Program Development

Designing for Worker Safety

Moving the construction safety process upstream

By Steven Hecker, John Gambatese and Marc Weinstein

EFFORTS TO IMPROVE WORKER SAFETY on construction sites can take many forms. While safety hazard mitigation measures have traditionally been implemented solely by the builder during the construction phase, many believe that additional actions can and should be taken earlier in the project, during the planning and design phases (Whittington, et al; Suraji, et al; Gibb, et al). Interventions to eliminate hazards before they appear on the jobsite are commonly known as "designing for construction safety." This approach is consistent with the hierarchy of controls, common to the SH&E profession, which identifies designing to eliminate or avoid the hazard as the preferred means for reducing risk (Manuele).

Steven Hecker *is associate professor and director of occupational safety and health programs at the University of Oregon (UO) Labor Education and Research Center (LERC), where he has been on faculty since 1980. Since 1995, he has directed a NIOSH-funded applied intervention research program in construction ergonomics and organizational safety management. Hecker is also program director of the Oregon Labor Safety and Health Education Program, a training project for Oregon's labor unions. Hecker holds an M.S. in Public Health/ Industrial Hygiene from the University of Washington.*

John Gambatese *is an assistant professor in the Dept. of Civil, Construction and Environmental Engineering at Oregon State University. He worked as a structural engineer for Degenkolb Associates in San Francisco and as a project engineer for the construction management firm of O'Brien-Kreitzberg & Associates in Seattle. Prior to Oregon State, he taught for three years at the University of Nevada, Las Vegas, and for one year at the University of Washington. He has developed computer programs related to construction safety, including* Design for Construction Safety ToolBox *and* Construction Inspection Guide. *Gambatese holds B.S. and M.S. degrees in Civil Engineering from the University of California at Berkeley, and a Ph.D. in Civil Engineering from the University of Washington, focusing on construction engineering and management. He is an associate member of ASSE's Columbia-Willamette Chapter.*

Marc Weinstein *is a research associate at UO's LERC. Prior to this, he was assistant professor of management at the UO Lundquist College of Business. Weinstein's research covers a broad range of issues related to occupational safety and health, employment relations, employee involvement and employee stakeholder rights. His work has appeared in a number of edited research volumes and peer-reviewed publications, including* The British Journal of Industrial Relations, The International Journal of Management & Organizations, East European Politics & Society, *and* The International Journal of Human Resource Management. *Weinstein holds a Ph.D. in Management from Massachusetts Institute of Technology.*

While designing for construction safety has become increasingly common in Europe and Australia, until recently, few, if any, large-scale design-for-safety initiatives have been launched in the U.S. This article describes a full-scale attempt to implement a design-for-safety effort in the U.S. The site for this initiative was a semiconductor manufacturing facility in the Pacific Northwest. To illustrate the potential and complexity of safety-in-design efforts, the authors trace the origins and evolution of this initiative, giving particular attention to the roles of the three primary organizations involved—owner, design firm, and construction management/general contracting (CM/GC) firm—and to the role of trade contractors in the process. Mediating and negotiating the relationships among these participating organizations was an important facet of this effort. This article largely presents findings about the process itself and the experience of the participants. (See Weinstein, et al, for an analysis of the impact of this effort on design changes of the facility).

Current & Recommended Industry Practices in Designing for Construction Safety

The foci of designing for construction safety efforts are typically the incorporation of construction knowledge in the design effort and consideration of safety early on and throughout the project. Hinze recommends a holistic approach of designing for the entire life cycle of a building, including the construction process. He contends that effectively addressing construction safety issues means the designer must consciously assess the implications of each construction phase on safety as the facility is being built. In addition, he suggests conducting a thorough risk assessment of each design component (Hinze, et al).

This assessment can be conducted in many ways. Coble and Haupt suggest that one effective method is to increase the coordination between designers and construction foremen, particularly those with excellent safety records. They contend that foremen can make significant contributions to the design-for-safety effort, provided that designers recognize and harness their skills and site experience. A complementary approach might entail a series of constructability reviews that incorporate the consideration of construction worker safety [Gambatese(b)].

An early impetus for design-for-safety initiatives came in 1991, when a European Commission study of four European countries found that 60 percent of construction accidents could have been eliminated, reduced or avoided if different choices had been made prior to the construction process itself (European Foundation). Recognizing the value of the safety-in-design concept, the European Commission enacted the Temporary or Mobile Construction Site Directive in 1992, which placed responsibilities on owners and designers as well as contractors for construction safety and health (CEC).

To comply with the European Union directive, Great Britain introduced the Construction Design and Management (CDM) regulations in the U.K. that translated these requirements for construction owners, architects and contractors into British law and practice (CDM Regulations). CDM places a duty on the designer to ensure that any design prepared avoids foreseeable risk to construction workers (MacKenzie, et al).

For this mandate to be effective, designers need clarity about what they are expected to achieve and guidance about how to reach those goals (Anderson). A lack of guidance and supporting resources has resulted in slow acceptance and fulfillment of designer responsibilities under the CDM regulations (Baxendale and Jones). Ash contends that success within CDM is often found when designers and constructors already work together more closely, such as in design-build and construction management companies. Processes developed and implemented to support the consideration of construction safety in the design stage can help to overcome these associated barriers.

In Australia, the construction industry and New South Wales government joined together to develop the Construction Hazard Assessment Implication Review (CHAIR) process (WorkCover). This design-for-safety tool is essentially a structured review process that incorporates focused reviews at different points in the design phase. The reviews examine the various elements of a design using guidewords or prompts such as size, height/depth, position, location, movement, load, force and energy. The reviews provide a detailed and systematic means of examining construction, maintenance, repair and demolition safety issues associated with a design.

Practical application of the design for construction safety concept has centered on the implementation of design assessment and review processes. In one example, Foster and Partners, an international architecture and design firm based in London, makes safety and health a facet of all of its programming and design activities (Istephan). Translating both the CDM regulations and its own design philosophy into practice, the firm uses a program that involves multiple components:

- training to increase employee competence;
- design reviews;
- integration of safety and health with existing quality assurance systems;
- integration of safety into other systems (e.g., specifications);
- production and transfer of information;
- management of knowledge through feedback, adjustments and lessons learned.

An early start and planned timing of the design reviews play a critical role in the effective application of this program (Istephan). Such programs are often bolstered by the use of risk assessment and hazard identification tools. Arup Project Management's approach, for example, involves the use of initial hazard identification and risk assessment tools during the design, plus involvement in the review of the design during the construction phase (Marino Duffy).

By contrast, formal practice of designing for construction safety is uncommon in the U.S. In addition to the country's lack of regulatory requirements, other barriers hinder the practice of designing for safety in the U.S. as well:

- OSHA places safety and health responsibility on the employer, most often the general or trade contractor in construction.
- Architects and engineers fear added liability for involvement in construction safety [Gambatese, et al(a); DeVries and Grigg].
- Construction and design practice tends to be narrowly specialized [Gambatese(a)].
- Preconstruction collaboration between the designer and constructor is commonly minimal due to the traditional contracting structure of the construction industry.
- Safety-in-design tools, guidelines and procedures are not widely available [Gambatese, et al(b)].
- Architects and engineers receive little or no formal education on issues of construction worker safety [Hinze and Wiegand; Gambatese, et al(b)].

While designing for construction safety has become increasingly common in Europe and Australia, until recently, few, if any, large-scale design-for-safety initiatives have been launched in the U.S.

