MPR-2610
Revision 2
September 24, 2004

Application of Advanced Construction Technologies to New Nuclear Power Plants

Prepared for

U.S. Department of Energy
under contract for DE-AT01-02NE23476

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Executive Summary

As part of the U.S Department of Energy Nuclear Power 2010 (NP2010) initiative, MPR conducted an evaluation of advanced construction technologies that could potentially decrease the construction time of new domestic nuclear plants planned for deployment in the 2010 timeframe. Advanced construction technologies are those construction methods and techniques that were developed after completion of the last domestic nuclear plant (nearly 10 years ago).

Existing U.S. nuclear power plants were constructed using the methods and technologies from the 1970's and 1980's. Since then construction technology has advanced and these new technologies have been used in several applications, including foreign nuclear plant construction. Construction time for these recent foreign nuclear plants has been reduced to four years or less through the use of advanced techniques and technologies.

Thirteen advanced construction technologies were evaluated. The evaluations considered:

- Current applications of the technology
- Primary benefit of the technology to nuclear power plant construction, e.g., construction schedule improvement
- Potential for successful application at a nuclear plant in the U.S., including qualitative assessment of NRC acceptance
- Technical maturity of the technology (assessed qualitatively)
- Activities recommended for DOE to further advance the technology, e.g., research and development

Table ES-1 lists the technologies evaluated and whether use of the technology should be planned in constructing nuclear plants in the U.S. in the 2010 timeframe. Of the thirteen evaluated, MPR found that 12 of these technologies would benefit construction schedules for new, domestic nuclear plants. DOE should disseminate information regarding these twelve technologies to NSSS vendors, utilities, and constructors. It is incumbent on the vendor to develop/obtain expertise with these technologies prior to bidding on a new domestic nuclear plant project.

Nine of the twelve construction technologies recommended for use in domestic nuclear plant construction are sufficiently mature and have proven economic benefits (for most applications). These nine technologies, listed below, do not require additional research and development:

- Steel-Plate Reinforced Concrete Structures
- Concrete Composition Technologies (advanced concrete admixtures)

- High Deposition Rate Welding
- Robotic Welding
- 3D Modeling
- GPS Applications in Construction
- Open-Top Installation
- Pipe Bends vs. Welded Elbows
- Precision Blasting/Rock Removal

The remaining three construction technologies show promise for use in building a domestic nuclear plant and potentially have the largest impact on construction schedule reduction. However, each of these three construction technologies has issues that need further technical development, as summarized in Table ES-2. These three construction technologies are:

- Prefabrication, Preassembly, and Modularization
- Cable Splices
- Advanced Information Management and Control

The third technology, "Advanced Information Management and Control," is part of a significant research initiative by the National Institute of Standards and Technology (NIST). NIST is funding a project called FIATECH (Fully Integrated and Automated TECHnology, see Appendix L for details) to develop more fully integrated information processes to improve the efficiency (cost and schedule) of construction projects and the reliability of completed projects. Thus, this technology does not require DOE research funding.

However, the nuclear industry (e.g., NEI) should obtain information on FIATECH from NIST and conduct an investigation to assess the applicability of this project to improving project coordination for new nuclear plant construction in the U.S. Also, the investigation could assess the applicability of the FIATECH project to improving communications between the plant construction team and the NRC throughout construction.

Table ES-2 summarizes the conclusions and recommendations regarding the advanced construction technologies reviewed as part of this report, with details concerning research to support the application of some of the advanced construction technologies.

ES-1. Technologies Evaluated

Technology	Description	Recommended for Implementation
Steel-Plate Reinforced Concrete Structures	An alternative to structural concrete reinforced with steel bars: parallel steel plates are tied together with steel rods, and are joined by headed studs to concrete poured between the plates.	Yes
Concrete Composition Technologies	Advanced concrete admixtures are used to achieve increased strength and workability. Technology includes self-compacting concrete (SCC), high performance concrete (HPC), and reactive powder concrete (RPC).	Yes
Fiber-Reinforced Polymer Rebar Structures	An alternative to steel bar reinforced concrete; same construction technique as traditional reinforced concrete except reinforcing bars are fiber-embedded polymeric resin.	No —Advantages do not offset higher costs.
High Deposition Rate Welding	Specialized versions of traditional welding processes, including GMAW, GTAW (orbital welding), flux cored SAW, and strip clad welding. Processes offer higher deposition rates than their predecessors.	Yes
Robotic Welding	Automated welding for most types of manual welding processes, including GMAW, GTAW, flux cored arc welding, and SAW.	Yes
3D Modeling[Note 1]	Solid, 3-dimensional modeling computer software used for design work, construction, operations and maintenance.	Yes
Positioning Applications in Construction (GPS and Laser Scanning)	Global Positioning System (GPS) is worldwide radio-navigation system used to determine longitude, latitude, and altitude. Use of "Indoor GPS" (laser scanning) for process control inside fabrication facilities is being developed.	Yes
Open-Top Installation	Reactor building is partially completed and left open so that large components, e.g., reactor vessel and steam generators can be installed from above. After placement of large components, building is completed while piping and electrical systems are installed.	Yes
Pipe Bends vs. Welded Elbows	Welds between straight pipe and elbows are eliminated by pipe bent to specified geometries.	Yes
Precision Blasting/Rock Removal	Precise use of explosives to remove rock instead of mechanical excavation methods.	Yes
Cable Pulling, Termination and Splices	Advancements in lubricants for cable pulling, termination and splicing technologies, e.g., cold shrink, and acceptability of cable splices.	Yes
Advanced Information Management and Control	Computerized design databases centralize all design information, allowing access by all parties.	Yes
Prefabrication, Preassembly, and Modularization	Off-site prefabrication and preassembly of portions (modules) of a plant that are transported to the site for placement and connection with other modules.	Yes

Notes:
1. Does not address full-scale, virtual reality modeling, which could be considered for plants after 2010.

ES-2. Summary of Recommended Actions

Technology	Issues for Use at Domestic Nuclear Plant	Recommended Actions	Estimated Construction Schedule Improvement*
All	U.S. nuclear industry has little recent construction experience.	Make information on the technologies to significantly reduce construction schedule for new nuclear power plants widely available to U.S. nuclear industry organizations.	n/a
Prefabrication, Preassembly, and Modularization	1. Facilities may not be adequate to fabricate the modules at the rate required to meet schedules, especially if more than one plant is ordered. 2. Quality assurance requirements may hamper expansion of module fabrication capability.	1. Industry should assess module manufacturing capability, define gaps in capability under various construction demand scenarios, determine whether capabilities exist to fabricate the modules needed, define any gaps in capabilities or barriers to their use, and develop approaches to overcome the gaps. 2. Industry should assess the impact of 10 CFR 50 Appendix B QA requirements on the availability and feasibility of using PPM. Options for development of new QA methods or programs should be investigated. The findings of this review could be presented to the NRC to discuss measures to resolve the obstacles to increasing the number of domestic and foreign suppliers that meet QA requirements.	5 months
Cable Splicing	Cable splicing enhances modular construction by eliminating the need to pull cable through adjacent modules. Splices, however, are only accepted by the NRC under “special circumstances.” The long lead time to adopt this technology will probably result in its not being available for the next nuclear plant in the U.S.	1. Perform environmental qualification testing of cold-shrink splices. This could be based on the application of splices in construction of nuclear-powered submarines or the testing used to certify cold-shrink splices for use on commercial ships. 2. Perform testing, possibly at a national laboratory such as Sandia or Brookhaven where cable insulation aging has been extensively studied, to show that aging of splices does not degrade overall cable performance. 3. Make results of this work widely available for evaluation to help change industry and NRC standard practice that restricts the use of splices, with the goal of the NRC revising applicable regulations to incorporate results of performance testing. These activities should be sponsored by an industry group such as EPRI, and DOE could consider co-sponsoring them to make this technology option available.	1.3 months
Steel-Plate Reinforced Concrete Structures	Ready for use in construction. Existing inspection techniques per ACI-349.3R will require modification since concrete is encased between steel plates and is not visible.	Plant operators will need to work with constructors and NSSS vendors that use this technology to adapt RC inspection methods and criteria for steel-plate reinforced concrete structures that meet NRC Maintenance Rule requirements.	2.3 months
Advanced Information Management and Control	Common formats for information sharing do not exist. Need to share information with NRC.	U.S. nuclear industry should assess the NIST FIATECH project for its applicability and usefulness. The results of this review could be presented to the NRC for possible application to the NRC’s CIPIMS project.	n/a

* See Appendix N for the basis and analysis used to estimate the approximate duration of schedule reduction.

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1 Introduction

1.1 Purpose

This report identifies and assesses advanced construction technologies potentially applicable to new domestic nuclear plants planned for deployment in the 2010 timeframe. Advanced construction technologies are those construction methods and techniques that were developed after completion of the last domestic nuclear plant (10 years ago). Based on these assessments, recommendations are provided for technology developments, improvements, demonstrations, or other activities needed to shorten the construction schedule for advanced nuclear power plants in the United States.

