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Final Report

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THE CURRENT ABILITY OF THE ARCHITECTURE, ENGINEERING, AND CONSTRUCTION INDUSTRY TO EXCHANGE CAD DATA SETS DIGITALLY

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

As the Architecture, Engineering, and Construction (AEC) industry continues to expand its use of computer-aided design (CAD) systems, the communication of project information among professionals and clients becomes more complex. The current ability of this industry to exchange CAD information digitally has been assessed through discussions with AEC CAD users and consultants, site visits to CAD installations, and reviews of CAD software and translator documentation. CAD systems from different vendors are generally incompatible, and this limits or prevents the flow of information between project participants. The information that is currently being exchanged between different CAD systems is primarily graphics, 2-D drawings with no attached databases. The received data sets are usually only used as reference outlines for new work and are not intended for revision. The principal conclusions and recommendations of this report are as follows:

1. In order to take full advantage of CAD and to maximize the utilization of digital project information, the AEC industry requires a dependable method for digital data exchanges.

2. The current generation of translator tools is inadequate for comprehensive AEC CAD operations. Incomplete translators, insufficient documentation, and differing interpretations of specifications have prevented accurate and complete data set exchanges.

3. There is a critical need for a public program to validate translator software, to identify problems in current implementations, and to develop guidelines for the use of computer data exchange standards.

KEY WORDS: AEC CAD; CAD data exchange; computer-aided design; computer integrated construction; construction documentation; data exchange standards; data translators; digital data interchange; IGES; intermediate data exchange formats; validation of translators.

CONTENTS

1. Introduction

Architecture, Engineering, and Construction (AEC) firms are striving to increase their efficiency and to improve their projects by incorporating computer-aided design (CAD) systems. The percentage of A/E firms using CAD has been steadily increasing during this decade. Recent surveys of design firms report that 40 percent of the responding firms currently have CAD capabilities, compared to 15 percent in 1984. At least 80 percent of all AEC firms are predicted to have CAD systems by 1987 [1].

The use of computers in these organizations has been evolving from separate computer-aided drafting, engineering, and project management applications toward integrated CAD systems, which address the full range of AEC operations. The common, critical component of all of these systems is the information that they manage. The usefulness of CAD systems is directly affected by how successfully this information can be exchanged between different systems and the various project participants.

The purpose of this document is to provide an assessment of the AEC industry's current ability to exchange CAD data sets digitally and to present recommendations for future action. This assessment was produced through discussions with AEC CAD users, consultants, and vendors, site visits to CAD installations, and reviews of CAD software and translator documentation. Many of the discussions were conducted over the telephone, and all of them were structured upon a broad list of "AEC CAD Data Exchange Questions" (included in this report as Appendix A).

During the period of April - July 1986, 82 AEC CAD professionals were contacted for their responses to these questions and for any other pertinent information that they chose to contribute. These contacts included representatives of 34 AEC organizations with varying amounts of CAD experience, 16 AEC CAD vendors, 7 AEC CAD consultants, and 6 CAD service bureaus. The findings and recommendations of this report were then reviewed by a panel of currently practicing AEC CAD professionals.

1.1 The Importance of AEC CAD Information Exchanges

In most large AEC projects, each participating organization operates independently, exchanging information with the other professionals in the form of drawings, schedules, and specifications. In order to fully exploit the potential gains offered by CAD, these professionals must be able to exchange this information in digital form. Currently, the primary deterrent to

AEC digital data exchanges is the limited capability to communicate data between CAD systems from different vendors.

Many private sector, municipal, and military projects involve several AEC contractors, each of whom may have a different CAD system. As of April 1986, there were 58 different CAD systems being offered for AEC operations [2], and other CAD vendors are preparing to introduce more systems this year. Although there are annual discussions at CAD conferences on the impending shakeout of vendors, the AEC CAD market continues to expand, mature, and diversify.

The increasing use of CAD systems is bringing fundamental changes in the operations of AEC offices and in the delivery of services and projects. The effectiveness of the design and construction process is, in part, determined by the manner in which information is exchanged and manipulated. In order to successfully integrate CAD systems, AEC organizations and owner/clients will have to develop a strategic conceptual framework, an industry-wide descriptive interchange language, and comprehensive operational procedures for exchanging CAD data sets.

1.2 Current AEC CAD Information Exchanges

With the increasing use of computers in the design and construction process, there is a growing demand for the exchange of information in digital form, i.e., as data sets. Many clients are requesting the delivery of both conventional paper, project documentation (drawings, schedules, etc.) and the digital files. Some clients are accepting the delivery of just the project's digital data sets, in a specified format.

Many organizations have identified facilities management as an essential AEC service which should use these new tools. Some owner/clients have extended their specifications for the delivery of project data sets to include the "as-built" data. These updated data sets are intended to be used as the base documentation for facilities management operations. Unfortunately, the extra costs of such requests have caused most owners to remove this requirement.

Additionally, since very few project owner organizations have CAD systems on which to use the data sets, CAD data may only be used during the design process. Due to this short-term perspective as to the value of the CAD data, there is no investment in developing data sets which can be exchanged throughout the life cycle of a project.

CAD systems produce drawings and other forms of project information quite efficiently, but unfortunately it is still difficult to transfer this graphic and non-graphic data from one CAD system to another. Most CAD systems are incompatible with one another since they use different data representations and formats. Although there are procedures for exchanging graphics, currently there is no way to guarantee that the graphic data can be manipulated on the receiving system or that the non-graphic data will retain their meaning.

At present, there have only been very limited CAD data set exchanges within the AEC industry. The majority of these exchanges have been between professionals who are using the same kind of CAD system (i.e., within a homogeneous environment), and the translated data sets are primarily used only for reference/background information or as supplementary archival documentation (and not as the master document).

Additionally, the flow of information has only been in one direction. The capability for bidirectional exchanges of CAD data sets is only being exercised <u>within</u> the larger A/E firms which work in homogeneous CAD environments. The AEC industry is just beginning to examine how to use CAD for the iterative refining, or cycling, of design solutions among all of the project participants, regardless of the differences in CAD tools.