Data Sources & Research Methodology

The design-for-safety effort that is the subject of this study took place from September 2000 through January 2002 during the programming and design phases for the construction of a $1.5 billion semiconductor research and production factory (known in the industry as a "fab") designated D1D on a large existing campus of Intel Corp. This project consisted of approximately $700 million in direct construction costs and was the third such fab built on this campus since 1995. Intel has constructed and operated semiconductor fabs in the U.S., Europe, Asia and Israel, and the construction and design firms involved in the current project, Hoffman Construction, and Industrial Design and Construction (IDC), also worked on several of these projects.

In the lead-up to the programming phase of the D1D project, Intel decided to develop and apply a

Programming Participant Interview Questions

Interviewee Background

1) How many years have you spent working in construction and/or design?

2) How long have you worked on Intel projects?

3) How long have you worked on the Ronler Acres site?

4) Have you been involved in a programming effort before D1D?

5) Which workgroup are you in and who were the other members in the group?

6) Had you worked with the other members of your workgroup prior to the D1D programming activity?

Defining/Describing the LCS Process

7) Are you familiar with the Life Cycle Safety (LCS) process?

8) Can you share what your understanding is of the goals and objectives of LCS on the D1D project?

9) Can you explain the LCS evaluation procedure as planned for the programming phase of D1D?

How Interviewee Workgroup Participated in LCS Evaluation

10) What was your responsibility in the LCS evaluation of proposed changes during programming?

a) How were these responsibilities communicated to you?

11) How did your workgroup go about evaluating LCS compared to other FSCS goals such as cost?

a) What specific tools and procedures did you use? How useful were the tools?

12) Outside of your workgroup, where else did you go to get input for LCS evaluations?

13) In retrospect, were there other sources that could have provided helpful input to your LCS evaluations?

Process Outcomes

14) How did the LCS evaluations affect your decisions in programming?

15) What did LCS add to or change in relation to earlier or standard methods of designing and constructing fabs?

16) What did you learn from the LCS evaluation during programming? What modifications would you make to LCS? Would you recommend doing it again?

17) Do you think the LCS evaluation resulted in the design of a safer building for construction workers and occupants?

18) In retrospect, were you adequately prepared for your role and responsibilities in LCS during programming? If not, what else could have been done?

design-for-safety process, which came to be called "life cycle safety" (LCS). Intel and the team of researchers from University of Oregon and Oregon State University negotiated an arrangement in which the research team would act as outside evaluators with the goals of documenting the process, assessing the experience of the various participants, and identifying and assessing measurable outcomes where possible. While the LCS process focused on safety over the entire life cycle of the facility, the research assessment concentrated on the construction phase.

The research team collected data through observation, document review, semistructured interviews and focus groups. University members of the research team periodically attended the weekly or biweekly meetings of the site team (LCS Task Force) that developed, implemented and monitored the safety-in-design effort. These meetings took place over a period of approximately 18 months. The team also had access to all meeting minutes, and two members of the task force acted as key informants in clarifying task force activities and LCS activities that were occurring in the field under the task force's purview. Two of the authors attended the major meeting and training session at the kickoff of detailed design where the process was rolled out and presented to wider audiences of design, construction and owner personnel with specific roles in the project. The research team had access to all but the most confidential documents used in the design process and the safety-in-design activities.

Three members of the research team conducted semistructured interviews with 23 members of the workgroups who had the major responsibility for assessing design options during the programming—or conceptual—phase of the design process. Those interviewed worked for the owner, the design firm or the CM/GC. The interviews were conducted using a script with 18 questions in four categories: 1) personal background and experience; 2) definition of the LCS process; 3) participation of the individual and his/her workgroup in the LCS review process; and 4) LCS process outcomes ("Programming Participant" sidebar, left). Questions in the first category were generally short and closed-ended, while the remaining questions were open-ended. Interviewers followed the script, but were permitted to explore other areas where the discussion might lead. Interviews were audio recorded and subsequently transcribed.

In addition to the interviews, two of the authors conducted separate focus groups with 1) the LCS Task Force; 2) the three facilitators who organized LCS evaluations of design packages during detailed design; and 3) a group of eight designers who worked on the project. These were also audio recorded and transcribed. Scripts similar to that used with the programming workgroup interviews were also used for these focus groups, but questions were tailored for each of the three groups.

The task force questions focused on the development of the process and its tools; monitoring of implementation; how the various project organizations supported the process and worked together; whether and how goals and objectives changed over time; and how the task force assessed its own performance and the impact of LCS.

The facilitator focus group questions were specific to the process and outcomes of the LCS reviews, but the facilitators were also asked for their broader assessment of whether and how LCS review participants exhibited changes in perspective or behavior regarding safety and life cycle considerations in the design process.

The questions for designers overlapped some with the other groups in terms of their perceptions of the process, interactions with other parties such as trade contractors and ultimate impact of LCS on the design. However, in this case, the discussion focused more on how design work actually proceeds and what impact the insertion of LCS made on their work as designers. It should be noted that in all cases the discussion was permitted to extend beyond those issues in the original script if it was relevant to the study goals.

A major component of the LCS process was the LCS reviews conducted on all design packages. The research team analyzed comments that were the output of these reviews as part of the assessment of the overall process. Finally, 28 additional "exit focus groups" were conducted with general foremen and field superintendents from 34 trade contractors that performed 91 percent of the project's construction work. Safety professionals from the project participated in a 29th focus group. Two members of the LCS Task Force led these focus group interviews, which were conducted at or near the time of completion of the contractors' work on the site.

The purpose of these sessions was to gather data on the impact of LCS decisions on the construction work as actually performed. Three to eight informants participated in these focus groups. In some cases, participants worked for a single contractor; in other cases, more than one contractor was represented. The facilitators asked participants to describe elements of the design that they felt contributed to improved safety and health or presented risks that could have been reduced. The contractor representatives sometimes brought construction drawings to describe and illustrate specific design elements that they found either positive or negative. The facilitator wrote observations on flipcharts and comments were recorded. Following each session, comments from these exit focus groups were transcribed and later entered into a spreadsheet for analysis. The research team documented 465 comments on design and/or construction safety in these focus groups.

The findings presented in this article are largely derived from transcripts of the 23 workgroup participant interviews and the three focus groups (LCS Task Force, LCS facilitators and IDC designers). The exit focus group interviews were analyzed as part of a larger effort to assess the impact of the LCS effort on design changes (Weinstein, et al).

Origin & Development of the LCS Process

Several separate but related events and experiences led to the focused safety-in-design effort on D1D. Intel's Factory Strategic Capability Segment (FSCS), a high-level group of corporate managers, established the overall goals for the project, including cost targets, schedule improvements, reductions in energy consumption, environmental emissions, adaptability for future manufacturing technologies and improved safety through design.

Intel's interest in pursuing design implications for construction and operations had been heightened during the construction of a fab in Ireland some years earlier, when the European Union Directive on Temporary and Mobile Construction Worksites was being converted and ratified into regulations in EU member states (CEC). The incorporation of construction safety considerations into the design phase was moving slowly, even where required by law in the U.K. and other European countries (Gibb), and survey and interview studies revealed little attention to the safety of construction workers in U.S. construction and design practice [Hinze; Gambatese, et al(a)].

Despite this, inclusion of improved safety through design among the FSCS goals was consistent with Intel's commitment to continuous improvement and its bringing forward "lessons learned" from earlier projects. IDC, the design firm, also had a standing interest in safety as illustrated by its development of a safety-in-design checklist, a database of design issues identified as potential problems for construction or facility operation. For some time, certain IDC designers had wanted to expand this into a more interactive, open-ended tool for the designers, rather than simply a "check-the-box" exercise.