1.2 Background

In February 2001, the United States Department of Energy (DOE) organized a Near-Term Deployment Group (NTDG) to examine prospects for deployment of new nuclear plants in the United States (U.S.) in this decade, identify obstacles to deployment, and develop actions for resolution. In October 2001, the NTDG published "A Roadmap to Deploy New Nuclear Power Plants in the U.S. by 2010." The recommendations of the Roadmap have been utilized by DOE to form the basis for a new initiative, Nuclear Power 2010 (NP2010). The NP2010 initiative is a joint government/industry cost-shared program to develop advanced reactor technologies and demonstrate new regulatory processes leading to a private sector order for a new nuclear power plant in the U.S. by 2005. NP2010 is an integrated program that aggressively pursues regulatory approvals and design completion in a phased approach, leading to the construction and startup of new nuclear plants in the United States in the 2010 timeframe.

Existing U.S. nuclear power plants were constructed using the methods and technologies from the 1970's and 1980's. Advanced construction technologies have been used abroad since the last new plant construction in the U.S. Specifically, Atomic Energy of Canada Limited (AECL) has built CANDU design reactors in China, South Korea has built System 80+ plants designed by Combustion Engineering (now owned by Westinghouse), and the Japanese have built several Advanced Boiling Water Reactor (ABWR) plants (designed by General Electric and licensed to Toshiba). Construction time for these recent facilities has been reduced to four years or less in some cases through the use of advanced techniques and technologies. These techniques and technologies were not used in the U.S. commercial nuclear industry. However, they are being used in the U. S. and internationally to accelerate the construction schedules of large construction projects (e.g., in fossil-fuel power plant construction, civil works, and shipbuilding). These techniques can potentially be applied to construction of new U.S. nuclear power plants.

In order to achieve the goals of the NP2010 Program, DOE initiated studies on evaluating construction time and cost, detailed engineering for construction, and operations costs for developing new nuclear power plants in the U.S. The DOE has selected a team of contractors having nuclear plant construction, architectural-engineering design, and operations experience to carry out these studies. This document reports the results of one of the studies carried out as part of the NP2010 Program. This report is a companion to MPR report MPR-2627, "DOE NP2010 Construction Schedule Evaluation," and a report by Dominion Energy titled "NP2010 Improved Construction Technologies, O&M Staffing and Cost, Decommissioning Costs, and Funding Requirements Study."

1.3 SCOPE

The NP2010 program addresses four reactor designs considered promising for near-term deployment in the United States:

- ABWR (offered by both GE and Toshiba)
- GE ESBWR
- Westinghouse AP1000
- Atomic Energy of Canada Limited (AECL) ACR-700

As shown in Table 1-1, the construction technologies applicable to each design are very similar. No advanced construction technologies have been identified that are uniquely applicable to a particular reactor design. The summary of findings regarding the various technologies is provided in Table 2-2 in the Conclusions and Recommendations section of this report.

1.4 APPROACH

The advanced construction technologies evaluated in this report were selected by reviewing developments in the construction industry that will have an impact on the major stages of the nuclear plant construction. These developments affect the following major activities:

- Excavation
- Reinforced concrete placement
- Material and component shipping
- Inventory Control
- Modularization
- Steel structure erection

- Vessel tank, piping and pipe support installation
- Electrical instrumentation and control installation
- Testing and startup
- Management of documentation design information

Technologies that have the potential to significantly improve the construction schedule for these major activities were selected. In particular, technologies that have been used successfully in similar applications, (e.g., foreign nuclear plants) or other large-scale construction activities (e.g., fossil fuel plants, petroleum plants or shipbuilding) were selected. The selection process was primarily based on professional judgment supported by company experience. Bechtel Power Corporation, a participant in the Dominion Energy study, also provided input to the technologies to be reviewed. Some candidate technologies were identified through literature reviews and participation in site visits. Site visits are documented in References 1, 2, and 3.

Each advanced technology was researched, evaluated, and summarized for this report. The evaluations consider:

- Primary benefit of the technology, e.g., construction schedule improvement
- Current applications of the technology
- Main hurdle to successful application at a nuclear plant in the U.S., including qualitative assessment of NRC acceptance
- Qualitative assessment of technical maturity
- Suggested follow-up activity by DOE, e.g., research and development

Detailed information on each construction technology is provided in a separate appendix to this report. References providing information about each construction technology are included in each technology's appendix to this report.

Table 1-1. Planned Use of Advanced Construction Technologies

Advanced Construction Technology	ABWR	ESBWR	AP1000	ACR-700
Steel-Plate Reinforced Concrete Structures	No	No	Yes	No
Concrete Composition Technologies	Yes	Yes	Not Determined	Yes
Fiber-Reinforced Polymer Rebar Structures	No	No	No	No
High Deposition Rate Welding	Yes	Yes	Not Determined	Yes
Robotic Welding	Yes	Yes	Not Determined	Yes
3D Modeling[1]	Yes	Yes	Yes	Yes
Positioning Applications (GPS and Laser Scanning)	Yes	Yes	Not Determined	Yes
Open-Top Installation	Yes	Yes	Yes	Yes
Pipe Bends vs. Welded Elbows	Yes	Yes	Not Determined	Yes
Precision Blasting/Rock Removal	Site Specific	Site Specific	Site Specific	Site Specific
Cable Pulling, Termination and Splices[2]	No	No	No	No
Advanced Information Management and Control[1]	Yes	Yes	Yes	Yes
Prefabrication, Preassembly, and Modularization[1]	Yes	Yes	Yes	Yes

[1] This technology is used by different vendors in varying degrees.
[2] Entries refer to use of splices between modules.

2 Conclusions and Recommendations

2.1 CONCLUSIONS

Thirteen advanced construction technologies were evaluated for their applicability to new domestic nuclear power plants. Table 2-2 summarizes the results of these evaluations. This table provides a brief description of each technology, and identifies the benefits and obstacles to implementation in domestic nuclear plant construction. Each construction technology is discussed in greater detail in the appendix noted in Table 2-2.

Twelve of the thirteen technologies evaluated should be planned for use in constructing nuclear plants in the U.S. in the 2010 timeframe. Nine of the twelve construction technologies recommended for domestic nuclear plant construction are sufficiently mature and have proven economic benefits (for most applications) that they do not require additional research and development. These nine construction technologies are:

- Steel-Plate Reinforced Concrete Structures
- Concrete Composition Technologies (advanced concrete admixtures)
- High Deposition Rate Welding
- Robotic Welding
- 3D Modeling
- GPS Applications in Construction
- Open-Top Installation
- Pipe Bends vs. Welded Elbows
- Precision Blasting/Rock Removal

The remaining three construction technologies show promise for use in building a domestic nuclear plant and potentially have the largest impact on construction schedule reduction. However, each of these three construction technologies has issues that need further technical development. These three construction technologies are:

- Prefabrication, Preassembly, and Modularization

- Cable Splices
- Advanced Information Management and Control

The first two technologies have the potential to individually reduce overall construction schedules by approximately 5 months and 1.3 months, respectively, compared to a schedule where the technology is not used, if the issues identified with their use in the construction of a domestic nuclear plant can be resolved. The nuclear industry would receive significant benefit from research and development support of all three of these technologies.

Because of the successful application of prefabrication, preassembly, and modularization in the construction of fossil power plants and various other projects in the U.S., and in nuclear plant construction outside the U.S., the nuclear industry has been preparing for extensive use of this technology in the next generation of plants to be built in the U.S. Additionally, the NRC has been preparing for the change in inspection processes to accommodate the fabrication and construction of large components away from the plant site, and has been working with industry to demonstrate these new inspection processes. These preparations are still in progress and further effort is needed to make the use of prefabrication, preassembly, and modularization a reality for nuclear plant construction. Recommendations for these actions are in section 2.2 of this report.

The third technology in the group requiring further effort, "Advanced Information Management and Control," is the subject of a significant research initiative by the National Institute of Standards and Technology (NIST), see Appendix L for details of this project. The need for the use of this technology is also explicitly recognized and required in the "U.S. Advanced Light Water Reactor (ALWR) Utility Requirements Document." The NRC is separately developing a Construction Inspection Program Information Management System (CIPIMS) to track inspection, test, analysis, and acceptance criteria (ITAAC) during construction of new nuclear power plants. Although Advanced Information Management and Control may not require industry and DOE research, the industry and NRC may benefit from an assessment of the NIST project and its applicability to new nuclear plant construction and the CIPIMS project.

2.2 RECOMMENDATIONS

2.2.1 Disseminate Findings of this Study to the Nuclear Industry

DOE should make the findings of this report available for NSSS vendors, architect/engineers, and potential plant owners. DOE should focus attention on the twelve advanced construction technologies identified in Table 2-2 to benefit construction schedules for new domestic nuclear plants. It is expected that NSSS vendors and constructors will develop/obtain expertise with these technologies prior to bidding on a new domestic nuclear plant project.

Additionally, DOE should consider sponsoring an information conference with NSSS vendors, nuclear industry A/E firms, and potential utility owners to ensure they have information available on each technology. Vendors that support the advanced technologies should be invited to present available information on the technologies.