The initial strategy for receiving CAD data sets, on the part of the large owner/clients, has been to require their projects to be designed on the same kind of CAD system as they use in-house and to specify the delivery of the project CAD data set in that system's format. During the past two years, the limitations of this strategy have been recognized, and the requirements have been expanded to encourage a broader range of A/E firms to participate. The more recent construction project specifications allow the use of subcontractors and service bureaus to translate the original CAD data sets into the required format, either by direct translators or via a neutral format (specifically the Initial Graphics Exchange Specification, IGES).

In order to transfer data sets stored in one CAD system into a different CAD system, a specified language and format for the exchange must be agreed upon by the developers and users of both systems. In the case of homogeneous exchanges (between the same kind of systems), this process is basically a direct transfer of files, in their native format, with no requirement for translation. As long as the representational conventions of the data sets (i.e., assignment of layers, symbol definitions, drafting standards, etc.) are commonly defined for both systems, this type of exchange is usually successful within homogeneous environments.

The broader range of possible data set exchange problems occurs within heterogeneous environments (i.e., different CAD systems exchanging data). Since each system uses its own concepts, terminology, and encoding schemes, the original data sets can not be directly used by the application programs in the receiving system. Therefore, the original data sets must be translated into the format of the receiving system.

The primary constraint to current CAD data set exchanges is that there has not been a comprehensive and acceptable (dependable and verifiable) method for the digital exchange of information between different AEC CAD systems. Successful AEC CAD information exchanges will require a documented taxonomy of modeling concepts and a protocol to communicate each concept.

2. Current AEC CAD Systems

There are numerous CAD systems available to AEC organizations, ranging from simple drafting aids to integrated (a common database management system supports all intradisciplinary and interdisciplinary functions) multi-user systems which address numerous aspects of an AEC project. These systems can generally be classified as 2-D drafting systems, 2-D drafting systems with database management capabilities, or as 3-D modeling systems, which include a database management system (DBMS).

Many AEC firms initiated their use of CAD with microcomputer drafting applications. During the past two years, the capabilities and the cost-effectiveness of these packages have significantly increased. Currently there is a sizeable market for add-on packages which provide libraries of symbols and which expand the basic drafting operations with specialized functions (such as automatic dimensioning or the insertion of doors and windows).

In the AEC CAD arena there is a growing appreciation and demand for database management functionality. A critical aspect of any construction project is the management of information, and CAD technology can provide powerful tools for controlling the relationships between graphics and data. The addition of database management systems may allow the users to make quantity takeoffs, to compile listings of components, and to perform facilities management functions.

However, the capabilities of a drafting-based DBMS are limited by the functionality of a 2-D system. Since the same information may be represented on different drawings, there will often be redundant descriptions of a building. This redundancy leads to problems in maintaining the consistency and the accuracy of the data attached to the graphics. This fact enforces the convention of considering 2-D drawings as "reports" extracted from an integrated, 3-D building description.

A 3-D modeling system maintains a three-dimensional description of a building, which provides the basis for the integration of AEC CAD operations. These systems use wire-frame, surface, or solid modeling methods (some systems will allow the user to select the specific method) and usually provide common access to a consistent, central database.

Wire-frame models describe objects as a series of vertices connected by edges and provide the most rudimentary 3-D description of a building. Surface models extend the wire-frame to include closed polygons as the faces of 3-D objects and allow properties to be attached to the faces. The most complete representation is provided by solid modeling, which describes a building as an assemblage of solids (with attached properties) and voids. The development of a full 3-D model of a building and all of its systems can be difficult and time-consuming, and the information required for such a representation can exceed the normal scope of services provided by an A/E firm.

Due to the large number and variety of components in a building, solid modeling is considered too computationally intensive for efficient AEC production of drawings and project documentation. The current focus in advanced AEC CAD organizations is to develop the capabilities of their surface modeling CAD systems into fully integrated design and management tools.

Numerous AEC firms first implemented CAD in order to automate portions of their drafting tasks. Yet, after the first year or two of automated drafting and an increase in computer literacy, many firms have become dissatisfied with this limited use of CAD. An increasing percentage of current AEC CAD users are investigating the integration of CAD within all of their firms' operations. This integrated use of CAD resources may include project management, engineering and design, drafting and documentation production, operational control, and strategic planning.

Four key elements have been advancing the integrated use of CAD: the continuing decrease in the price-performance ratio of AEC CAD systems, greater emphasis on 3-D modeling, more comprehensive implementations of DBMS's for developing computerized project databases, and the development of local area networks (LANs). The combination of comprehensive DBMS's and the use of LANs promotes dynamic interference checking, more timely design reviews, and the reduction of errors and field rework.

2.1 The Range of Systems Used in AEC Organizations

The AEC industry in the United States is extremely fragmented, and most firms are subject to sizeable fluctuations in work loads and types of projects. With individual disciplines having differing requirements, no CAD system has yet fulfilled all of the requirements for every type of AEC firm.

The simplest way in which individual AEC firms have implemented CAD is to use the same system for all of their CAD functions. This is the strategy that many small and mid-size (less than 100 employees) firms have adopted during the past two years, and it has proven particularly successful when the application programs of the selected CAD system can support the majority of the firm's requirements.

Unfortunately, most of the larger firms have not had the luxury to choose that implementation strategy. Many of the larger firms began investing (both resources and databases) in CAD five to ten years ago, when AEC CAD systems were primarily extensions of mechanical and electronic engineering CAD/CAM systems. In many cases, their use of CAD has evolved out of a series of separate decisions. As new projects or work loads were initiated, specific applications programs, sometimes from different CAD vendors, were selected to support the tasks of individual divisions or to fulfill the requirements of the project.

This scenario has progressed in two different directions. In some large firms, multiple systems are used throughout the organization, and the CAD managers allocate their computing resources based on project priorities, requests from division managers, contracted specifications for deliverables, and the optimization of resources.

The other way in which multiple CAD systems are being used within a single firm is that each system is dedicated to the operations of a specific division (or divisions). This strategy has usually been adopted because, over the years, individual divisions have selected different systems which best suited the way in which they were currently doing their work.

Some of the larger AEC firms in the United States are using as many as five different CAD systems for in-house operations, and some of those firms have only recently decided to centralize the management of their CAD operations. AEC organizations which use multiple CAD systems are faced with significant challenges, ranging from the management of multiple versions of company standards to the monitoring the internal exchange of data sets between incompatible CAD systems.