Intel's ergonomic initiatives on the same campus also contributed to FSCS's recognition of the role of design in construction safety [Hecker, et al(b)]. These initiatives in 1995-96 and 1998-99 heightened awareness of risk factors for musculoskeletal injuries during construction and had identified several specific instances of design decisions that exacerbated some of these risk factors.

An example of a lesson brought forward came from a decision not to include a "waffle deck" on an earlier fab construction project. To accommodate the many electrical and mechanical utilities that must pass from the subfab up to the semiconductor tools at the cleanroom level, the concrete floor of the cleanroom is typically poured as a waffle deck containing thousands of circular openings covered by steel "popouts." This type of floor design permits the utilities to be installed without having to core drill concrete each time a pipe or conduit needs to be rerouted. However, a value engineering decision on this earlier project resulted in a section of the floor being poured without the circular openings. The planners determined that this section would never be needed as cleanroom.

However, two years later during a retrofit of this fab, this section was converted to cleanroom use. As a result, thousands of 14-inch concrete cores had to be drilled from above and handled from below, creating exposure to ergonomic risk factors among the workers, especially those doing overhead work. The initial savings of about $100,000 by not pouring the waffle deck eventually became a $1.1 million core-drilling contract. This sequence of events not only provided the D1D task force a good lesson regarding waffle decks, but also highlighted the need to consider the entire life cycle of the building in design decisions.

It is important to note that the safety-in-design process on D1D was introduced into an environment where an already extensive construction safety and health program was in place. The project was under an owner-controlled insurance program. The owner and construction manager maintained strong prequalification criteria for trade contractors including both incident rate and safety and health program standards. The site mandated extensive safety and health training requirements for all employees, including topics that went well beyond OSHA requirements. The ergonomic programs introduced on earlier projects on this campus had evolved into a more intensive ergonomics initiative introduced on D1D, involving three tiers of training for trade workers, foremen and contractor safety personnel, and a field intervention program staffed by a part-time ergonomist.

The short-hand for the objectives of the process, "right people, right time," meant that input from the right people had to be heard when it could still make a difference in the building design.

Safety-In-Design Task Force

The Intel project manager established a Safety-In-Design Task Force to develop a process for increasing focus in the design stage on safety issues in construction and subsequent building phases. This group met weekly in the early part of the programming phase of design, when major building concepts were evaluated against a plan of record and the building layout was determined. The group's membership included senior representatives of the three main parties of the design process: owner, design firm and construction manager. Having built several previous fabs for the owner, Hoffman was retained as the construction manager for the programming phase in recognition of the importance of bringing the knowledge and experience of the construction community into the process, but at that point the firm was not guaranteed the construction management contract for the construction phase.

Intel's members of the task force represented different departments within the company. Some were from Construction Projects and Engineering, which oversees capital projects and delivers them to the production part of the company. Intel Facilities Operations was also represented because operating and maintenance technicians were groups affected by design decisions, along with construction workers. A third-party consultant facilitated the task force to help provide visibility to hidden assumptions and manage potential power struggles that might arise from a traditional construction hierarchy.

At the start of its work, the task force struggled with translating the concepts of safety in design into a concrete process that could be applied on the D1D project. An earlier area of agreement was to:

> . . . accelerate the input of craft workers specifically and engage them in that design process so that we could take advantage of their vast knowledge as well as advance the progress in design (LCS Task Force Focus Group).

Subsequently, the task force:

> . . . actively sought a way to collect information that would legitimize some of the issues and would allow decision makers to see there was substantive information that people could bring to the process and how it could be useful in the early conceptual deliberations about . . . what was built (LCS Task Force Focus Group).

To this end, members of the task force conducted focus groups with trade contractor personnel who had worked on earlier projects at the campus. Four disciplines—structural/architectural, dry mechanical, electrical and piping—provided input concerning design-related elements that they believed affected safety and constructability for members of their trade on previous or current projects. Subsequently, the Intel operations member of the group conducted a similar exercise with facilities maintenance personnel. The focus groups provided a database of 196 safety and health items with concerns and suggested design solutions (LCS Task Force). This information went to the discipline-based workgroups, which were composed of representatives from the owner, the designer and the construction manager, and who would transition from the programming phase into design development of D1D.

As the Safety-In-Design Task Force continued meeting, it began to crystallize its goals. One member summarized the group's purpose:

> . . . to come up with a process then roll it out, implement it, get feedback, find out what's not working and what is, and fix it. We would kind of feed and nurture this thing as it continues to really grow (LCS Task Force Focus Group).

The task force's initial organizational and brainstorming efforts produced the following objectives and deliverables:

•Short term: Involve trade contractors immediately in the design phase to more accurately assess risks that will enable better decisions to be made.

•Long term: Develop a process that includes accountability, involvement by all players and recognition for life cycle safety throughout the life of the project.

•Develop a database for tracking problems and solutions for use in the future.

A shorthand for the objectives of the process was "right people, right time," signifying that good ideas were only effective if they were contributed early enough to be incorporated into the design and that people with the appropriate expertise and authority need to participate. Therefore, the input from the right people had to be heard when it could still make a difference in the building design.

Within the first months of its work, the task force decided to change the name of the initiative from Safety in Design to Life Cycle Safety. The concepts were distinct, but a task force member recalled:

> The notion of life cycle didn't come from safety in design, but piggybacked [it]. So this was a project that also was ready to move beyond these first thoughts as a way to look at the programming of the building concept (LCS Task Force Focus Group).

Intel's overall goals for the D1D project were aimed at designing and constructing a fab that would satisfy needs and address safety issues throughout all phases of the building's life cycle: construction, operation, maintenance, retrofit, decommissioning and demoli-

Figure 1

Option Evaluation Sheet—Programming

Option Evaluation Sheet — **Intel D1D Programming**

Option Title

Option Description

Description of Issue:

	Evaluation Criteria *FSCS GOALS*	wt.	Score (worse 5- … *0 … 5+ better)	total	Comments
C1	Dollars / Sq Ft	1		0	
C2	Tool Install Cost	1		0	
E1	Energy Conservation	1		0	
E2	Reduce Emissions	1		0	
S1	Support 2 Technology and 5 HVM Generations	1		0	
S2	Maintain Existing Reliability and Maintainability	1		0	
S3	Improved Life Cycle Safety	1		0	
S4	Maximize Reuseability and Fungibility	1		0	
D1	Overall Construction Duration	1		0	
D2	Consructability	1		0	
D3	Tool Install Duration	1		0	
		1		0	
				0	Total Score

Comments:

tion. In turn, all phases of the life cycle needed to be considered during each stage of design including: programming, detailed design, field design, tool install, startup, conversion and demolition. This was one reason for the name change. Another was that the task force felt that "safety in design" implied that all safety responsibility rested with the design firm, and the group wanted it to be clear that all parties had to contribute both to safer design and to overall project safety.

The task force work was not focused only on safety issues. Rather, members paid equal attention to the other FSCS goals and assumed the responsibility of balancing cost, quality, schedule and safety. Many conversations focused on what was an acceptable level of risk in relation to this balancing process.