2.2.2 Research and Development Activities

DOE should consider co-funding industry-led research in the application of the two advanced construction technologies listed in Table 2-1 as requiring work to be ready to support construction. These technologies are listed in order of priority based on the expected benefit of the technology relative to the expected costs. The basis for the assigned priorities is as follows:

First Priority -- Prefabrication, preassembly, and modularization. This technology has the most potential for nuclear plant construction time savings (estimated to be at least five months). However, significant investment will be required to implement this technology for construction of new nuclear power plants in the United States. Given the extensive recent use of this technology for fossil power plants and for nuclear powered aircraft carriers and submarines, the remaining issues are the application of commercial nuclear power quality standards, ensuring non-U.S. module fabricators can produce the required quality and meet tight schedule demands, and maximizing the cost-effective incorporation of this technology into new plant designs and construction plans.

Second Priority -- Cable splicing. Using splicing on a more widespread basis is expected to decrease construction times by approximately one month. Although this is a small time savings relative to other technologies presented here, the cost to implement cable splicing should be very low. The primary hurdle is regulatory, and a long lead time is anticipated for research required to demonstrate the acceptability of splices, change regulatory positions, and make this a feasible alternative to standard industry practice. Thus, this technology will probably not be available for inclusion in construction plans for the next new nuclear plants to be built in the U.S.

2.2.2.1 Prefabrication, Preassembly, and Modularization

Prefabricating major sections of nuclear plants has the potential to shorten the overall construction schedule by an estimated 5 months. Prefabrication, preassembly, and modularization (PPM), which relies on off-site fabrication capability and transportation infrastructure, will place heavy loads on the existing module fabrication infrastructure in the U.S., will require significant quality assurance effort to obtain modules from foreign fabricators, and could place the shortened construction schedules at risk because of those schedules' dependence on timely delivery of modules. Further evaluation and support for resolution of these issues, possibly by a DOE-nuclear industry cost-share arrangement, is recommended as follows:

1. Industry should conduct a review of manufacturing facilities to determine whether capabilities exist for fabricating the large modules needed for this technology at the rate required to support proposed construction schedules, define any gaps in capabilities or barriers to their use, and develop approaches to overcome the gaps. While DOE trips to U.S. Navy shipyards and to facilities in Japan found substantial capability for module fabrication for nuclear plants, some obstacles to use of PPM that should be considered are: ability to increase production capacity if more than one plant is ordered, and the ability to meet challenging production and delivery schedules.

2. Assess the impact of 10 CFR 50 Appendix B quality assurance (QA) requirements on the availability and feasibility of using PPM. The quality assurance requirements will prevent some suppliers capable of producing modules from participating because of the expense of establishing and maintaining a 10 CFR 50 Appendix B QA program. The number of fabricators that can meet presently defined QA requirements may be small and the industry may not have the capacity to respond to increased demand or short construction schedules. Options for development of new QA methods or programs should be assessed. The findings of this review could be presented to the NRC to discuss measures to resolve the obstacles to increasing the number of domestic and foreign suppliers that can meet QA requirements.

2.2.2.2 Cable Splicing

The use of cable splices as part of modular construction is estimated to shorten new nuclear plant construction schedules by approximately 1 month out of a 66-month construction schedule. Therefore, the feasibility and desirability of using this technology should be investigated. MPR recommends that the following actions be taken as part of a nuclear industry-sponsored effort:

1. Perform environmental qualification testing of cold-shrink splices. This could be based on the application of splices used in construction of nuclear-powered submarines and the testing used to certify cold-shrink splices for use on commercial ships. The testing should be planned with NRC participation to ensure it addresses potential regulatory concerns.

2. Perform testing, possibly at a national laboratory such as Sandia or Brookhaven where cable insulation aging has been extensively studied, to show that aging of splices does not degrade overall cable performance. The testing should be planned with NRC participation to ensure it addresses potential regulatory concerns.

3. Make results of this work widely available for use in efforts to change industry and NRC standard practice that restricts the use of splices, with the goal of the NRC revising regulatory guidance to incorporate results of performance testing and accepting the use of splices to enhance modular construction. This will support envisioned application of a modularization strategy incorporating splices in new domestic nuclear plant designs and construction plans.

These activities could be co-sponsored by DOE if DOE and industry determine that making this technology available as a construction technique would be a worthwhile effort. The long lead time to adopt splicing technology as industry practice will probably result in its not being available within the next 5 years for the next nuclear plant construction in the U.S.

2.2.2.3 Advanced Information Management and Control

The NIST is funding a project called FIATECH (Fully Integrated and Automated TECHnology, see Appendix L for details) to develop more fully integrated information processes to improve the efficiency (cost and schedule) of construction projects and the reliability of completed projects. Thus, this technology does not require DOE research funding.

However, the nuclear industry (e.g., NEI) should obtain information on FIATECH from NIST and conduct an investigation to assess the applicability of this project to improving project coordination for new nuclear plant construction in the U.S. Also, the investigation could assess the applicability of the FIATECH project to improving communications between the plant construction team and the NRC throughout construction. The investigation should determine steps needed to resolve any NRC concerns about safety-related electronic documentation and safeguarding any sensitive information related to plant security. An assessment of the NIST project is recommended because it could improve the process of inspections and approvals by NRC during plant construction, in addition to increasing efficiency during construction. Industry should conduct this assessment and invite the NRC to participate.

Table 2-1. Summary of Recommended Actions

Technology	Issues for Use at Domestic Nuclear Plant	Recommended Actions	Estimated Construction Schedule Improvement*
All	U.S. nuclear industry has little recent construction experience.	Make information on the technologies to significantly reduce construction schedule for new nuclear power plants widely available to U.S. nuclear industry organizations.	n/a
Prefabrication, Preassembly, and Modularization	1. Facilities may not be adequate to fabricate the modules at the rate required to meet schedules, especially if more than one plant is ordered. 2. Quality assurance requirements may hamper expansion of module fabrication capability.	1. Industry should assess module manufacturing capability, define gaps in capability under various construction demand scenarios, determine whether capabilities exist to fabricate the modules needed, define any gaps in capabilities or barriers to their use, and develop approaches to overcome the gaps. 2. Industry should assess the impact of 10 CFR 50 Appendix B QA requirements on the availability and feasibility of using PPM. Options for development of new QA methods or programs should be investigated. The findings of this review could be presented to the NRC to discuss measures to resolve the obstacles to increasing the number of domestic and foreign suppliers that meet QA requirements.	5 months
Cable Splicing	Cable splicing enhances modular construction by eliminating the need to pull cable through adjacent modules. Splices, however, are only accepted by the NRC under “special circumstances.” The long lead time to adopt this technology will probably result in its not being available for the next nuclear plant in the U.S.	1. Perform environmental qualification testing of cold-shrink splices. This could be based on the application of splices in construction of nuclear-powered submarines or the testing used to certify cold-shrink splices for use on commercial ships. 2. Perform testing, possibly at a national laboratory such as Sandia or Brookhaven where cable insulation aging has been extensively studied, to show that aging of splices does not degrade overall cable performance. 3. Make results of this work widely available for evaluation to help change industry and NRC standard practice that restricts the use of splices, with the goal of the NRC revising applicable regulations to incorporate results of performance testing. These activities should be sponsored by an industry group such as EPRI, and DOE could consider co-sponsoring them to make this technology option available.	1.3 months
Steel-Plate Reinforced Concrete Structures	Ready for use in construction. Existing inspection techniques per ACI-349.3R will require modification since concrete is encased between steel plates and is not visible.	Plant operators will need to work with constructors and NSSS vendors that use this technology to adapt RC inspection methods and criteria for steel-plate reinforced concrete structures that meet NRC Maintenance Rule requirements.	2.3 months
Advanced Information Management and Control	Common formats for information sharing do not exist. Need to share information with NRC.	U.S. nuclear industry should assess the NIST FIATECH project for its applicability and usefulness. The results of this review could be presented to the NRC for possible application to the NRC’s CIPIMS project.	n/a

* See Appendix N for the basis and analysis used to estimate the approximate duration of schedule reduction.