2.2 Data Set Translation Methods

Central to the coordinated use of multiple CAD systems and to the successful exchange of CAD data sets is the development of dependable data set translation methods. There are basically two ways to transfer data between incompatible CAD systems: direct translation and translation via an intermediate format.

A direct translator is a software program which converts data sets from their original format into the specific format of a receiving system. Although direct translators can be an efficient way to exchange data sets between two systems, they do not provide a viable strategy for exchanging data sets between multiple systems.

The writing of direct translators requires a complete understanding of the internal data format used by both the sending and the receiving system. This information is usually proprietary, and is subject to periodic revisions. With each new revision to either of the two systems, the direct translator must be revised. Additionally, this strategy requires an excessive number of translators to support data exchanges between multiple systems. With "n" CAD systems, there must be n x (n-1) one-way, direct translators.

One informative example of the limitations of direct translators is the experience of the U.S. Army Corps of Engineers. The Corps has maintained both neutral and direct translators to support the CAD operations of their Huntsville Division. After incurring excessive development and maintenance costs to implement a direct translator, the Corps concluded that it was "impractical to maintain a direct translator as a custom implementation" and that "neither vendors nor the Government can afford to maintain a direct translator for every combination of equipment." [3]

The use of neutral translators is intended to resolve these limitations. A neutral translator is based on the concept of an intermediate format and utilizes two programs (a preprocessor and a postprocessor) to perform the translation. The preprocessor reads the format of system A and writes into the intermediate format, and the postprocessor reads the intermediate format and writes the output into the format of system B.

There are several advantages to this process. First, the writing of either program only requires an understanding of the internal data format of one system. Second, there is only the need for 2n programs (one-way translators) for "n" CAD systems, rather than n x (n-1) one-way translators. Whenever a CAD system is revised only two programs have to be updated, instead of all direct translators that work with that system.

A key problem of neutral translators is the difficulty of establishing an intermediate format which supports the features of all of the CAD systems and the requirements of all of the users. Consequently, any intermediate format must represent a compromise between many systems and approaches, and the intermediate format may not accommodate all of the information in an originating system.

The use of an intermediate format can reduce the users' risks of vendor dependence and can allow greater flexibility in the utilization of CAD resources. In order for an intermediate format to provide this foundation for data exchanges, its specification must be precise and unambiguous, and the CAD vendors (software developers) must interpret and implement the specification uniformly.

Many of the problems with the current generation of neutral translator software are caused by dissimilar interpretations of the same specification. A critical component in the successful use of an intermediate format is the establishment of methods for validating translators' conformance to a clear and precise specification.

2.3 Existing Intermediate Data Exchange Formats

Currently, there are four intermediate data exchange formats available for AEC CAD communications: the Initial Graphics Exchange Specification (IGES), the CalComp 900-Series plot file formats, the AutoCAD DXF file format, and the Intergraph Standard Interchange Format (ISIF)[1]. IGES is the only one of these four formats that is maintained by a national committee.

Each of these formats are being used for specific types of AEC applications. In addition to these public intermediate formats, some of the larger AEC firms have established their own "neutral file primitives" and database structures for the internal exchange of project data.

The Initial Graphics Exchange Specification grew out of the work done by the Boeing Corp., the General Electric Corp., the NASA-sponsored Integrated Program for Aerospace Vehicle Design (IPAD), and the U.S. Air Force Integrated Computer-Aided Manufacturing (ICAM) program. Each of these organizations had identified the lack of a standard for the exchange of CAD graphics as a critical roadblock to moving toward computer integrated operations.

IGES is an intermediate format for the exchange and archiving of product description data sets. This format was designed initially for the exchange of the drawings of manufactured parts and has been extended to include finite element models, 3-D wire-frames, and process plant flowsheet drawings. The user of one CAD system translates his system's data sets into the IGES format using a preprocessor. The user of a different CAD system translates the resulting IGES-formatted files into his system's format using a postprocessor.

An additional goal of the IGES effort has been the use of this format as an archival file format. Since vendor products are continuously evolving, CAD users are frequently confronted with the decision of upgrading their system to the latest version to

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[1]Certain commercial equipment, software, or materials are identified in this paper in order to adequately specify existing CAD software and data exchange formats. Such identification does not imply recommendations or endorsement by the National Bureau of Standards, nor does it imply that the software or equipment are necessarily the best available for the purpose.

take advantage of new capabilities while risking the integrity of archived databases. This issue of establishing a reasonable approach for storing neutral archival files in a database management system has not been resolved. At present, "the issue of archival in a neutral format to avoid data loss due to system updates has taken a very secondary role." [4]

In early 1980, the National Bureau of Standards published IGES, Version 1.0, and in 1981, this version was approved as an ANSI standard. Version 2.0 was published in February 1983, and Version 3.0 was published in April 1986. IGES "will not solve all the information needs of CAD/CAM systems, and it will need further extension beyond its current definition. However, IGES goes a long way toward alleviating the current data exchange problems, and is a significant response to today's needs." [5]

The IGES standard is more complex than the other formats, and it can represent sophisticated data structures, such as networks, connectivity, and 3-D surfaces. Although IGES was initially designed to support CAD/CAM and printed circuit board technology, Version 3.0 has been developed to support a broader set of applications, including AEC.

In February 1984, the IGES/AEC Committee was established to ensure that the IGES standard and the next generation of data exchange specifications, PDES (Product Data Exchange Specification), facilitate the electronic exchange and archiving of AEC projects. This committee proposes and implements specific IGES enhancements for improving data set exchanges among AEC CAD users (extensions are currently being developed for incorporation into Version 4.0). The second goal of this committee is to inform the AEC community of the need for consensus data exchange standards and to maintain effective liaison with that community and the CAD vendors.

The CalComp plot file formats were developed by the CalComp Corp. to support the CalComp 900 Series on-line and magnetic tape controllers for pen plotters. These are procedural files which contain the commands for controlling the movement of the pens in the plotter. Since all geometric elements are processed as 2-D chains of vectors, all symbols and text lose their meaning.

The AutoCAD DXF format was developed to support the 2-D graphics generated by Autodesk's drafting software and is being used for transferring drawings to CAD systems. AutoCAD was introduced in November 1982 as a CAD software package for personal computers.