By the same token, interviews with Intel and Hoffman personnel familiar with the D1D planning process also suggest that project management recognized that an expanded design review process at the front end could have schedule benefits during construction. The schedule milestones set out for this project were unprecedented, and management recognized they could not be met without other changes to the design and construction process. The decision to build the fab from the center out ("center build") was one of these changes. The desire to minimize late changes to design and construction drawings was another motivation for introducing LCS and more extensive upfront design review.

LCS in the Programming Phase

Programming is the first stage of the design process in which major building concepts and scope are laid out. During programming, design options were evaluated against a plan of record (POR). For this project, the POR was primarily based on an earlier fab concept initially built on the Ronler Acres campus and secondarily on a copy of this design built in another state. The evaluations were carried out in seven discipline-based workgroups:

- civil/structural/architectural (CSA);
- telecommunications;
- instrumentation and controls (I&C);
- process;
- electrical;
- mechanical;
- life safety.

Each workgroup included at least one representative of each major party: owner, designer and construction manager. Workgroups ranged widely in size from three to 12 or more depending on the scope of the work. Some groups used outside resources in conducting evaluations, including trade contractors, vendors, end users and safety personnel from Hoffman or Intel. The workgroups were responsible for making design recommendations for the major systems of the fab at the conceptual level. Design options were to be assessed against the building goals that had been set by FSCS.

To address the FSCS goal of increasing safety through design, workgroups evaluated specific design options to assess their positive or negative impact on safety at each stage of the building's life cycle. When workgroups reported their programming decisions to the Design Review Task Force

Figure 2

Risk Comparison Form

D1D Life Cycle Safety Evaluation

RISK COMPARISON

Description: Subfab height / Basement Decision
Evaluation By: LCS WG (1/19/01)
Instructions: *1. Compare each option against POR. Options with risks equal to the POR option are assigned 0.*
2. Assign a relative value from -5 (high risk relative to POR) to +5 (low risk relative to POR) to each risk.
3. Using the attached checklist as a guide identify Risk associated with each of the four specific categories.
4. Identify the Work Group or Area Group performing the evaluation.
5. Include the evaluation as backup to the presentation for the particular option.

Category	Risks	Relative Evaluation of Options					
		POR	16'9"	2 SF			
Construction	subtotal	0	-1	7	0	0	0
	Trench construction and deep AWN pit create excavation hazards relative to cave-in. After backfill of trench/AWN, fall exposures remain during basebuild.	0	0	2			
	Increasing height of subfab requires taller ladders & ladders on catwalks to access utilities during basebuild. Increased fall exposure and use of subfab space for wider bases.	0	-1	0			
	Access to tie-off points for fall protection difficult due to utility congestion and rack design.(e.g. Electrical distribution, duct sizing)	0	-1	2			
	Elevated material handling of large conduit in central trench because in slab locations under subfabs	0	0	1			
	Congestion of utilities in overhead (from electrical distribution & duct sizing) creates limited routing for other utilities, awkward postures, difficult access.	0	1	2			
RetroFit/Tool Install	subtotal	0	3	8	0	0	0
	Cutshops & pre-fab areas remote from fab/subfab. Increased material handling.	0	0	1			
	Congestion in subfab requires climbing out on steel over the utilities increasing exposure to fall.	0	1	2			
	Increasing height of subfab requires taller ladders & ladders on catwalks to access utilities during tool install & retro-fit. Increased fall exposure and use of subfab space for wider bases.	0	-2	0			
	Access to tie-off points for fall protection difficult due to utility congestion and rack design.(e.g. Electrical distribution, duct sizing)	0	1	2			
	Congestion of utilities in overhead (from electrical distribution & duct sizing) creates limited routing for other utilities, awkward postures, difficult access.	0	1	2			
	Catwalk height and utility space options create head-knockers.	0	2	1			
Mfg. O&M	subtotal	0	0	5	0	0	0
	Subfab congestion. Restricted access to equipment for PMs.	0	0	1			
	Leaks & drips into tool's electrical equipment.	0	0	3			
	Housekeeping issues due to restricted space for spare parts & PM supplies.	0	0	1			
Facilities O&M	subtotal	0	0	14	0	0	0
	Increasing height of subfab requires taller ladders & ladders on catwalks to access utilities during basebuild. Increased fall exposure and use of subfab space for wider bases.	0	-1	0			
	Access to tie-off points for fall protection difficult due to utility congestion and rack design.(e.g. Electrical distribution, duct sizing)	0	-1	2			
	Subfab congestion. Restricted access to equipment for PMs.	0	0	2			
	Leaks & drips into facility electrical equipment.	0	0	3			
	Access to isonlation valves and POCs.	0	1	2			
	Working above energized equipment at stacked transformers.	0	0	2			
	Overflows due to use of bucket pumps.	0	0	1			
	Sprinkler head obstruction by utility congestion.	0	1	2			

(DRTF), they were required to include LCS evaluations that also considered the implications of these options for other FSCS goals.

Members of the LCS Task Force developed several instruments that workgroups could use to perform the LCS evaluations. A visual chart—dubbed the "Cliffometer" after its developer—provided a format for workgroups to quickly evaluate a design option in a systematic and uniform manner (Figure 1). The Risk Comparison Form and Risk Mitigation Form (Figures 2 and 3) allowed for a side-by-side risk comparison of multiple design options for all relevant life cycle phases and provided a format for detailing mitigation plans for risks that could not be eliminated through design.

There was variation among workgroups and individuals in how they applied LCS to their programming tasks and how they perceived its utility. The LCS process and its tools were being developed concurrently with the kickoff of the programming phase. This, in part, explains why familiarity with the process varied among programming participants. Nine of the 23 participants interviewed about their programming experience had a detailed understanding of LCS. Workgroup leaders in general had the clearest understanding of their responsibilities while other members tended to follow their direction. The late start also explains why some groups used the LCS tools in a *post hoc* fashion—that is, they had already discussed several design questions before going back and using the Cliffometer or other instruments to perform their evaluations.

While LCS added a formal safety evaluation step to the programming phase, in reality it was most often integrated into procedures already used by the workgroups. In other words, most groups did not explicitly perform LCS evaluations as a separate step because some found LCS to be somewhat redundant with procedures they already used. For instance, the process group used a process safety analysis that mirrored the safety evaluation step in the programming phase.

A common theme in many interviews was the challenge of balancing competing goals. One respondent noted:

> That incremental increase in your safety is really a fuzzy increment. You don't know really if it's that much safer or not, or if it would ever be an issue. Is that worth $100,000? Is that worth $500,000? What's that really worth to you? Is that worth a month on your schedule to get that? Trying to sort out those kinds of issues is pretty tough (Electrical WG member interview, Aug. 2001).

LCS prompted initial consideration of designs from a safety perspective, but final decisions took into account all the goals. Cost and schedule were drivers for many decisions, but about half the respondents commented that safety was given

Figure 3

Risk Mitigation Form

D1D Life Cycle Safety Evaluation

MITIGATION PLAN

Description:

Evaluation By:

Instructions:
1. *Complete this evaluation for each change or option being evaluated.*
2. *Using the attached checklist as a guide, identify risk associated with each of the four specific categories. Add lines as required.*
3. *For each risk, identify what is required to mitigate the risk. In doing so you should evaluate if the risk can be minimized through design.*
4. *Identify the Work Group or Area Group performing the evaluation.*
5. *Include the evaluation as backup to the presentation for the particular option.*

Category	Risks	Mitigation
Construction		
RetroFit/Tool Install		
Operation		
Maintenance		

greater consideration in programming as a result of the LCS evaluation process.