Table 2-2. Summary of Findings

<table>
<tr><th rowspan="2">Appendix</th><th rowspan="2">Technology</th><th rowspan="2">Description</th><th colspan="2">Current Applications</th><th rowspan="2">Primary Benefit</th><th rowspan="2">Main Obstacle to Domestic Nuclear Plant Use</th><th rowspan="2">Recommended for Implementation</th></tr>
<tr><th>Country</th><th>Project</th></tr>
<tr><td>A</td><td>Steel-Plate Reinforced Concrete Structures</td><td>An alternative to structural concrete reinforced with steel bars: parallel steel plates are tied together with steel rods, and are joined by headed studs to the concrete poured between the plates.</td><td>Japan</td><td>Low level radioactive waste incinerator building</td><td>Speeds construction of structural concrete because rebar mats are eliminated, and formwork is integral with the structural member, i.e., no need to remove formwork after concrete cures</td><td>Ready for use in construction except for structures with steel liners; these will have additional design issues, e.g., Code does not count strength of liners.
For other applications, the plant operators will need to adapt existing inspection methods and criteria to meet ACI-349.3R and NRC requirements.</td><td>Yes</td></tr>
<tr><td rowspan="2">B</td><td rowspan="2">Concrete Composition Technologies</td><td rowspan="2">Advanced concrete admixtures are used to achieve increased strength and workability.
Technology includes self-compacting concrete (SCC), high performance concrete (HPC), and reactive powder concrete (RPC).</td><td>Worldwide</td><td>Various civil construction projects</td><td rowspan="2">Reduces quantities of concrete for same strength
Improves concrete workability</td><td rowspan="2">None
Techniques are treated in the same manner as traditional methods</td><td rowspan="2">Yes</td></tr>
<tr><td>France</td><td>Medium-level radioactive waste storage</td></tr>
<tr><td>C</td><td>Fiber-Reinforced Polymer Rebar Structures</td><td>An alternative to steel bar reinforced concrete: same as traditional reinforced concrete except reinforcing bars are fiber-embedded polymeric resin.</td><td>Worldwide</td><td>Bridge beams and decking</td><td>Reduces weight of concrete structures
Better corrosion resistance than steel reinforced concrete</td><td>Reduced fire resistance compared to conventional reinforced concrete
Higher costs</td><td>No — Advantages are less significant for nuclear plants than for bridges, so higher costs are not offset.</td></tr>
</table>

Appendix	Technology	Description	Current Applications		Primary Benefit	Main Obstacle to Domestic Nuclear Plant Use	Recommended for Implementation
			Country	Project			
D	High Deposition Rate Welding	Specialized versions of traditional welding processes, including GMAW, GTAW (orbital welding), flux cored SAW, and strip clad welding, that have higher deposition rates than their predecessors.	Japan	Used for production of nuclear plants	Speeds production of: 1. steel-plate joining, e.g., between SC modules 2. large bore pipe installation 3. components requiring cladding	None Techniques are treated in the same manner as traditional methods	Yes
E	Robotic Welding	Automated welding for most types of manual welding processes, including GMAW, GTAW, flux cored arc welding, and SAW.	Japan, China, France	Used for fabrication of nuclear plant components	Greater productivity and higher quality in welding	None Techniques are treated in the same manner as traditional methods	Yes
			U.S.	Used for some nuclear plant component repairs			
F	3D Modeling[Note 1]	Solid, 3-dimensional modeling computer software is used for design work, construction, operations and maintenance.	Worldwide	De facto industry requirement	Speeds design and allows verification of finished assembly layouts	None Technique is treated in the same manner as traditional methods	Yes
G	Positioning Applications in Construction (GPS and Laser Scanning)	Global Positioning System (GPS) is worldwide radio-navigation system used to determine longitude, latitude, and altitude. Use of "Indoor GPS" (laser scanning) for process control inside fabrication facilities is being developed.	Worldwide	GPS is de facto requirement for site prep on geographically extensive projects	Speeds site preparation and survey work with increased accuracy and reduced re-work	None Technique is treated in the same manner as traditional methods	Yes

Appendix	Technology	Description	Current Applications		Primary Benefit	Main Obstacle to Domestic Nuclear Plant Use	Recommended for Implementation
			Country	Project			
H	Open-Top Installation	Reactor building is partially completed and left open so that large components, e.g., reactor vessel and steam generators can be installed from above. After placement of large components, building is completed while piping and electrical systems are installed.	Japan, China, Taiwan	Nuclear plant construction since mid-1990's	Speeds completion of work in reactor building	None Technique is treated in the same manner as traditional methods	Yes
I	Pipe Bends vs. Welded Elbows	Welds between straight pipe and elbows are eliminated by pipe bent to specified geometries.	Japan, China	Nuclear plant construction	Reduces lifetime costs of in-service inspections by reducing number of welds	None Technique is treated in the same manner as traditional methods	Yes
			U.S.	Construction of various projects including U.S. Navy nuclear plants			
J	Precision Blasting/Rock Removal	Precise use of explosives to remove rock instead of using mechanical excavation methods.	U.S.	Used to excavate Millstone Unit 3	Faster excavation of rock without shutting down nearby operating plants.	None This technology has been used at a domestic nuclear plant	Yes
K	Cable Pulling, Termination and Splices	Advancements in lubricants for cable pulling, termination and splicing technologies, e.g., cold shrink, and acceptability of cable splices.	U.S.	Used in military and commercial shipbuilding to aid modular construction	Splices would allow significant reduction in cable pulling time, especially when used with modular construction	Splices are accepted by NRC but only under "special circumstances" Splices could be aging management issue	Yes

Appendix	Technology	Description	Current Applications		Primary Benefit	Main Obstacle to Domestic Nuclear Plant Use	Recommended for Implementation
			Country	Project			
L	Advanced Information Management and Control	Computerized design databases centralize all design information, allowing access by all parties.	U.S.	Fossil power plant construction	Speeds access to design and construction drawings, specifications, inspection records, etc.	Need NRC acceptance for safety-related electronic documentation. Need development of common information standards for sharing by construction project team.	Yes
M	Prefabrication, Preassembly, and Modularization	Off-site prefabrication and preassembly of portions (modules) of a plant that are transported to the site for placement and connection with other modules.	Japan, China	Used for nuclear plant construction	Speeds construction time	1. Facilities may not be adequate to fabricate the large, complex modules needed for this technology at the rate required to meet schedules, especially if more than one plant is ordered. 2. Quality assurance requirements may hamper expansion of module fabrication capability both in the U.S. and abroad for construction of U.S. plants.	Yes

Notes:
1. Does not address full-scale, virtual reality modeling, which could be considered for plants after 2010.

3 Discussion

Thirteen technologies that could potentially be applied in the construction of nuclear power plants in the U.S. were researched and evaluated as described in Appendices A through M. These technologies were selected by identifying major activities required to support nuclear plant construction by the year 2010 and surveying construction experience to identify progress since the last domestic nuclear plant construction was completed in the early 1990's[3]. Construction activities include:

- Excavation
- Reinforced concrete placement
- Material and component shipping
- Inventory control
- Modularization
- Steel structure erection
- Vessel tank, piping and pipe support installation
- Electrical instrumentation and control installation
- Testing and startup
- Management of documentation design information

For the next nuclear plant built in the U.S. to meet the goal of the DOE NP2010 Program the period of construction must be essentially halved relative to the historical average. Over the thirty-two year history of domestic nuclear plant construction, the construction period has averaged in excess of 9 years[4]. The NP2010 goal is approximately half that duration. It should be noted that construction schedules consistent with the NP2010 goal were achieved for a number of older domestic nuclear plants and are currently being achieved in the construction of foreign nuclear plants.

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[3] Watts Bar 1, the last domestic reactor to come on-line, first operated on May 27, 1996. However, the major construction activities on the unit were complete by the early 1990's.

[4] Another benchmark construction project duration, used elsewhere in this report, is 66 months (Reference 12). This value, measured from construction permit issue date to fuel load, includes only domestic nuclear power plants completed by 1979 (Reference 1), thereby omitting the effects of the regulatory changes following the 1979 accident at Three Mile Island Unit 2.

The goal of this evaluation was to identify technologies developed during the last 20 years that could significantly shorten the construction period in the US.

The evaluations of the different technologies considered the following: current applications and experience with the technology, potential benefit of the technology and potential code/regulatory issues. Twelve technologies were determined to have potential application in new domestic nuclear plant construction.

One additional group of technologies, advanced cutting methods, was evaluated but not included in the appendices. It was concluded that use of advanced cutting methods would not significantly shorten the construction schedule or considerably reduce costs.

The potential improvement in construction schedule was quantified for three of the construction technologies: steel-plate reinforced concrete structures; cable splicing; and prefabrication, preassembly, and modularization. The potential improvement in construction schedule from each advanced construction technology is summarized in Table 2-1. Appendix N details the estimates developed. For these three technologies to be available for new domestic nuclear plant construction, additional research and development is required. Quantifying the potential schedule improvement provides a basis for determining whether funds should be allocated to resolve the issues with each technology and to prioritize these efforts. Since the other eight technologies recommended for implementation do not require significant resources from DOE to assist in reaching maturity, they were not quantitatively assessed for construction schedule improvement.

4 References

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A
Steel-Plate Reinforced Concrete Structures

Many of the structures, foundations, and containments (e.g., reactor containment, auxiliary buildings, spent fuel storage, etc.) in previous nuclear power plants were constructed from reinforced concrete. This construction used built-in-place, reinforcing bars with external forms to frame and reinforce the structure prior to the placement of concrete. This construction technique required a long construction period including the construction and demolition of the form work and its supports. The placement of reinforced concrete structures was a major part of the overall plant construction schedule, typical of large-scale construction projects.

An alternative construction technique for reinforced concrete is steel-plate reinforced concrete (Reference 1). A steel-concrete-steel composite structure is constructed by placing concrete between two steel plates that form the concrete and provide the permanent exterior face of the structure. Studs welded on the inner surface of the steel plates are embedded in the concrete to tie the concrete and steel plates together. For erection purposes, the steel plates are connected together with tie-bars. Figure A-1 shows isometric views comparing standard reinforced concrete and steel-plate reinforced concrete construction. This new building construction technique can be used in the construction of the floors and walls of the reactor building, and for atmospheric tanks, as proposed in Westinghouse's AP600 and AP1000 (References 2, 3 and 10).