ISIF was developed by the Intergraph Corp. and is widely used for exchanging drawings generated on Intergraph systems. This format is designed to work with the files generated by the Interactive Graphics Design Software (IGDS) and by the Data Management and Retrieval System (DMRS), the hierarchical attribute database. It can be used to exchange 2-D or 3-D graphics and associated databases.

3. Types of AEC CAD Data Set Exchanges

Data set exchanges between professionals in the AEC industry may occur for a variety of applications and often within diverse CAD environments. These exchanges may include drawings, equipment schedules, bills of materials, numerical analyses, administrative information, and 3-D models, and they may happen both within an organization (intra-organizational) and between organizations (inter-organizational).

While AEC CAD users want to exchange drawings with symbols and dimensions, CAD systems provide the facilities to create, manipulate, and exchange specific types of data. The types of data to be exchanged between these systems are:

* geometry (lines, surfaces, etc.) and location
* annotation (text, dimensions, etc.)
* topology and structure (means of representing and presenting information)
* associativity (logical relationships among data)
* property (information attached to data)

Combinations of these data types are used to digitally represent drawings and AEC project information in the CAD systems.

The elementary classification of CAD data set exchanges is based on the types of CAD environments employed, homogeneous or heterogeneous. A homogeneous CAD environment includes only one kind of CAD system. All data sets are written in the same format and are directly readable by all of the communicating workstations. A heterogeneous environment includes more than one kind of CAD system, and consequently, the data sets written by one CAD system must be translated in order to be read by a different system.

The homogeneous CAD environment provides the most direct and the least error-prone facilities for data set exchanges. As long as comprehensive CAD operating procedures (such as the assignment of layers for specific types of information and the coordinated use of symbols) are implemented and enforced, there can be extensive, bidirectional exchanges of CAD information. These may include the selective transmission of portions of CAD projects or the transfer of a complete project data set.

Comparatively, there are far more problems with the heterogeneous CAD environment. Since the systems are structured differently, all graphic and non-graphic data must be mapped from the storage files of the originating system to those of the receiving system. These mapping procedures must resolve such basic software differences as conversions from 3-D to 2-D, different line and font styles, and differences in the assignment of layers.

In heterogeneous environments, each time a CAD data set is translated between systems, some information may be lost. This becomes especially detrimental when subcontractors are providing portions of the project design and there is a need for bidirectional exchanges of data sets. The common way to work around this problem is to digitally exchange only those types of information common to both systems, using predetermined entities and modeling conventions and to exchange the rest of the required information on paper.

3.1 The Use of Translators and Intermediate Formats

Although vendors and users recognize the need for dependable information transfers between CAD systems, they have not always agreed upon the solution. "The amount of work necessary to meet IGES is extensive, and the resources the vendor is willing to divert to this activity are often inadequate for the task. New hardware or additional software features are perceived as adding more to the sales potential of a product line than drawing portability. But in fact this strategy results in reduction in the use of and the market for CAD in the construction industry. The unrestricted exchange of electronic information is in the best interest of the construction industry and the CAD vendors." [6]

Initially the larger vendors only promoted in-bound direct translators (into their systems' format), for obvious marketing reasons. Some vendors considered out-bound translators (from their native format to any other format) to be comparable to putting "a six inch drain line into 'their' customer base". Due to the costs of supporting the development of an intermediate exchange standard, such as IGES, many vendors initially resisted this solution to CAD data exchange requirements.

Most large AEC CAD users agree on the limitations of only having direct translators. Although a direct translator can provide an efficient way to transfer data sets between two particular CAD systems, it does not provide a viable strategy for exchanging data sets among multiple systems.

During the past four years there has been increasing pressure by AEC CAD users for the development of a comprehensive intermediate exchange format. This pressure has been exerted in various ways. Most federal agencies and many AEC organizations are requiring extensive IGES capabilities in their future CAD procurements, and an increasing number of RFPs (request for proposal) for AEC projects are specifying the delivery of project documentation in IGES format.

For an intermediate format to be successful, it must be sufficiently powerful to express all the information in the originating system, without the receiver having to know the original (internal) file structure. No intermediate format has as of yet been fully successful in supporting the data set exchange requirements of all AEC CAD users.

The early versions of IGES (Ver. 1.0 and 2.0) were inadequate for the data set exchange requirements of the AEC industry, produced excessively large files, and did not address the archival requirements. Although IGES is intended to serve as an archival format, the primary focus of the IGES effort has been on successful system to system communications using IGES translator implementations.

Initially, many of the vendors only implemented a small percentage of the specification (although they would advertise IGES capabilities) and did not provide adequate documentation or software tools for diagnosing translation problems. These limitations frustrated many AEC CAD users and gave IGES a poor reputation.

A key AEC example of this situation is the limited implementation of the subfigure entity in most vendor provided IGES translators. Each element of data in an IGES file is an entity, and the subfigure entity is a collection of entities which can be used in multiple instances.

AEC project definitions contain a large number of repetitive elements which results in frequent instancing of the same symbol (i.e., subfigure entity). The use of the subfigure entity provides a way to retain the intelligence of the symbols, replicates what A/Es do in practice, and reduces the IGES file size. This is a crucial issue for construction industry firms that need to exchange detailed drawings, and yet many vendor provided IGES translators still do not support the subfigure entity.

During the past five years (since becoming an ANSI standard), IGES has added increasingly sophisticated capabilities and has gained extensive support. Some of these enhancements have added to the complexity and ambiguity of the specification, and this has increased the difficulty of using IGES effectively.

The quality of IGES translators has significantly improved during 1986, and the Version 3.0 document has resolved some of the earlier problems in the specification. This new version enhances the user defined MACRO's so as to better represent standard part libraries and defines a new extension for External Reference Files. Additionally, the new version allows the use of the Compressed ASCII Format as a means of reducing the IGES file size to one third of its previous size.

Still, for IGES to be completely successful, the vendors must implement the specification uniformly. "Interpretations of the specification can be different because there are ambiguities. It's difficult to tell whose fault it is (when there is a problem in an IGES translation)." [7]

Of the 58 CAD systems currently available for AEC operations, 44, over 75 percent, report to support IGES capabilities [2]. Additionally, "Several companies with extensive in-house CAD/CAM systems and proprietary software, including John Deere, Ford Motor Company, General Electric, General Motors, Lockheed, Martin Marietta, Structural Dynamics Research, and Westinghouse are writing their own IGES translators." [8]

Many large organizations have established IGES as part of their mid-term digital exchange strategy. Critical to the most recent gains in the acceptance/implementation of IGES are the various efforts undertaken by DoE, DoD, and each of the individual forces (Air Force, Army, and Navy) to adopt IGES as part of their transition to an "integrated mode of operation".