> [On] previous projects it was informal. This is formal and this is tracked. See where it says champion here? You put somebody's name on there [and] they were responsible for it. They had to finish it and turn it in at some certain time. That way all the groups could see what other people were doing and what their progress was. It was a cool thing. I was beleaguered by it because there were a lot of changes going on, but when I look back on it, it was a worthwhile thing to do (I&C WG member interview, July 2001).

Some of those who felt that engineers already paid attention to safety considerations in previous programming efforts still agreed that formalizing the process added value:

> I think just having it out there as a requirement, actually as a formal process, helps us. I don't think that in another programming effort that we're not thinking about safety either. I think that we've done programming efforts in the past that have been very well thought through and people, I think, do think of safety items in those kinds of efforts, especially engineers need to be doing that because that's their charge (Electrical WG member interview, July 2001).

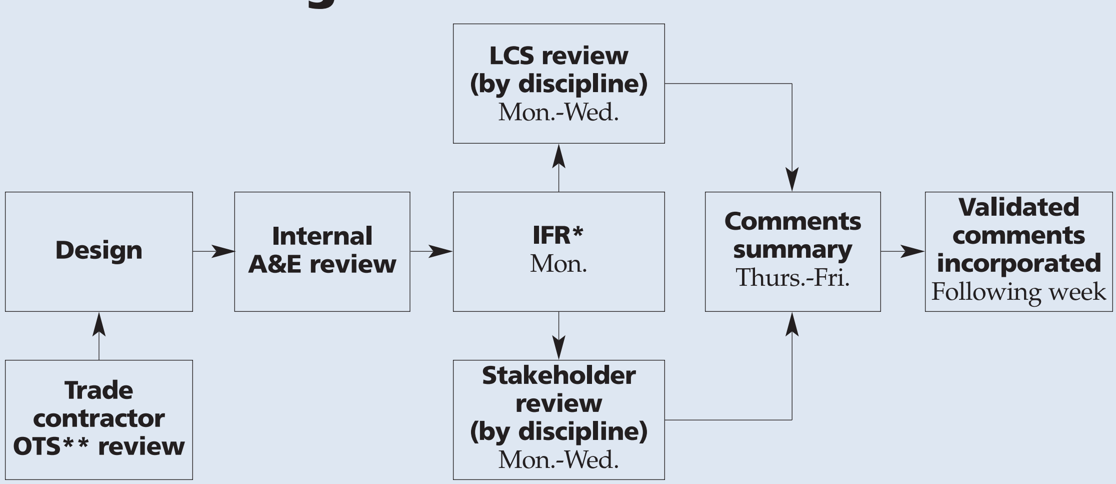
Furthermore, several participants commented that LCS increased the amount of cross-disciplinary discussion, a process that identified and, in some cases, resolved conflicts early in the design.

The involvement of targeted trade contractors in programming was a particularly notable departure from traditional design practice. These contractors provided preconstruction and predesign services, offering expertise usually not available at this stage of a project.

In a typical design-bid-build delivery model, neither trade contractors nor a general contractor are involved in programming or design. In this case, some contractors were hired as consultants without any guarantee of performing the work on which they consulted. The reliance on trade contractors throughout the design phase was somewhat curtailed later in the project due to an increasing focus on cost containment, but it was nevertheless a significant departure from past practice (LCS Task Force).

Figure 4

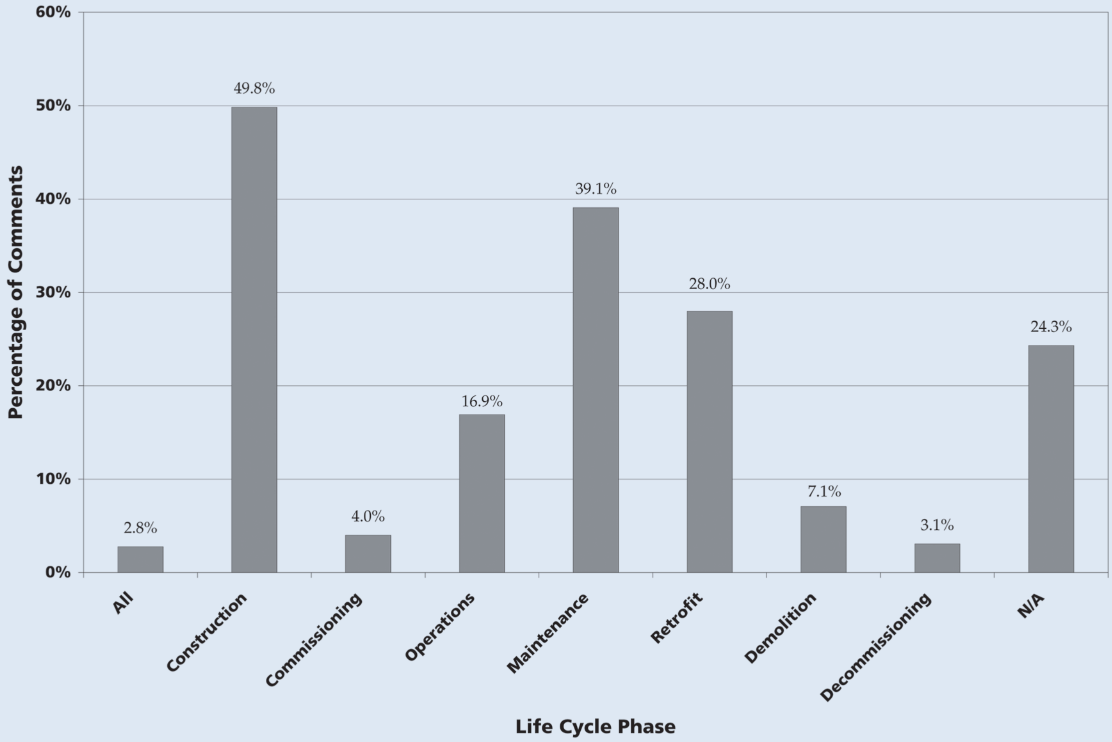
Detailed Design Review Process



**Issued for review.*
***Over the shoulder.*

Figure 5

LCS Review Comments by Life Cycle Phase



LCS During Detailed Design

After programming, the design process moved into the detailed design phase, which consisted of three subphases: 1) schematic design; 2) design development; and 3) construction documents. Safety in design was again incorporated into this phase as a continuous improvement process, specifically through the introduction of LCS reviews at the end of each subphase as a required concurrent step for all design packages. Design packages define a particular scope of work, such as site (excavation, grading, etc.), electrical in the main fab building or mechanical in the central utility building.

The D1D project had 22 design packages. As illustrated in Figure 4, packages were issued for review by the design team following trade contractor input and internal review by the design firm. The packages were then subject to two major external reviews: stakeholder review and LCS review. The design disciplines and Intel personnel responsible for the package scope of work performed the stakeholder reviews. Along with the internal A&E review, the stakeholder review is the main opportunity for cross-disciplinary technical review of the design packages. The separate LCS review included Intel maintenance technicians, trade contractors and SH&E staff, and focused on safety and health issues during construction, operations and maintenance, and subsequent building phases. Fifty-eight stakeholder reviews and 58 LCS reviews were conducted on the 22 design packages. According to LCS review documentation, trade contractor personnel were present for all but two of the reviews, and facilities technicians (operations and maintenance personnel) participated in all 58 LCS reviews.

The schedule for these reviews was quite compressed (Figure 4). Packages were typically issued for review on Monday of a given week. LCS and stakeholder reviews were held by Wednesday, with summarization of review comments and adjudication by the design team to follow.

