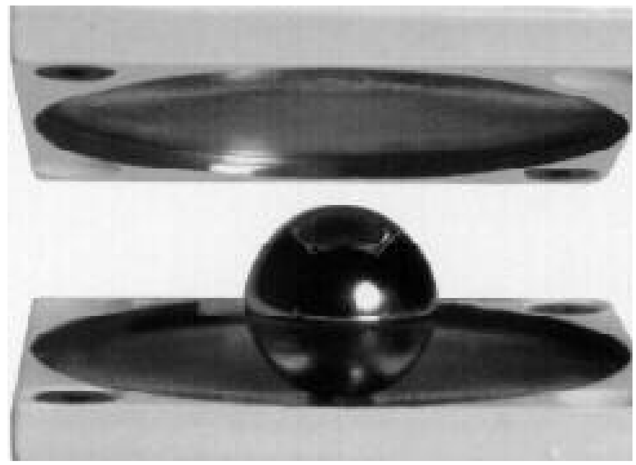

Figure 5. Exploded View of Ball-N-Cone â Bearing. (Tekton Inc., U.S. Pat. No. 5,599,108, and other patents pending)

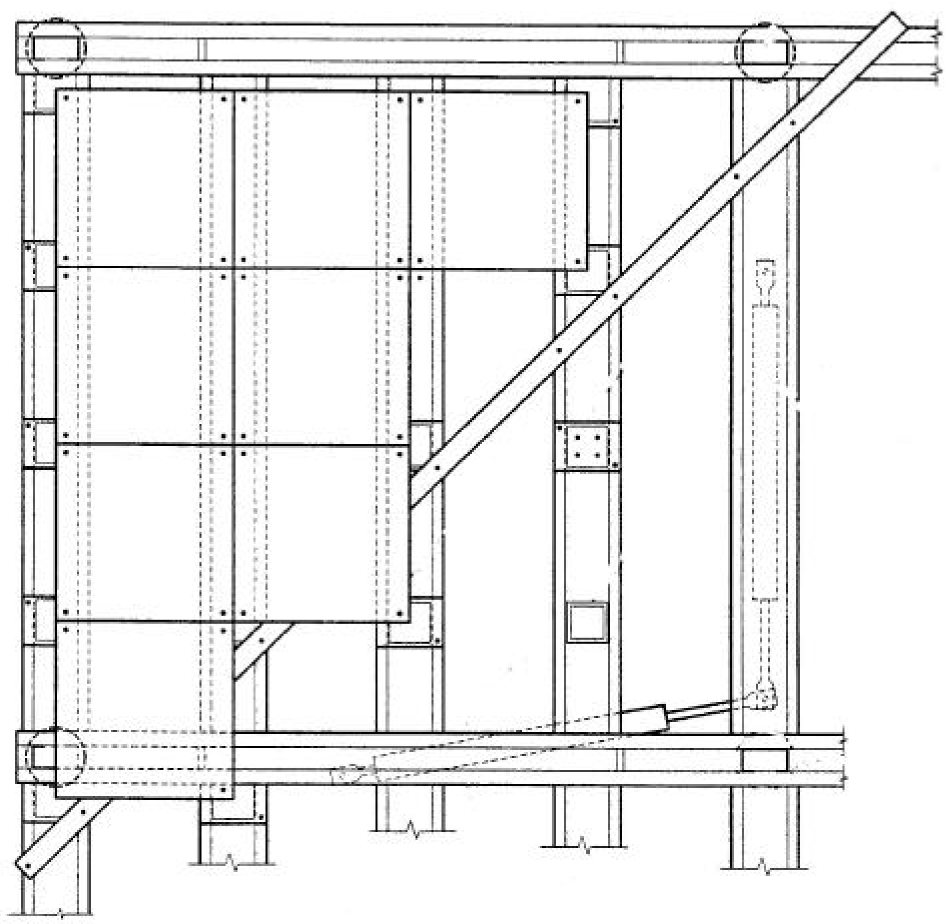

Figure 6. Plan View of Proposed System for Isolating Raised access Floor

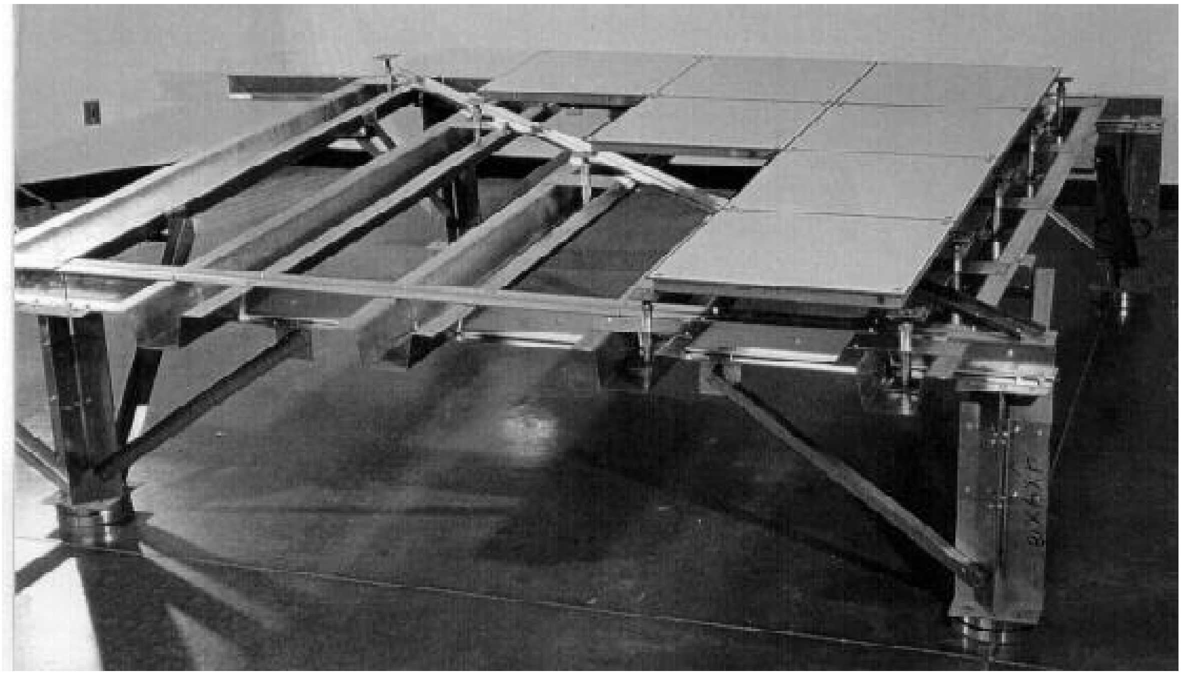

Figure 7. Photograph of Prototype System of Isolated Raised Floor

Figure 8. Close-up of Base Isolator