The Department of Defense has established the CALS (Computer Aided Logistic Support) program in order to increase the effectiveness of its communications and data processing systems and to move DoD into highly automated operations. "A key element in this program is the development of DoD specifications for digital delivery by industry of engineering drawings, illustrations for technical publications, and future product definition data using the Initial Graphics Exchange Specification (IGES) and the Product Data Exchange Specification (PDES). "

Office of the Under Secretary of Defense, September 1985 [9]

The CalComp plot file formats and ISIF were the first intermediate formats to receive general acceptance in the AEC industry, and each has supported specific CAD tasks. The CalComp formats were originally designed to only support the transfer of graphic information and has primarily been used for graphic plotters. The development of ISIF grew out of Intergraph's applications software, which initially supported cartography, petrophysical exploration, and utilities.

ISIF was designed to be "format-free" so as to facilitate user editing. The CERL technical report on graphics translators (November 1984) states, "This capability has a price. First, the non-graphic information that can be associated with the graphics has limitations. Also, there is no ability to provide backpointers in the data. In the hierarchical DBMS that Intergraph currently markets, this is not a problem. However, in the network DBMS soon to be offered, the backpointers would be lost. ... Currently, the backpointers may be of little use in some drafting systems; this will soon be a very important feature in design systems and advanced drafting systems as well." [3] Intergraph has continued to improve the software tools which use this format, and ISIF is being used for a significant portion of current AEC data set exchanges.

Although IGES does have limitations, an increasing percentage of AEC CAD users are integrating IGES into their data set exchange operations. If the AEC CAD vendors commit themselves to providing comprehensive implementations of the IGES specification and if the quality of the translation software tools (and documentation) improves significantly, IGES will offer a viable digital exchange mechanism for current AEC CAD operations.

4. The Current Ability of the AEC Industry to Exchange CAD Data Sets

The AEC industry has only recently embraced CAD technology as a primary medium for producing future projects, and most firms are still investigating the issues of exchanging CAD data. Many AEC organizations have only recently started to define and document their CAD data set exchange requirements and procedures.

There is a general consensus in the AEC industry that in order to fully implement the capabilities of CAD technology, a dependable method of data set exchange must be established. Fortunately, numerous groups are working on these issues, and some resolutions are being formulated. These efforts include task groups within corporations, professional societies (ASCE, ASHRAE, ASME, IES, and AIA), federal organizations (DoC, DoD, DoE, DoT, FAA, U.S. Naval Facilities Engineering Command, and U.S. Army Corps of Engineers),and within large public works projects.

Currently, very few construction projects are completely designed on CAD. The percentage of a project that is done on a CAD system is determined by numerous factors, including the optimization of CAD resources within the firm and the cost-effectiveness of the CAD utilization. Many times CAD drawings/files grow so large that they become unmanageable, and therefore, it is cheaper to manually finish the last 5 percent of a project's drawings and hard copy documentation.

The issues of coordinating the use and control of conventional hard copy with CAD databases are still unresolved in most AEC organizations. Some firms are now developing "transition strategies" for evolving toward integrated, CAD based operations. Most firms recognize that comprehensive management and archival procedures will be needed so as to ensure successful data set exchanges and comprehensive transfers of project deliverables.

Until recently, most AEC CAD systems supported very limited data set translation capabilities. Some A/E firms have concluded that the current generation of translation software tools are either insufficient for their requirements or just not reliable. This has caused numerous A/Es to digitize or re-enter data into a different format rather than risk the expenses of translating.

An increasing number of AEC clients are requiring the delivery of CAD data sets in a specified format, in addition to conventional drawings. Many AEC firms are sending CAD data sets to project participants, both by using the same kind of CAD systems and by using direct translators. A few AEC organizations have recently, successfully implemented IGES capabilities for exchanging limited subsets of project databases. Each of these IGES implementations have required cycles of start-up testing and the "tailoring" of the IGES translators to the requirements of the specific projects, so as to maximize the amount of data that can be transferred.

4.1 Types of Information Being Exchanged Digitally

The information that is being exchanged between dissimilar CAD systems is primarily graphics, 2-D drawings with no attached databases. This may include geometry (points, lines, arcs, etc.), annotation (text, dimensions, etc), associativity (logical relationships among geometry entities), and display information (line weight, font, etc.). The most common uses of AEC CAD data set translations are for transferring reference outlines and title blocks between project participants, for the delivery of the project documentation to the client, and for transferring mapping and finite element modeling (FEM) information.

The acquisition of topological and topographic information has become an important element in the use of CAD in civil engineering and cartography. With the ongoing advances in photogrammetry and digital mapping systems, there is an increasing use of translators to port digitized terrain models into CAD systems (as base documentation for civil engineering projects).

Some AECs are experimenting with exchanging existing hard copy drawings by using digital imaging scanners. This procedure converts a raster image into vectors which can then be translated into IGES or into the native format of some CAD systems.

Although there is strong interest in exchanging complete CAD models and their attached databases, successful exchanges of graphic and non-graphic data have only occurred in homogeneous environments. These exchanges have included 2-D drawings, bills of materials, material standards, and schedules. Although the current IGES specification can transfer drawings to different CAD systems, it is inadequate for transferring much of the intelligence behind those drawings.

The AEC industry is in the transition to CAD-based operations, and most firms are still examining their options for transferring information between CAD systems. The most extensive interchanges of AEC CAD data sets have occurred in homogenous environments, and these exchanges have included 2-D drawings, networks, and attached databases (bills of materials, schedules, etc.). Except for some recent RFPs' qualification procedures and the testing of translators, almost all AEC CAD data set exchanges have been in only one direction. As of yet, there have not been requirements for the cycling or iterative exchanges of AEC CAD data sets.

4.2 Data Exchange Problems and Issues

As long as the representational conventions of the data sets (modeling conventions) are commonly defined for both systems and transmission protocols are established, homogeneous data set exchanges will have minimal problems. Comparatively, the exchange of information between dissimilar AEC CAD systems (i.e., within heterogeneous environments) involves several potential problem areas.