Each of the three major organizations—owner, design firm and construction manager—provided a facilitator to organize and manage the LCS reviews. At least two facilitators were present for each review, one to run the meeting and the second to keep notes. The facilitators oriented the review group to the process, emphasizing the focus on safety during construction, operation and maintenance of the facility rather than a technical review. Technical comments were also recorded and became part of the package as well. After each review the comments were summarized by the facilitators and forwarded to the design team for adjudication. Most packages were reviewed three times, corresponding roughly to the 30, 60 and 90 percent points in design completion. For the second and third reviews, the adjudicated comments from the previous review(s) were provided and discussed.

Quality of LCS Reviews

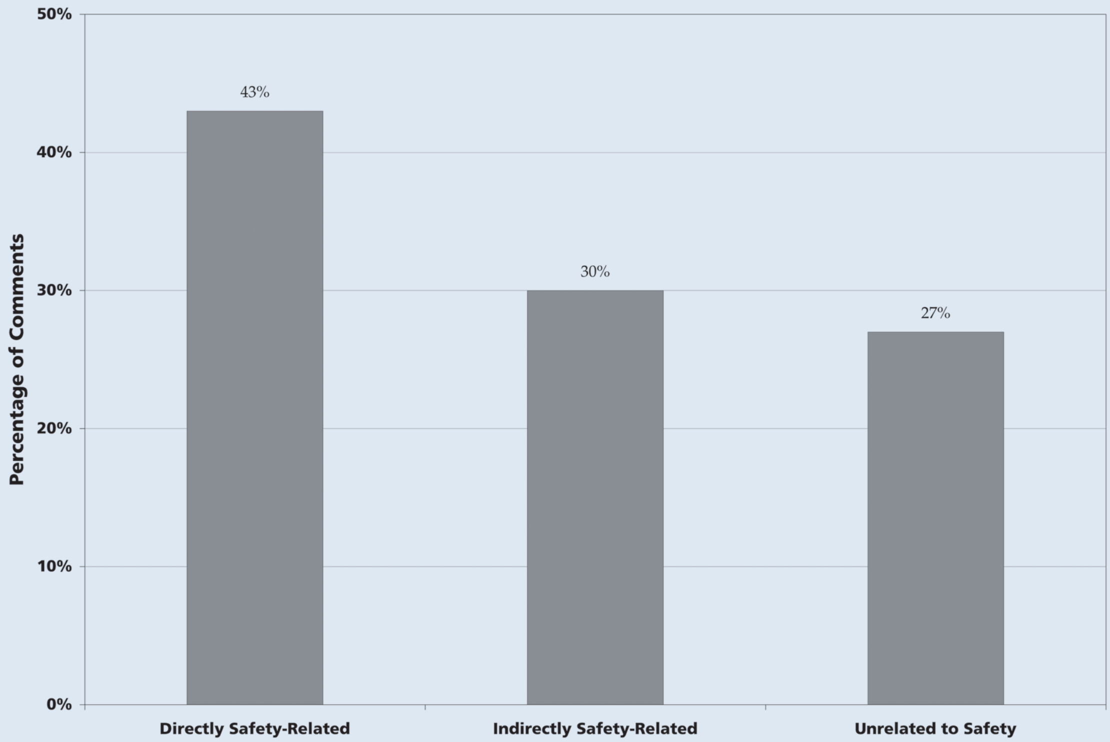
The quality or effectiveness of the LCS reviews can be assessed on multiple levels. In this analysis, the primary focus is participation and process in order to provide a brief summary of the output of the reviews. The discussion of participation and process is based on the analysis of transcripts from focus groups with the LCS facilitators and designers, interviews with participants and LCS review documentation.

Participation

The facilitators felt that the right people were present for most reviews. Typically, the participants

Figure 6

Relationship of LCS Review Comments to Safety



were at the general foreman level or above. These people understood the work firsthand and were aware of safety issues involved from past incidents. The gaps in attendance tended to be where multiple crafts were needed but were not all represented. For example, in one case of a concrete package, the concrete contractor participated but the organizers had failed to invite the steel reinforcement contractor. The three rounds of reviews could often compensate for these omissions, so if a discipline was absent the first time around, it could provide comments at subsequent rounds. One facilitator believed that the process would have benefited from greater involvement of contractor safety personnel.

Some concern was expressed about the level of authority and ownership of the design package of those present during reviews. Facilitators generally felt that the presence of the package owner at the review improved it in two ways. This person was able to orient the review team to the overall package, which was harder for a facilitator who typically would not have expertise or deep knowledge of all packages. The package owner would also then be able to hear all of the comments and carry them to the design team.

> If we had the package owner there who sat through the comments, who takes these comments to the face-to-face, then we have the continuity there and I think he can make the transition and explain to the designer what's going on here (LCS Facilitator Focus Group).

The facilitators also commented on the benefits and limitations of having designers present in LCS reviews. While the direct experience of hearing design comments from construction and operations/maintenance personnel would have had some benefits, it is balanced by the need for a filtering mechanism provided by the owner's workgroup lead, who has financial and scope authority. According to the facilitators:

> The quality of the comments . . . improved over time since we started because people are understanding better what it is we're looking for. They're beginning to get into the mindset of "this is the kind of thing. We can look at this now. We don't have to accept it. We can change it" (LCS Facilitators Focus Group).

Facilitators suggested that the major sources of effective comments were trade contractors and maintenance technicians, with safety personnel also providing additional input.

Barriers

Several potential and real barriers to trade contractor participation were identified in the LCS review process. Larger economic forces in the form of a depressed semiconductor market caused shifts in contracting strategy in the middle of the project. At this point, it became more difficult to justify preconstruction services contracts with trade contractors for design input. Some were concerned that advantages would be gained by trade contractors who participated in reviews because they would have an opportunity to view documents before packages were issued for bid. The facilitators commented on this potential role conflict, but their experience was generally that these contractors erred on the side of being more forthcoming to demonstrate competence rather than holding back comments to achieve a competitive advantage.

Another obstacle was the construction manager's reluctance to continue to request participation in

Table 1

Design Features Changed through LCS Process

Design Feature	Safety/Health Impact
Utility level below subfab	Added space for utilities reduced trade congestion, reduced awkward postures.
Subfab ceiling height	Reduced congestion, prevented "head-knocker" injuries.
Welded truss connections	Prefabbed trusses reduced work-at-height exposure and awkward postures from welding/bolting in place.
Mechanical restraints replace thrust blocks on underground utilities	Reduced excavation and material handling where underground utilities changed direction.
42-inch parapet height	Eliminated need for separate guardrails.
Greater coverage with anchorage points	Improved fall protection by making tie-off points more accessible throughout facility.
Walkable ceiling above cleanroom	Improved access to mechanical equipment without requiring fall protection systems.

detailed design from contractors who had participated in LCS during programming but then subsequently were not awarded construction contracts. Finally, some CM representatives perceived that they did not need to obtain trade contractors' input because providing construction input is their job. Needing input from trade contractors would be perceived as a sign of weakness.

LCS Review Output

The scope of the LCS reviews is reflected in the comments generated on the 22 design packages. The facilitators recorded a total of 789 individual comments from the 58 LCS reviews. Due to constraints on time and resources, the research team elected to analyze a large sample of these comments rather than the entire universe. The team analyzed 325 (41.2 percent) comments from seven representative design packages, chosen to encompass different structures, design and construction disciplines, and phases of the project.