1. Implementation Experience

This method of erecting reinforced concrete structures was first used in 2002 in the construction of an auxiliary building (the incinerator building) at the Kashiwazaki-Kariwa 6 and 7 nuclear power plant site in Japan (Reference 1). TEPCO is planning to use this method for construction of the reactor containment building for the Fukushima 7 & 8 reactors scheduled to begin commercial operations in 2007 and 2008. The specific methods used by TEPCO were developed in Japan.

Similar techniques are being developed in the U.S. and United Kingdom (References 4 and 10). However, literature describing the use of this specific technique in U.S. construction projects was not found.

2. Benefits

Steel-plate reinforced concrete construction (SC) methods offer significant schedule advantages compared with conventional reinforced concrete construction (RC). The construction schedule is shortened because placement of rebar and removal of formwork are eliminated by the steel plate method. Based on information published by TEPCO (Reference 1), the steel-plate reinforced

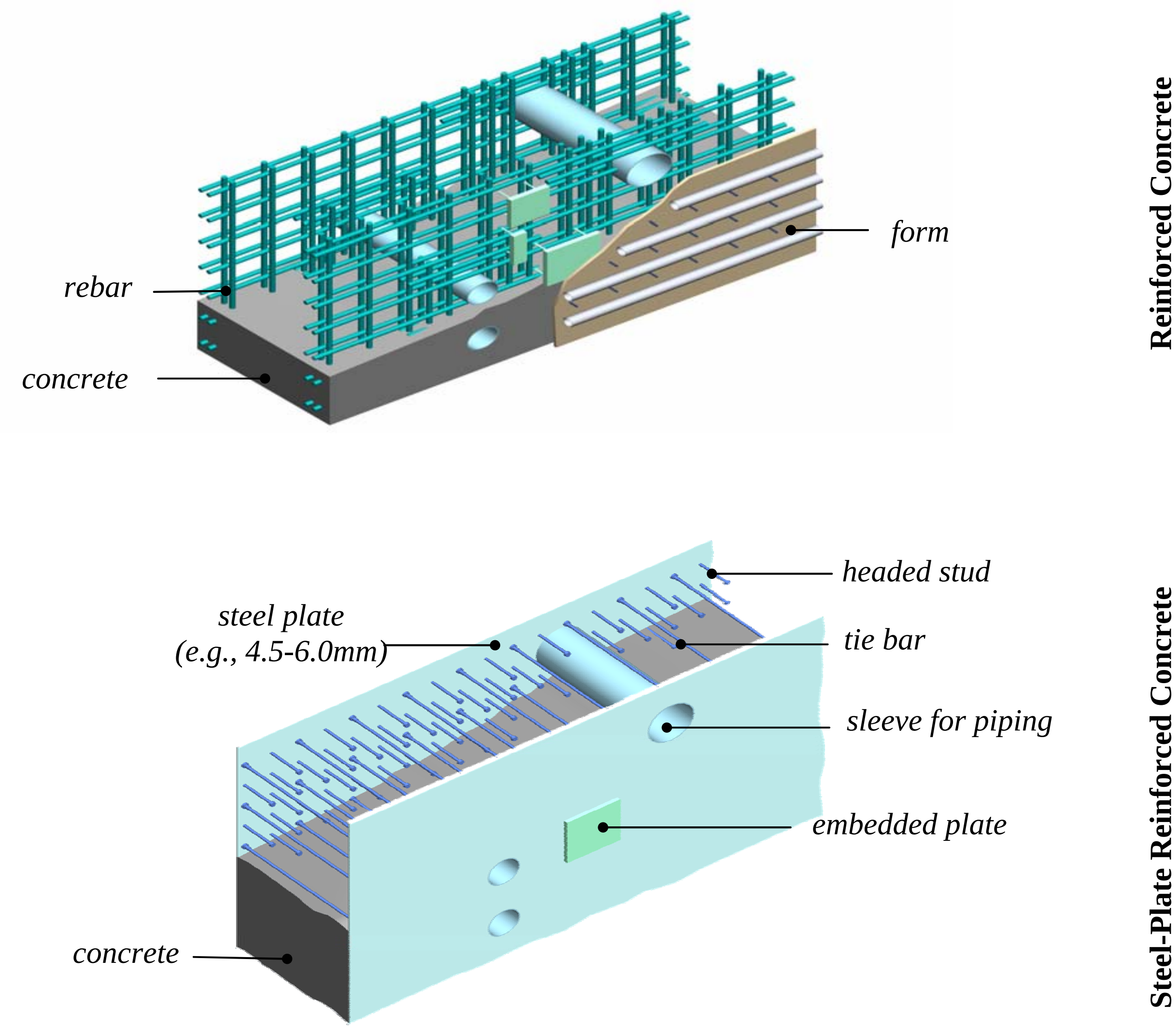

Figure A-1. Comparison of Reinforced Concrete Construction (Reference 1)

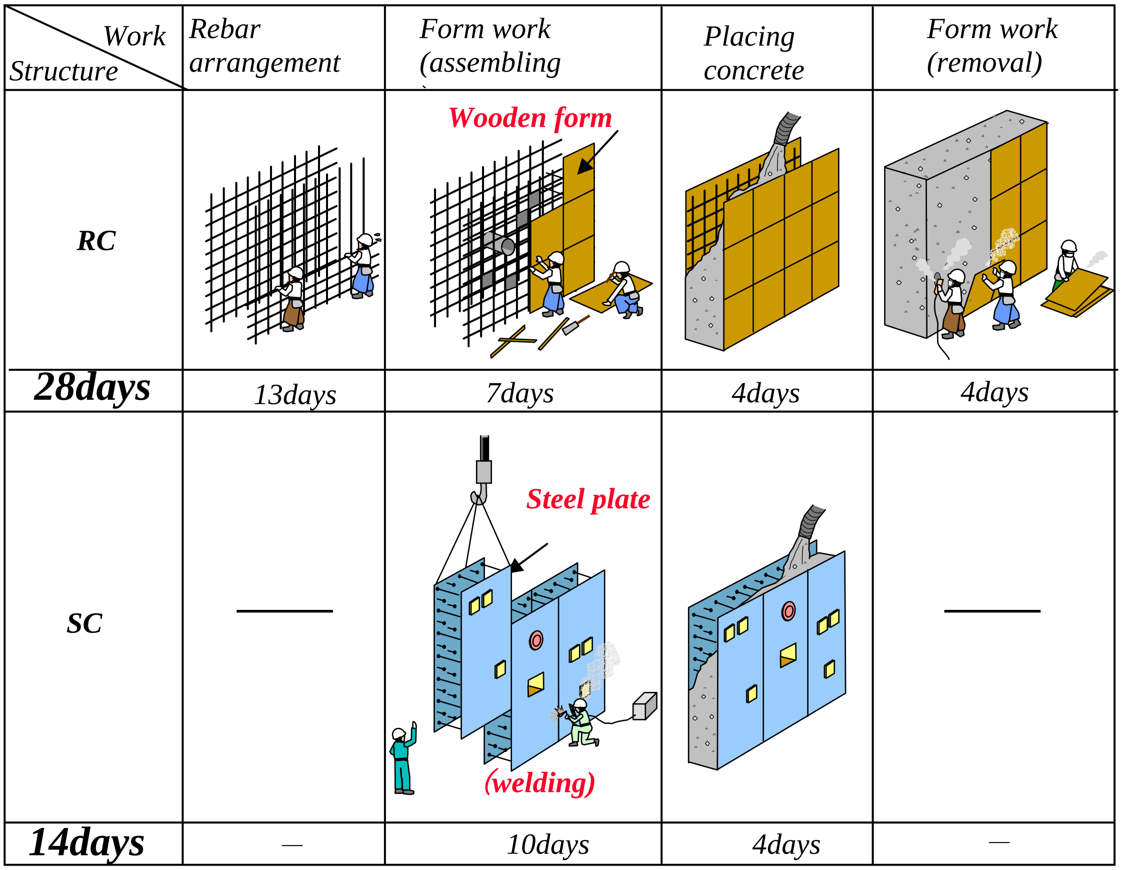

Figure A-2. Comparison of Construction Schedules for Reinforced Concrete

concrete wall construction is twice as fast as similar reinforcing bar reinforced concrete construction (see Figure A-2). Since the steel-plate structure is designed to be self-supporting, it is possible to fabricate the reinforced concrete sections as modules off-site, transport them as a unit to be placed on-site, and welded together (Reference 5). This construction technique results in a significant reduction in the work on-site prior to the concrete pour. Further, there is only limited form work to remove after the concrete has set.

Based on a cost analysis performed by TEPCO, the difference in cost of steel-plate reinforced concrete compared to the cost of RC reinforced concrete is dependent on several factors. Specifically, SC reinforced concrete construction method reduces the on-site work man-days by about 25%, as shown in Figure A-3. This corresponds to a reduced cost in labor. Additionally, the quantity of steel needed for an SC structural element (e.g., slab) is about 25% less than that required for an RC structural element with comparable strength (see Figure A-4). Although the fabrication cost is higher for the SC method, since the cost of steel plate is higher than the cost of reinforcing bar, the overall net production costs with the SC method are lower.