With just drafting systems, these problems include differences in functionality and terminology (levels/layers or drawing/view), entity mismatches, conflicting model sizes and scales, and incompatible line styles, fonts, and symbols. The data translation problems become far more complex when exchanging information between 3-D modeling and engineering software systems.

The principal cause for these problems is differences in the logical structure of the CAD systems (such as subfigure and connectivity definitions). Most early CAD systems were computerized drafting systems which only produced 2-D drawings. The more advanced CAD systems now work with 3-D models of building projects, from which 2-D drawings can be extracted. A 2-D system will never be able to accurately receive or manipulate a 3-D model. A 3-D system can receive a 2-D drawing and extend it into the third dimension by adding a "z" coordinate, but that extension will only create a subset of any complex 3-D model.

Other types of structural differences between CAD systems are their use of attached databases and the structure of the data components. Each CAD system employs a different database management strategy for managing the non-graphic data (product specifications, responsibility assignments, procurement dates, etc.) that are attached to the graphics. All of these factors can make the exchange of CAD data sets between different systems extremely problematic. When these problems are combined with a lack of common modeling conventions, it is extremely difficult to exchange useful information.

Generally, there has been marginal success with heterogeneous exchanges via an intermediate format. The received data sets are usually used as reference outlines for new work and are not intended for revision. Some common problems are:

* problems with units of resolution, scale, and positional units; e.g., match lines do not match-up on segmented drawings.

* entity, symbol, and subfigure mismatches; e.g., parts of drawings are missing, title blocks, text, and dimensions are incorrectly positioned.

* crosshatching, certain line styles, and most line font patterns are not successfully translated; so A/E's avoid putting section details or material information into their CAD data sets.

In most cases, translated data sets have to be edited in order to make them "visually equivalent" on the receiving system.

As of yet, there are very few methods for monitoring the quality of data set exchanges and for ensuring that the data were translated correctly. A common complaint by CAD users is that many of the translator programs do not output any messages as to individual entity translation problems and that most translators do not generate a translation error log during execution. A translator program should at least tell the user what entities could not be translated.

An important tool for improving the quality of data set exchanges is the monitoring and documenting of problems and successes. Some firms have begun to record this type of information, and many AEC organizations have initiated new programs to test and refine their data set exchange capabilities. Yet, an overriding factor in construction projects is expedience, and the demands for completing a job can cause some of these quality assurance procedures to be short-circuited.

Data set verification procedures should ensure numerical accuracy and the usability of the translated data. The method used by most AECs is to do a visual comparison between the received "digital drawings" and the original hard copy drawings. This is usually accomplished by plotting the translated data sets and overlaying the plot on top of the original.

Even if a visual inspection is successful, this does not ensure that the translated data sets are "functionally equivalent" on the receiving system. One example of the potential for functional degradation is when subfigures are translated into separate vectors such that the subfigures can no longer be manipulated as single entities on the receiving systems. Any comprehensive measure of successful data set translation must include methods to assess the degree to which the received data sets can be revised in an effective manner on the receiving system.

Currently, most AEC firms have limited management and control procedures for the exchange of CAD data sets or for the coordination of CAD data sets with conventional hard copy drawings. The management of CAD data set exchanges requires controls on the libraries of CAD reference plans and symbols and should include comprehensive archiving procedures. Most firms have minimal controls on reference libraries, and in some projects, there are multiple sources for the "master documents" being referenced by project participants.

A critical CAD issue that has not been resolved within most AEC organizations is the requirement for archiving the design documents, the CAD digital files, and the audit trails of design responsibility. Additionally, the issue of archival in a neutral format to avoid data loss due to system updates has not been resolved. "Interface difficulties also need to be anticipated when records from the CAD system are archived, because future use may be on a different system." [10]

The assignment of responsibility for A/E design decisions usually includes a professional stamp with a dated signature. The signed design document has traditionally become the legal record for all potential liability concerns. With the increasing use of CAD data sets as the primary repository of design decisions, AEC archival procedures must be revaluated so as to digitally include the audit trails of responsible individuals and all other information necessary for legal considerations.

With conventional CAD data storage (magnetic tape and disk), there is no easy way to guarantee that the digitally encoded design documents, with the approval signatures, cannot be altered at a later date. Due to this limitation, most organizations are archiving duplicate design documentation, both the digital data sets and the signed hard copy (usually on microfilm). In addition to the costs of this duplication, such procedures may lead to inconsistencies in project documentation and redundant version controls.

CAD data set translation can be full of problems, and no one wants to take the responsibility for the translated data. Many service bureaus are avoiding translation jobs until they are confident as to the reliability of the software tools. There are numerous examples of AEC firms giving-up on translating data sets and choosing to manually re-input the data.

Additionally, the early translators had marginal capabilities, which did not fully support the requirements of the AEC industry. These translators were expensive to maintain and to operate (excessive file sizes and run times). The documentation on many translators is still limited. At best, the documentation shows how to <u>run</u> the translator, but not how to <u>analyze</u> the translation problems. Very few translators provide comprehensive error recovery capabilities or diagnostic transaction reporting.

Another limitation on AEC CAD data set exchanges is the ambiguity and the flexibility of the current IGES specification. Since the vendors do not interpret the specification uniformly, there are incompatibilities in the mappings between the preprocessor of one vendor and the postprocessor of a different vendor. AEC firms (except for the larger) do not have a budget for verifying translators or to custom build translating and archiving utilities. In order to effectively exploit the capabilities of CAD, the AEC industry requires a dependable method of data set exchange and reliable translation tools.

The AEC industry, having recently adopted CAD as a primary tool, is now confronting the issues of compatible data formats. Many AEC firms recognize the importance of transferring "intelligence" with the graphics and are expanding their CAD capabilities to support the exchange of project models with their attached databases. Across the full range of large construction projects, from major public works projects to corporate facilities, there is growing interest in full, project life cycle exchange capabilities.

An increasing number of clients are requesting the delivery of their projects' documents in a specified data format so that they can use them for facilities management on the in-house CAD system. Major public works projects are currently deciding how to specify the format for the intermediate transfer of CAD data sets among subcontractors. The Federal Aviation Administration (FAA) has decided to require airports to furnish them with airport layout plans in IGES format by 1987.