All comments in each selected package were coded and analyzed so there was no selection within a package. Figure 5 shows the distribution of these comments with respect to the life cycle phases that they affect: construction, commissioning, operations, maintenance, retrofit, demolition and/or decommissioning. Half of the comments related to initial construction and nearly 40 percent to facility maintenance. Retrofit and operations were the other two phases that garnered significant attention.

Figure 6 shows the comments coded in terms of their relationship to safety and health issues. In this case, almost 70 percent were related in some way to safety with the remainder unrelated. Forty percent were directly related to safety, meaning that the primary reason for the comment was a perceived safety or health hazard. The 28 percent that were "indirectly" safety-related were comments whose primary thrust was not safety, but that had clear safety implications. An example would be a comment that related to accessing a particular piece of equipment, but the lack of such access could have safety implications for workers.

LCS Outcomes

Outcomes of the LCS process are detailed elsewhere (Weinstein, et al), but Table 1 provides a flavor of the types of safety and health issues that were addressed in the LCS review process and the overall LCS program. The listed items are a selection of cases in which some part of the LCS procedure was at least partially responsible for their being brought to the attention of the design team and other decision makers. These represent cases in which exposure reduction can be demonstrated fairly clearly. A number of other design changes were either less successfully implemented or less clearly reduced exposure.

Assessing the impact of LCS on workers' compensation claims presents methodological challenges due to the array of safety programs on D1D and the difficulty of identifying the impact of any single program. However, unpublished data from Intel indicates that while the number of workers' compensation claims on D1D was higher than other comparable sites, the average cost of claims and the total cost of claims were substantially lower on D1D than on other Intel fabs, suggesting a low number of serious injuries on the site. This low average cost rate is notable given that Intel safety programs, other than LCS, are designed to be uniform across sites and Intel injury rates are far below industry levels.

Discussion & Conclusions

The concept of designing for construction worker safety and health has rarely been applied in an explicit way in the U.S. construction industry. This article describes the experience of the development and implementation of a design-for-safety process on a large capital project. The LCS process at Intel D1D encountered many of the obstacles noted in the European literature on this topic (Gibb; Cosman; Maloney and Cameron).

At the same time, however, it demonstrates that such a process is feasible on a U.S. project. As a pioneering effort in this field, many of the obstacles could be anticipated. A blueprint for designing for safety did not exist at the outset of the D1D project. Programming was already underway while the LCS Task Force was developing the process and the tools to be used. Comments from many of the 23 programming workgroup respondents and from LCS Task Force members reflect this.

About 40 percent of the programming participants indicated they had a detailed understanding of LCS when they were doing their evaluations during programming. Workgroup leaders had greater familiarity with the process and its goals than did other group members. This is consistent with the findings of Wulff, et al in one of the rare studies of designer experience with safety, health and human factors related to the construction industry [Wulff, et al(a); (b)].

Other group members tended to take their cues from the workgroup lead. This undoubtedly reduced the effectiveness of some evaluations because the full knowledge and expertise was not resident in each member of the group. Most interviewees expressed that they would have liked to have had a greater understanding of the process and goals. This could have been attained through a training session, but they acknowledged that they would have been unlikely to welcome additional training, given the fast pace of the design process.

The process of doing LCS evaluations seemed to smooth out as the design process went forward, suggesting that 1) the process was unfinished at the start; 2) there was a learning curve among participants; 3) the facilitators assigned to the process by the three major organizations had a positive impact; and 4) perhaps it was easier for participants to grapple with smaller details rather than larger conceptual decisions.

Designers' reaction to the input of construction personnel in reviews was mixed, although on balance positive. In interviews and focus groups, many designers recognized the gap that often exists between design and construction. They appreciated the input on location of valves, ladders versus stairways, and other design decisions from those who would actually install and use these features. Sometimes, the three-dimensional vision of the constructor could identify what a drawing meant in reality, leading to remedying a conflict that the drawing by itself could not reveal.

On the negative side, the opportunity for input led, in some cases, to vague and general comments, such as "more tie-offs" or "make everything more accessible," that were difficult to address. Time was also a constant concern. The pace of the design and construction on this project was already fast, so the design team did not always welcome additional review steps and more opportunities for comments to which they had to respond.

The general conclusion from the substantial qualitative data collected and analyzed is that the increased collaboration and insertion of field construction knowledge in the early stages of project design was viewed as adding value to the design process. One lead designer on the project insisted that he saw the increased collaboration and dialogue with top construction manager and trade contractor personnel as the greatest benefit of the LCS process, more so than any specific design changes (personal communication). Both he and the construction project manager saw this as carrying over to other aspects of the project, including scheduling and sequencing.

Participants also noted that the owner, designer and contractor personnel working on the project had relationships from past projects. They went so far as to say that although this was a design-bid-build delivery method, these relationships sometimes made it feel like a design-build job that avoided some of the barriers posed by traditional procurement methods. Whether this collaboration translates into improved safety performance during construction and subsequent phases of the building's life cycle requires further analysis of this and future projects.

As noted, several significant barriers exist to implementation of design for safety on construction projects in the U.S. and elsewhere. Most of these barriers presented themselves in this case, and the experience with them is instructive for the construction industry as a whole. The typical separation between design and construction was overcome in this case through preconstruction services agreements with Hoffman and several trade contractors. This allowed significant constructor input into the design discussions during programming and detailed design even within a design-bid-build procurement process. The financial and organizational barriers to this involvement that arose in this case are likely to be found in much of the U.S. construction industry and will only be overcome by a commitment on the part of the owner and further demonstration of benefits of the process.

The liability concerns of designers and potential effect on design fees is another issue that is frequently raised. The designer's project manager responded to the latter question this way:

> It didn't cost me any more money as a designer—we didn't ask Intel for a larger fee to implement this process. In fact, at the beginning of the process it was in our contract that we were going to do this; we didn't really know what *it* was at the time, but after it was defined through the process we didn't come back and say, "Wait a minute, this is going to cost a lot more than we anticipated and therefore we need to change the fee" [Hecker, et al(a)].

This is far from the universal view among designers, but it should be noted that this comes from a designer who had a central role in the design-for-safety process.

Insurance liability is a more difficult issue. Attorneys and insurers caution that taking on design-for-safety responsibilities outside of a design-build organization may create new liabilities (DeVries and Grigg). In this case, the owner's contract with the design firm called for participation in the LCS process without any particular changes in insurance. This does not imply that the design firm was unconcerned with this issue, but that these concerns did not limit participation in the design-for-safety process. In the broader world of design and construction, efforts are needed to address these liability concerns for design-for-safety to move forward on a larger scale.

The LCS process at Intel D1D, with all of its limitations, demonstrated the feasibility of carrying out a safety-in-design effort and bringing together constructors and designers in a collaborative process. Some will argue that the scale of the D1D project permits a process such as LCS to take place because of the large amount of resources and expertise available. However, this is a double-edged argument. The

Many designers recognized the gap that often exists between design and construction. They appreciated the input on design decisions from those who would actually install and use these features.

size, complexity and fast-track schedule of this project presented considerable challenges to adding a program such as LCS into the design-construction mix. A counter-argument could be made that a smaller, simpler, more-straightforward construction project with fewer players could more easily accommodate a process such as LCS. This hypothesis needs to be tested, along with determining whether safety-in-design delivers benefits that outweigh its costs, whatever the project size. ■

References

Anderson, J. "Finding the Right Legislative Framework for Guiding Designers on Their Health and Safety Responsibilities." *Proceedings of the Designing for Safety and Health Conference.* London: European Construction Institute (ECI), 2000. 143-150.