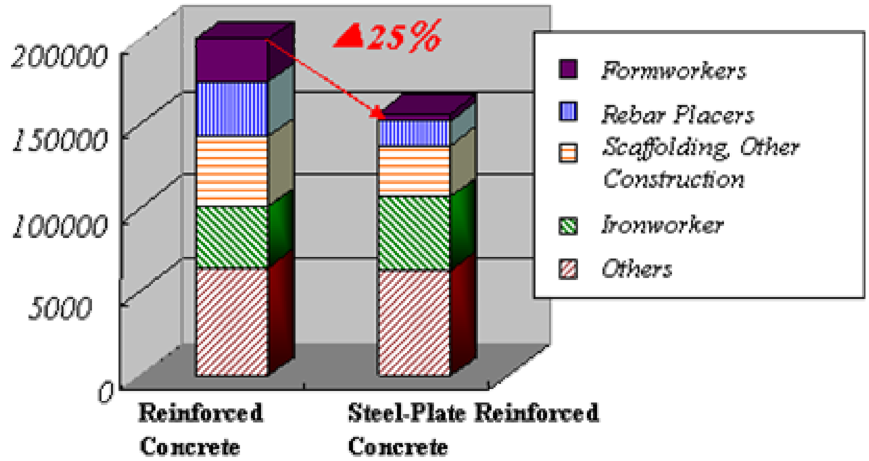

Figure A-3. Comparison of the On-Site Man Power Requirements

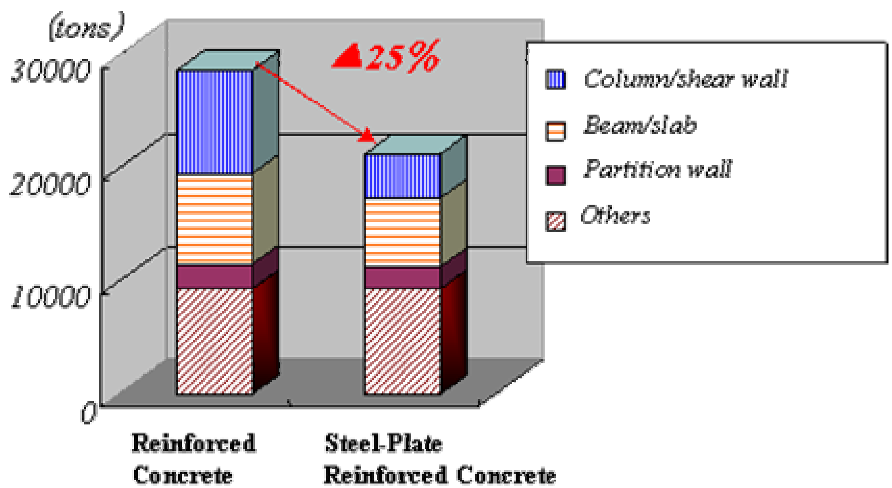

Figure A-4. Comparison of the Quantity of Steel Requirements

The seismic load carrying capability of SC construction design is a key factor for a nuclear structure. Based on TEPCO data, the deformation capacity for the SC reinforced concrete structure is 1.5 times greater than for an RC reinforced concrete structure. Figure A-5 shows plots of shear stress capability versus the deformation angle for each of these structures.

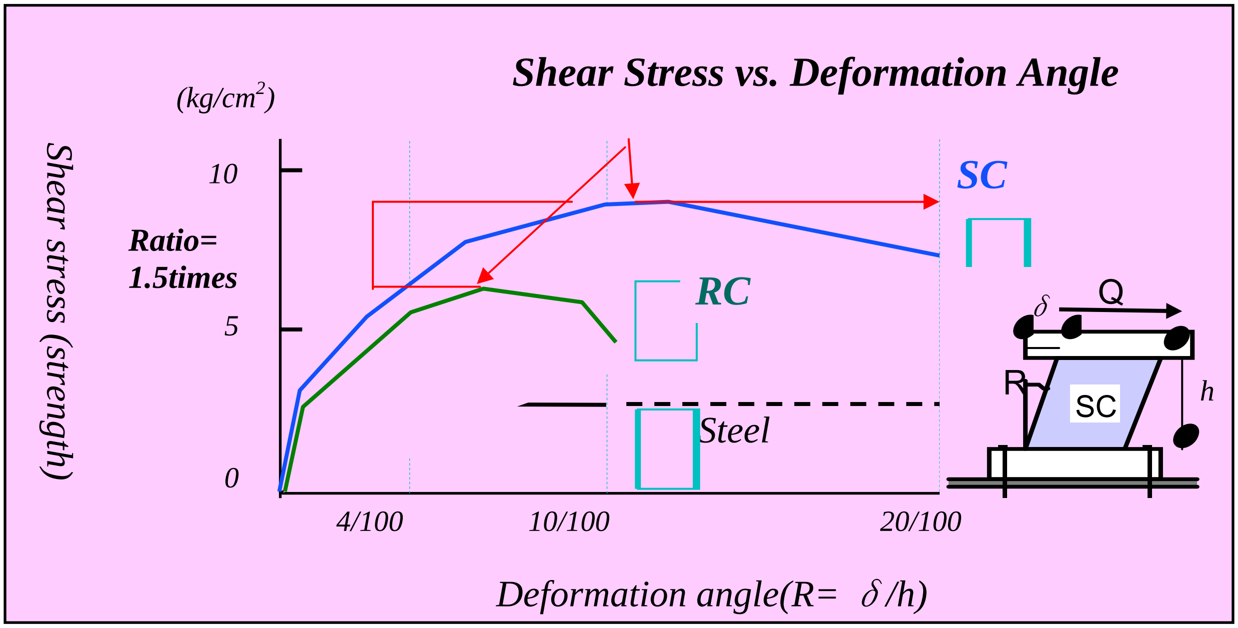

Figure A-5. Shear Stress vs. Deformation Angle

Additionally, TEPCO states that a building constructed using SC technology can be more easily dismantled and for less cost than a conventional RC building. Therefore, decommissioning these structures could be more easily achieved. This potential benefit of steel plate construction, which appears to be technically reasonable, was not supported in detail by the available references.

3. Code and Regulatory Issues

Based on discussions with Westinghouse (Reference 10), their AP1000 design would not use SC construction for the containment, although other structures, e.g., some floors and pools/tanks, would use the SC technology. Therefore, the ASME Boiler and Pressure Vessel Code for Steel-Lined Concrete Containments does NOT apply, and the governing code is ACI-349 (Reference 7).

The NRC has addressed the use of SC modular structures for safety-related applications in regulatory position 13 of Regulatory Guide 1.142. The NRC requires that design of SC modular structures follow guidelines in ACI-349 to ensure adequate structural strength to support required loads and withstand the design basis earthquake. Regulatory Guide 1.142 states that the NRC will evaluate applications of SC structures in safety-related buildings on a case-by-case basis until ACI-349 is revised to contain more specific requirements regarding SC.

SC construction is potentially more susceptible than RC to loss of strength or deformation when exposed to fire because, unlike RC construction, the steel reinforcement is not covered by concrete. According to Westinghouse, when the NRC certified the AP600 design they accepted the Westinghouse approach of analyzing the fire loading in each space enclosed by SC construction. For areas that have very low fire loading, the steel plate alone is an acceptable fire barrier. This approach would likely be accepted again for other advanced designs.

Although the NRC did not address aging management of SC structures in their certification of the AP600 or in Regulatory Guide 1.142, the NRC's Maintenance Rule does require periodic evaluation of safety-related structures, some of which may be SC construction (see ACI-349.3R, Reference 8). For RC construction, the periodic evaluations in ACI-349.3R depend mainly on visual inspection. The ACI-349.3R committee presently does not consider that use of SC structures will require development of special inspection processes or guidance. The NRC has not indicated that they will disagree with this approach. Westinghouse, in its planning for preparation of COL applications for the AP1000, also does not anticipate the need to develop specific inspection guidance for SC structures. The owner/operator of a plant containing SC safety-related structures will need to develop inspection guidelines, procedures, and techniques for inspection, especially as a plant built using SC structures ages.

4. SUMMARY

The steel-plate reinforced concrete construction method offers the potential for significant reduction in construction schedule and costs in the next generation of nuclear power plants. Improvements in plant layout and overall size may also be realized from the improved structural capability of steel-plate reinforced concrete construction methods. Attention to the NRC-sanctioned approach to fire protection of steel-plate reinforced concrete will be required in implementing this construction technique.

This is a promising technology whose development for use in domestic nuclear power construction should result in benefits to the constructor and plant owner. Note that after the plant is constructed, the owner will need to have detailed processes in place for complying with the periodic inspection requirements for SC construction in the governing ACI Code and NRC Maintenance Rule.

Although not applicable to containment structures of Generation III+ plants considered by the NP2010 Program, it is noted that extension of this construction technique to primary containment structures will require further development of the technique and expansion of the existing code design requirements.

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B

Concrete Composition Technologies

Traditional concrete has been revolutionized since the construction of the most recent domestic nuclear power plants. These advancements are due to the use of admixtures to conventional concrete that modify its characteristics. In addition to increasing the comprehensive strength of the concrete, available admixtures can improve other characteristics, such as low permeability, limited shrinkage, and increased corrosion resistance. These changes can also reduce the curing time required by reducing the required thickness of concrete members as well as the reducing the number of special construction steps involved in curing.