An interesting aspect of the "Mobilization Plan" for the Boston Harbor Tunnel project is that the primary AEC contractors are also examining how to get the state to accept the data sets as the deliverable master document. Another major project which is also in the midst of establishing the format for AEC CAD data set exchanges is the Orlando International Airport. This project is intended to establish the data set exchange and archival procedures for supporting operations for the rest of the century.

As part of this increasing understanding of the importance of data set exchanges, numerous corporations and government agencies have decided to adopt IGES. Key reasons for these decisions are that IGES allows AEC firms far more flexibility in how they use their CAD resources and that it provides clients more flexibility in selecting AEC contractors. The CERL Technical Report on graphics translators concludes that "a translator format is needed that can support both current drafting systems and future modeling systems. To date, IGES is the only format that provides that capability. ... Only IGES has the technical capability to capture the building and site "model" and further, it has the largest following in the industry as a whole. Therefore, it is expected to have the best chance of meeting the AEC community's future needs." [3]

Management at many AEC firms have decided that IGES has matured into a viable standard for their projects, and some are defining an application subset of IGES for their types of work. Recent RFPs for large international projects have included IGES test cases as part of the qualification criteria, and some major AECs, who have decided to integrate their multiple CAD operations, have selected IGES for some internal data set exchanges.

During the past year, there have been significant improvements in the quality of IGES processors and in the support by the vendors. The vendors now recognize that working together to establish data communication standards serves their strategic interests. "Giving up proprietary secrets may be the price, but the potential is so enormous that there should be plenty of opportunity for all." [11]

All of these factors, along with the increasing participation of users and vendors in the IGES committees, are providing a viable framework for the continued improvement of IGES. As more AEC organizations develop comprehensive IGES implementation strategies and with the continued improvement of the specification and of the translator software, IGES should provide a good foundation for the majority of the current digital data set exchange requirements within the AEC industry.

5. Summary and Recommendations

This assessment of the current ability of the AEC industry to exchange CAD data sets has identified numerous issues which must be resolved so as to ensure successful data set exchanges and the comprehensive archiving of AEC projects. In order to take full advantage of CAD and to maximize the utilization of digital project information, the AEC industry requires a dependable method for digital data exchanges.

It is important to understand that, at present, the successful transfer of CAD drawings between multiple, dissimilar systems has a significant price. This price is the time spent to understand each system's operations, the time spent to understand the system vendor's implementation of the translation software, the time spent to understand the error messages' meanings and their consequences, and the resources required to test and validate the translators and the data set translations.

5.1 Key Issues

* The current generation of translator software tools is inadequate for comprehensive AEC CAD data set exchanges. Incomplete translators, erroneous processors, and differing interpretations of IGES have prevented accurate data set exchanges. Translator programs should include editing, analysis, and transaction reporting capabilities. Their documentation should show how to run the translator and how to analyze translation problems.

* The terminology of each CAD system and of the intermediate exchange format may be different, or there may be common terms which are used to convey different information. Data set exchanges will often fail when these inconsistencies are not resolved. The language and format of the data exchange (such as IGES) should be clearly defined prior to any data set exchange.

* The use of symbols and libraries. Some CAD systems store the complete description of a symbol at each instance, and other systems encode a pointer to a permanent library in which the complete description is stored. In the latter case, a time-stamped version of the symbol library will have to accompany all exchanged data sets. User defined associativities, properties, and entities should be included in data set exchanges so as to minimize misinterpretation.

* Entity mismatches between CAD systems and intermediate formats. CAD users can expect a mismatch of CAD systems' capabilities and data entities. A native entity may have no direct equivalent in another CAD system (or multiple possible representations in IGES) and may be translated into less sophisticated data elements. This can result in inconsistent, inaccurate, or inefficient translations. It is advisable that the sender and the receiver establish common modeling conventions for encoding CAD information.

* The extra requirements for the configuration management of multi-system interaction. This issue has been avoided in much of the AEC industry; specifically by using direct translators for the one-way transfer of data sets. Key concerns are: the use of libraries of master specifications and details; defining common entities and functionality; and the exchange and control of the definitions of symbols.

* The limitations of IGES, in performance, ambiguity, complexity, and capabilities. Early versions required excessive resources, both in actual processing time and in storage costs. IGES is continuously evolving, and Version 4.0 is currently being developed. AEC organizations must understand the capabilities and the limitations of IGES.

* Professional liability ramifications of digital exchanges; who assumes responsibility for the accuracy and completeness of the translated data sets. This issue is not resolved in the AEC industry. At present, all AEC firms consider CAD data sets as supplementary documentation, with the traditional hard copy drawings being the "master documents". Translated CAD data sets must be reviewed, just as conventional drawings are inspected prior to being stamped and delivered.

5.2 Recommendations

* AEC organizations should establish standardized operating procedures which coordinate the use of CAD and manual documentation / drawings. Few firms have fully resolved these issues. Some key concerns are: predefined project modeling conventions (operations, sheet layout, layer assignments); single source of standard symbols; change control and problem resolution procedures; the ability to segment files for efficient updating, and comprehensive data set archival procedures.

* AEC organizations should document the complete data flow in exchanges (operator to operator, intended future uses of the information, and archival requirements). It is essential to document what information needs to be exchanged and by what means. Currently, very few AEC firms have documented data set exchange procedures, translation audit-trails, or translation start-up test plans. Each of these play a critical role in ensuring the quality of the translations.

* Comprehensive data translation quality assurance programs and evaluation criteria, for monitoring the quality of the translated data (accuracy and functionality), should be developed. These should include translation start-up and testing procedures. In most AEC operations, these do not exist.

* Recommended practices and guidelines for the use of IGES in the AEC industry need to be established. These should include translation verification procedures, a library of AEC benchmark files, implementation guidelines, and archival strategies.

* Performance measures and detailed specifications for data set translators must be developed. At present the users of CAD translation software must test each program for the specifics of the intended application. With functional measures and specifications, the users could far more easily assess the quality of the available translation packages.

* A public program to validate translator software and to identify problems in current implementations must be established. The quality of a data set exchange is dependent upon the correctness and completeness of the translator implementations. A public validation program would provide an uniform basis for the objective evaluation of these products by the AEC industry and would generate valuable feedback for improving the translators and the application procedures.