Ash, R. "CDM and Design: Where Are We Now and Where Should We Go? A Personal View." *Proceedings of the Designing for Safety and Health Conference.* London: ECI, 2000. 151-158.

Baxendale, T. and O. Jones. "Construction Design and Management Safety Regulations in Practice—Progress on Implementation." *International Journal of Project Management.* 18(2000): 33-40.

Coble, R.J. and T.C. Haupt. "Potential Contribution of Construction Foremen in Designing for Safety." *Proceedings of the Designing for Safety and Health Conference.* London: ECI, 2000. 175-180.

Cosman, M. "Harnessing Designers' Skills to Deliver a Healthier and Safer Construction Industry. In *Designing for Safety and Health in Construction,* S. Hecker, J. Gambatese and M. Weinstein, eds. Eugene, OR: University of Oregon Press, 2004. 59-68.

Construction (Design and Management) Regulations. SI 1994 No. 3140. London: HMSO, 1994.

Council of the European Communities (CEC). Council Directive 92/57/EEC of June 24, 1992, on the Implementation of Minimum Safety and Health Requirements at Temporary or Mobile Construction Sites. Brussels: European Commission, 1992.

DeVries, S. and D. Grigg. "An Insurance Perspective on the A/Es Role in Work Site Safety: Can the Current Paradigm Shift without Opening Pandora's Box?" In *Designing for Safety and Health in Construction,* S. Hecker, J. Gambatese and M. Weinstein, eds. Eugene, OR: University of Oregon Press, 2004. 178-185.

European Foundation for the Improvement of Living and Working Conditions. *From Drawing Board to Building Site.* London: HMSO Books, 1991.

Gambatese, J.A.(a). "Liability in Designing for Construction Worker Safety." *Journal of Architectural Engineering.* 4(1998): 107-112.

Gambatese, J.A.(b). "Safety Constructability: Designer Involvement in Construction Site Safety." *Proceedings of Construction Congress VI.* Reston, VA: American Society of Civil Engineers (ASCE) Publications, 2000. 650-660.

Gambatese, J.A., et al(a). "Pilot Study of the Viability of Designing for Construction Worker Safety." In *Designing for Safety and Health in Construction,* S. Hecker, J. Gambatese and M. Weinstein, eds. Eugene, OR: University of Oregon Press, 2004. 22-43.

Gambatese, J.A., et al(b). "A Tool to Design for Construction Worker Safety." *Journal of Architectural Engineering.* 3(1997): 32-41.

Gibb, A. "Designing for Safety and Health in Construction: A European/U.K. View." In *Designing for Safety and Health in Construction,* S. Hecker, J. Gambatese and M. Weinstein, eds. Eugene, OR: University of Oregon Press, 2004. 44-56.

Gibb, A., et al. "The Role of Design in Accident Causality." In *Designing for Safety and Health in Construction,* S. Hecker, J. Gambatese and M. Weinstein, eds. Eugene, OR: University of Oregon Press, 2004. 11-21.

Hecker S. and J. Gambatese. "Safety in Design: A Proactive Approach to Construction Safety and Health." *Applied Occupational & Environmental Hygiene.* 18(2003): 339-342.

Hecker, S., et al(a). "Life Cycle Safety: An Intervention to Improve Construction Workers Safety and Health Through Design." In *Designing for Safety and Health in Construction,* S. Hecker, J. Gambatese and M. Weinstein, eds. Eugene, OR: University of Oregon Press, 2004. 212-241.

Hecker, S., et al(b). "Making Ergonomic Changes in Construction: Worksite Training and Task Interventions." In *Applied Ergonomics.* D. Alexander and R. Rabourn, eds. London: Taylor & Francis, 2001. 162-189.

Hinze, J. "Designing for the Life Cycle Safety of Facilities." *Proceedings of the Designing for Safety and Health Conference.* London: ECI, 2000. 121-128.

Hinze, J. and F. Wiegand. "Role of Designers in Construction Worker Safety." *Journal of Construction Engineering and Management.* 118(1992): 677-684.

Hinze, J.W., et al. "Integrating Construction Worker Protection Into Project Design." *Implementation of Safety and Health on Construction Sites.* Balkema, Rotterdam, 1999.

Istephan, T. "Collaboration, Total Design and Integration of Safety and Health in Design: Project Case Studies." In *Designing for Safety and Health in Construction,* S. Hecker, J. Gambatese and M. Weinstein, eds. Eugene, OR: University of Oregon Press, 2004. 264-279.

Life Cycle Safety Facilitator Focus Group. Conducted Oct. 30, 2001.

Life Cycle Safety Task Force Focus Group. Conducted Dec. 10, 2001.

Life Cycle Safety Task Force. D1D LCS Process Final Report. Intel Corp., 2002.

MacKenzie, J., et al. "Communication: The Key to Designing Safely." *Proceedings of the Designing for Safety and Health Conference.* London: ECI, 2000. 77-84.

Maloney, W.F. and I. Cameron. "Lessons Learned for the U.S. from the U.K.'s C(DM) Regulations." In *Designing for Safety and Health in Construction,* S. Hecker, J. Gambatese and M. Weinstein, eds. Eugene, OR: University of Oregon Press, 2004. 69-80.

Manuele, F.A. *On the Practice of Safety.* New York: John Wiley and Sons Inc., 1997.

Marino Duffy, B. "From Designers' Risk Assessment to Construction Method Statements: Techniques and Procedures for an Effective Communication of Health and Safety Information." In *Designing for Safety and Health in Construction,* S. Hecker, J. Gambatese and M. Weinstein, eds. Eugene, OR: University of Oregon Press, 2004. 118-135.

Suraji, A., et al. "Development of Causal Model of Construction Accident Causation." *Journal of Construction Engineering and Management.* 127(2001): 337-345.

Weinstein, M., et al. "Outcomes of a Design-for-Safety Process: A Case Study of a Large Capital Project." In *Designing for Safety and Health in Construction,* S. Hecker, J. Gambatese and M. Weinstein, eds. Eugene, OR: University of Oregon Press, 2004. 242-263.

Whittington, D., et al. "Research into Management, Organizational and Human Factors in the Construction Industry." HSE Contract Research Report 45/1992. London: HMSO, 1992

WorkCover New South Wales. *CHAIR Safety in Design Tool.* 2001. <http://www.workcover.nsw.gov.au>.

Wulff, I.A., et al(a). "Ergonomic Criteria in Large-Scale Engineering Design—I. Management by Documentation Only? Formal Organization vs. Designers' Perceptions." *Applied Ergonomics.* 30(1999): 191-205.

Wulff, I.A., et al(b). "Ergonomic Criteria in Large-Scale Engineering Design—II. Evaluating and Applying Requirements in the Real World of Design. *Applied Ergonomics.* 30(1999): 207-221.

Acknowledgements

The authors wish to acknowledge the essential contributions of the following members of the research team: Tony Barsotti, Billy Gibbons, Don Gerber and Bill Hardwick. We are also deeply indebted to the following organizations and individuals for the access, insights and time they provided to these research efforts. Intel Corp.: Jon Preston, Mike Porter and Brian Mattson; Industrial Design and Construction: Terry Wheeler and Catherine Myers; Hoffman Construction: Cliff McDonald. Funding for this research was provided by the National Institute for Occupational Safety and Health through The Center to Protect Workers' Rights, NIOSH grant No. U02/CCU317202.