Admixtures are used to improve a specific characteristic of the concrete for a specific application. Some of these improvements include water reduction in the mix, strength enhancement, corrosion protection, set acceleration, and crack control. Hardening accelerators, like Rapid-1, are used to allow the development of very early high strengths in concrete (Reference 1). This hardening accelerator is non-chloride (non-corrosive) and does not limit the long-term strength gain of concrete, whereas the strength gain may be sacrificed when other set accelerators are used. The advantages are a more placeable concrete for improved construction productivity without performance tradeoffs. Additionally, this product can be used in combination with a superplasticizer without modifying its properties. ASTM C494 specifies the requirements for several of these concrete admixtures.

Self-compacting concrete (SCC) is a special type of concrete mixture that has a high resistance to segregation (References 2 and 4). It can be cast without compaction or vibration. SCC, also known as self-placing concrete, is obtained by the addition of a water reducing agent to a conventional concrete mix. The water cement ratio remains the same in the mixture. SCC is a "flowable" concrete with high compressive strength. MELFLOW is an example of the type of superplasticizer used to produce SSC (Reference 1). This admixture optimizes the water/cement ratio of the concrete, dramatically improving its workability without having to add more water.

High performance concrete (HPC) is made with a combination of several different admixtures (e.g., superplasticizer, flyash, silica fume, etc.) to produce the required mix design properties (Reference 1). When properly mixed, transported, placed, consolidated, and cured, it provides higher performance (e.g., high compressive strength, high density, and low permeability) than traditional concrete. In addition, compressive strength for HPC is typically between 101 MPa (14.7 ksi) and 131 MPa (19 ksi), whereas traditional concrete compressive strength ranges from 2.5 ksi to 5 ksi.

Reactive powder concrete (RPC) provides the capability for even higher compressive strengths than can be achieved with HPC (Reference 1). Concrete compressive strength can be increased as high as 200 MPa (29 ksi). RPC is produced by including individual metallic fibers in a dense cement matrix. This reinforcement also increases the ductility of RPC in comparison to traditional concrete.

1. IMPLEMENTATION EXPERIENCE

SCC is widely used in Japan in the construction of large scale projects such as bridges, buildings, tunnels, dams, and LNG tanks (Reference 1).

HPC has been used extensively in bridges in Germany, Virginia, and New York (References 5 and 6). The use of HPC is being encouraged for bridges and other highway structures by the Federal Highway Administration.

The French Atomic Energy Commission (CEA) has permitted the use of RPC to fabricate High Integrity Containers (HIC) for long-term interim storage of medium-level nuclear wastes (Reference 3). Current technology involves steel or cement-based multiple-walled containers in which wastes are immobilized by the injection of concrete or grout. Containers made with RPC are currently being developed for "bulk" packaging of the wastes. RPC has also been used to construct a pedestrian bridge in Canada.

Hardening accelerators have been used in the United States for several years. Applications include repairs to bridges, highways, and other concrete structures. Due to the internal heat generation, hardening accelerators are usually limited to repair pours and smaller structures, but can be used in larger structures using the improved, non-calcium accelerators.

2. BENEFITS

SCC provides improvements in strength, density, durability, volume stability, bond, and abrasion resistance. SCC is especially useful in confined zones where vibrating compaction is difficult (Reference 1). The reduction in schedule is limited since a large portion of the schedule is still controlled by the time required to erect and remove formwork. Although the schedule reduction is limited, it is still sufficient that the reduction in labor costs overcomes the higher material costs.

The direct advantage of HPC to the nuclear power plant construction schedule is the early stripping of formwork. In addition, the greater stiffness and higher axial strength allows for the use of smaller columns in the construction. This will improve the construction schedule by reducing the amount of concrete that must be placed. These factors combined lead to construction elements of high economic efficiency, high utility, and long-term engineering economy (Reference 1).

The high-performance properties of RPC provide many enhancements compared to conventional concrete structures (Reference 3):

- Reduction of structural steel allows for greater flexibility in designing the shape and form of structural members

- Superior ductility and energy absorption provides structural reliability under earthquakes

- Reduction of structural steel allows numerous structural member shape and form freedom

- Superior corrosion resistance

Admixtures and accelerators provide improved concrete properties such as increased strength, reduced weight, or the elimination of flow problems and compaction. With increased strength, the volume of concrete required may be decreased, which in turn reduces the time that is required to pour the concrete. Since the pour time is short compared to the time required to erect and remove forms, the reduction in schedule is limited.

Self-compacting concrete may be especially beneficial when used in combination with steel-plate reinforced concrete structures, which requires a flowable concrete due to the complicated geometries.

3. Code and Regulatory Issues

The present regulatory and building codes permit the use of admixtures in concrete for structures, including structures that are safety-related. The ACI codes include specific rules concerning the use of admixtures and accelerators. As part of the design acceptance, calculations and test data are required to ensure that the concrete satisfies the applicable code requirements.

4. Summary

SCC, HPC, and RPC offer some potential to reduce construction time and costs. Applications have previously been limited to large-scale civil construction projects, mostly internationally, but there has been significant use of HPC here in the U.S. by the Department of Transportation in several states. Concrete admixtures are becoming commonly used and do not require additional testing or analysis. Admixtures are also permitted by the governing codes for concrete construction. No further research support is required for this mature technology, but DOE should inform the industry of this technology through publication of this report and possibly through participation in a conference on advanced construction technologies.

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C
Fiber-Reinforced Polymer Rebar Structures

Traditional reinforced concrete construction uses steel reinforcing bars (rebar) to provide tensile load carrying capability in concrete structures. Steel rebar is generally a cost-efficient method for the reinforcement for concrete. However, steel rebar is susceptible to oxidation when it is not protected by the high alkalinity in the concrete. Further, corroded steel is larger in volume than the original metal. Since concrete cannot sustain the tensile load developed from this volume increase, spalling of the concrete cover over the rebar may occur and lead to further deterioration of the reinforcing steel. The combination of ongoing deterioration and loss of reinforcement properties ultimately requires costly repair and maintenance, and can endanger the structure itself. Additionally, traditional reinforced concrete structures require extensive field assembly during the initial construction phase to place the steel rebar, which contributes to the long construction period.

Although epoxy-coated rebar has an enhanced corrosion resistance compared to standard steel rebar, it is expensive. Recently, composite materials made of fibers embedded in a polymeric resin, known as fiber-reinforced polymers (FRP), have become a corrosion resistant alternative to steel for reinforced concrete structures. Carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) are two commercially available alternatives (Reference 4). FRP reinforcement offers tensile strength nearly 3 times that of steel rebar and built-in corrosion resistance (Reference 4). The FRP reinforcement is an economically feasible alternative to steel rebar when the higher strength/weight ratio can be taken advantage of in the design, or when the maintenance of concrete exposed to severe environments, e.g., salt and ice on bridge decks, is considered. General design recommendations for flexural concrete elements reinforced with FRP reinforcing bars are given in ACI 440.1R-01, "Guide for the Design and Construction of Concrete Reinforced with FRP Bars."

1. IMPLEMENTATION EXPERIENCE

FRP composites have been used in the U.S. for the construction of bridges and external strengthening (Reference 1). In 1996, the nation's first all composite FRP vehicular bridge, No-Name Creek Bridge (Kansas), was constructed. Two similar vehicular bridges are currently being built in Kansas. These structures are constructed using pre-constructed, fiberglass-reinforced concrete panels that only require sealing at the joints to complete the bridge construction (see Figure C-1). This experience offers evidence that the speed of installation and the weight advantages of composite bridges are significant compared to steel rebar reinforced construction.

Figure C-1. Pre-Fabricated Fiber-Reinforced Polymer Concrete Panel

2. Benefits

The advantages of FRP are (References 1 and 2):

- High strength/weight ratio
- Long service life due to non-corrosive FRP material (not susceptible to rusting or cracking)

These advantages do not significantly benefit nuclear plant construction. Strength-weight ratio is not an important figure of merit for nuclear plant construction. Service life of steel-reinforced concrete used in existing plants is considered adequate. In addition, the cost of FRP compared to steel is considerable. Specifically, the cost of FRP reinforced concrete is approximately 5 to 8 times the cost per pound of steel-reinforced concrete (References 1, 3, and 4).

3. Code and Regulatory Issues

The present regulatory and building code environment is based on steel rebar reinforced concrete construction (References 5 and 6). Acceptance of FRP rebar reinforced concrete construction techniques in future nuclear plant construction would require resolution of code and regulatory issues, particularly in the following areas:

- Fire-resistance – FRP has a reported susceptibility to deformation or loss of strength when exposed to fire

- Seismic adequacy – Seismic performance of FRP reinforced concrete construction needs to be demonstrated to gain regulatory approval

- Glass fiber reinforced polymer (GFRP) is less ductile than steel rebar and may not be able to with stand extreme loading conditions, such as those found during severe earthquakes and Design Basis Accidents

- FRP reinforced concrete has not been used in past nuclear plant construction and the effects of radiological degradation are not known

- As with other types of concrete composition technologies, analysis or testing will be required to prove that the concrete used during construction meets all required applicable requirements

4. SUMMARY

FRP is not recommended for use in nuclear plant construction. The advantages of FRP, (i.e., high strength/weight ratio and corrosion resistance), are not well-suited to this application. Material costs are also significantly higher than for existing techniques. FRP is more suitable for civil structures which can better utilize its advantages. No actions are recommended for DOE regarding this construction technique. Any proposal to use FRP in nuclear plant construction should be viewed skeptically.