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Appendix A

AEC CAD DATA EXCHANGE QUESTIONS

Name of Company	....		
Type of Business	....	No. of Empl	....
Prof Disciplines	....	No. of Offc	....
Address	....		
	....		
Telephone No.	....		
Contact Name	....		

1.1 Has your organization exchanged CAD data digitally with other professionals?

1.2 For what types of projects?

1.3 What kinds of CAD systems have been used within your firm?

1.4 What types of information have been exchanged digitally?
- just drawings
- bill of materials
- drawings with databases

1.5 What were the disciplines of the parties exchanging data?
Your system: .... Rec. systems:.............

1.6 Could the transferred data be manipulated on the receiving system?

1.7 Did you produce the transfer files or did you use a job shop / service bureau?

1.8 What interchange formats have been used and with which systems?
.... IGES, Ver. .... ISIF
.... CalComp .... DXF
.... Other, specify ....

1.9 Which interchange formats are you currently using?
.... IGES, Ver.
.... Other, specify ....
What determined this selection?

1.10 What is your standard data format for internal usage?

2.1 How successful were the data exchanges in a homogeneous environment?
- complete file dump or selective transmission
- difficulties and limitations

2.2 How successful were the data exchanges in a heterogeneous environment; what is received, with what kind of functionality?
- one-way transfer via direct translator
- one-way transfer via "neutral format"
- full-cycle, from sys A to sys B, and back to sys A
- graphic and non-graphic entities
    - display information: line weight, fonts, etc.
    - annotations: dimensions, text
    - logical structure of the data: associativities, subfigures, and properties (data attached to the graphic constructions)

3.1 Does your company have documented operating procedures as defined for CAD use?

3.2 Who is responsible for the accuracy and completeness of the digitally translated drawings (or CAD model)?

3.3 How are the definitions of symbols, that are used in the CAD drawings, stored and exchanged between systems?
- stored with the CAD drawings as a supplementary file
- stored by reference to an external 'standards' library so that when the symbol is updated, any future reproduction of a drawing containing a reference to that symbol is also updated? (helpful for maintaining company standards, but this procedure may prevent the accurate reproduction of the archived drawing)

3.4 Is this library of symbol definitions passed as a separate file and then manually installed on the receiving system?

3.5 Have you examined the issues of archiving CAD data in a neutral format to avoid data loss due to system updates?

4.1 Are you currently using any direct conversion translators? From whom? Who provides customer support for using the software?

5.1 What have been your major problems in using IGES to transfer data between different CAD systems?
- entity mismatches in dissimilar implementations of IGES; specific entities not accurately processed
- organization of data : structure entities
- handling of size and scale, lines and text
- accuracy of placement
- imprecise values generated by translation matrix
- error recognition and recovery

5.2 Have you documented the errors and problems that have been identified? Compiled a list of current fixes / resolutions?

5.3 To what degree do your IGES processors comply with Ver. 2.0?

5.4 What useful entities are not mapped into or out of the IGES file by your current processors (pre and post)?
- geometry, annotations, connectivity

5.5 Is documentation developed to define common entities, supported by both CAD systems, so as to avoid using unsupported entities?

5.6 Do your IGES processors terminate upon encountering unsupported or incorrect entities?

5.7 How extensively is the START section of your IGES files used by the sender to insert messages to be read by the human receiver?
- notes on matching levels, e.g., various types of information be constrained to appear on fixed levels

5.8 Is there a summary report or translation log produced by the IGES processors?
- an information message on the status of the process, on the actions completed, and the errors identified

5.9 Do you have to edit any of the files (orig., IGES, or post-) to obtain comparable (the intended) functionality on the receiving system?
- are entities or attributes changed to accommodate the 'target' system

6.1 Have you developed any test case drawings for validating your digital data exchanges?

6.2 Do you use any software tools for validating and diagnosing IGES files or processors?
- conformance testing : to ensure that individual entities and data items are accurately processed
- entity analysis and functional checking

6.3 Do you use full-cycle tests as a start-up procedure for new projects using dissimilar CAD systems?

6.4 What are your methods of measuring and monitoring the success of digital data transfers (e.g., 90 percent complete)?
- file verification methods
- graphical and functional checks

7.1 How do you evaluate translator software?
- required capabilities; acceptance criteria
- validation criteria; accuracy and functionality
- performance measurement (benchmark tests, test cases)

7.2 How would you describe the quality of current translator software and of the supporting documentation?

7.3 Do you think there is a significant need to improve the current generation of IGES processors?

7.4 Have you discussed these limitations with the vendors or requested that they make improvements to their IGES processors?

8.1 Do you plan to use any other translators within the next 2 years? If yes, please specify

8.2 Do you plan to expand your current levels of digital data interchange during the next two years?

8.3 What do you consider to be the prime reasons for your operation/development of interchange facilities?

.... To optimize existing CAD resources	.... In response to client demands
.... To improve project team coordination/commun.	.... To prepare for future work/expand CAD resources
.... Other	

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Mark E. Palmer

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

As the AEC industry continues to expand its use of CAD, the communication of project information among professionals and clients becomes more complex. The current ability of this industry to exchange CAD information digitally has been assessed through discussions with AEC CAD users and consultants, site visits to CAD installations, and reviews of CAD software and translator documentation. CAD systems from different vendors are generally incompatible, and this limits or prevents the flow of information between project participants. The information that is currently being exchanged between different CAD systems is primarily graphics, 2-D drawings with no attached databases. The received data sets are generally only used as reference outlines for new work and are not intended for revision. The principal conclusions and recommendations of this report are as follows:

1. In order to take fully advantage of CAD and to maximize the utilization of digital project information, this industry requires a dependable method for the digital data exchange.

CONTINUED ON ATTACHED SHEET

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

AEC CAD; CAD data exchange; computer-aided design; computer integrated construction; construction documentation; data exchange standards; data translators; digital data interchange; IGES; intermediate data exchange formats; validation of translators

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2. The current generation of translator tools is inadequate for comprehensive AEC CAD operations. Incomplete translators, insufficient documentation, and differing interpretations of specifications have prevented accurate and complete data set exchanges.

3. There is a critical need for a public program to validate translator software, to identify problems in current implementations, and to develop guidelines for the use of computer data exchange standards.