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D High Deposition Rate Welding

The welding processes used in nuclear power plant construction include:

- Structural welds used to connect structural members
- Pressure welds used to join pressurized components
- Weld cladding (i.e., deposition of weld metal on the surface of another metal to improve the characteristics of the component)

Quality welding, crucial to the construction of nuclear power plants, is time consuming. To shorten the plant construction period, depositing weld metal at the highest rate achievable without jeopardizing quality is desired. The weld deposition rate typically achievable today is higher than the rate achievable during construction of the existing domestic nuclear power plants. Therefore, high deposition rate welding can offer a significant contribution to shortening the construction period for nuclear power plants.

This appendix assesses the status of four common standard welding methods used in large-scale construction projects: gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), submerged arc welding (SAW), and weld cladding.

Gas Metal Arc Welding

GMAW welding, which includes metal inert gas (MIG) and metal active gas (MAG) welding, involves an arc created between a consumable electrode and the base metal. Shielding of the arc from the atmosphere is provided by a gas emitted from a nozzle surrounding the electrode. The standard GMAW welding process is illustrated in Figure D-1.

Several advanced GMAW techniques have been developed since existing nuclear power plants were built in the United States. These techniques include the Rapid Arc and Ultramag processes.

A disadvantage of the gas metal arc welding process is that strict process controls, including extensive work piece preparation and cleaning, are necessary to ensure quality at higher deposition rates.

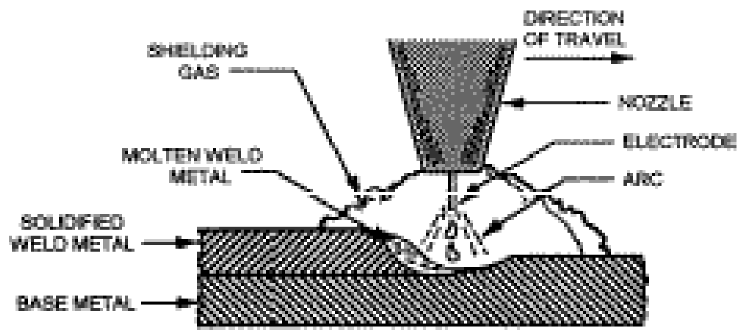

Figure D-1. Gas Metal Arc Welding (GMAW)

Gas Tungsten Arc Welding

Gas tungsten arc welding (GTAW), also referred to as tungsten inert gas (TIG) welding, is illustrated in Figure D-2. This process involves an arc created between a non-consumable tungsten electrode and the base metal. Shielding of the arc from the atmosphere is provided by an inert gas emitted from a nozzle surrounding the electrode. A filler metal may or may not be added to the weld pool. GTAW is a relatively slow, high-quality process.

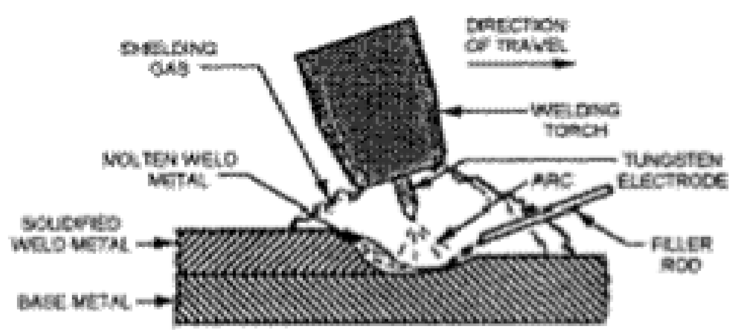

Figure D-2. Gas Tungsten Arc Welding (GTAW)

An automated version of GTAW, known as orbital welding, is now an accepted practice in nuclear applications. Figure D-3 shows a commercially available orbital weld head. Orbital welding offers significant improvements over manual methods for butt welds on piping. Some problems associated with manual GTAW are difficulty in controlling process variables to achieve desired quality and difficulty in accessing weld locations. Both of these problems tend to slow the construction process and increase cost.

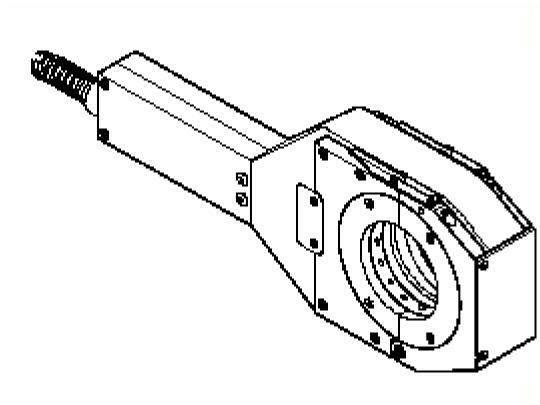

Figure D-3. Swagelok Orbital Weld Head

Submerged Arc Welding

SAW, or submerged arc welding, involves a consumable electrode that provides filler metal and shielding. The standard SAW process is illustrated in Figure D-4. The arc between the consumable electrode and the base metal is shielded by the gas generated by the melting and re-deposition of the flux coating the electrode. The flux floats to the outside of the deposited weld metal covering it and providing additional protection.

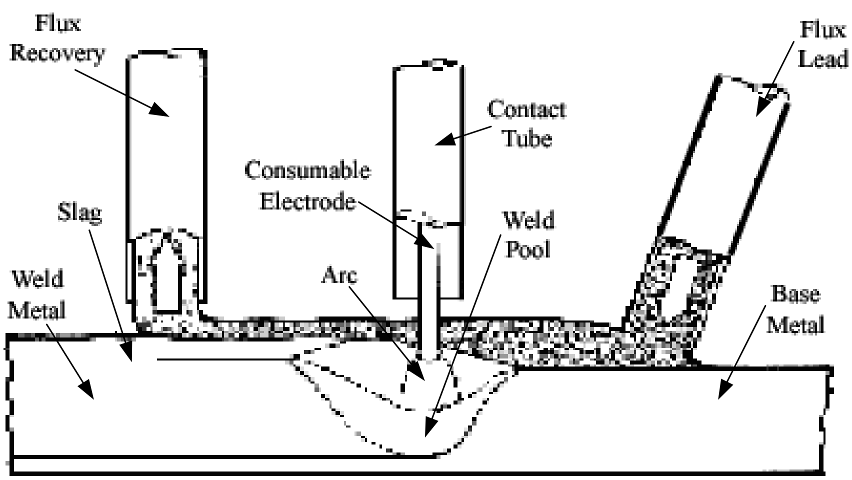

Figure D-4. Submerged Arc Welding (SAW)

An improvement to the SAW process is the technique of multiple wire welding. This process involves more than one consumable electrode producing an arc and contributing to the same weld pool. Multiple wire welding provides an increase in deposition rate due to the higher rate at which heat and weld metal are added in the process.

SAW with flux-cored wire is a high deposition welding technique whose potential has not been fully realized (Reference 1). Flux-cored wire is used as the consumable electrode in the process. The flux is contained at the core of the wire. The use of flux-cored welding significantly mitigates the major shortcomings of subarc welding, which are:

- The mechanical properties that can be obtained at high deposition rates

- Sensitivity to base metal surface impurities (e.g., rust, moisture, etc.)

A disadvantage of the SAW process is the additional cost due to the large amount of flux cleanup required.

Weld Cladding

Weld cladding involves deposition of weld metal over the surface of another metal. Different methods have been used for this purpose in nuclear power plant construction. The earliest method was the attachment of sheet metal over the base metal. In the late 1980s, the technology for internal cladding for in situ vessel applications was still based on equipment designed in the 1950s (Reference 3).

Strip clad welding is a process that provides high quality weld cladding with weld deposition rates at least three times faster than those achieved by current technology (Reference 4). This process, developed for internal cladding of piping and pressure vessels, involves the use of relatively wide strips of filler material. The cladding can be applied in situ in either a horizontal or vertical orientation. Either a submerged arc or electroslag welding process is employed to join the strip cladding to the base metal.

A prototype process for vertical strip cladding was developed in the late 1980s, as shown in Figure D-5. In the process illustrated in Figure D-5, the weld pool, flux, and slag are supported by a ceramic "hot top." A water-cooled copper shoe supports and cools the weld metal as it solidifies into a solid strip. The electrode (filler material) is fed as a strip (also referred to as a ribbon) instead of as wire form.

1. IMPLEMENTATION EXPERIENCE

Gas tungsten arc welding has been used in Japan to narrow-gap-weld a cylindrical pressure vessel, or shroud, to existing shroud supports with minimal heat input (Reference 5). The process was also used to manufacture the shrouds in the shop.

Orbital welding is commonly used for high quality butt welds on piping. It can be used on a broad range of pipe sizes. The equipment is commercially available and has been used in many industries. In the aerospace industry, a single aircraft can contain more that 1,500 welded joints, all automatically created with orbital equipment. The pharmaceutical industry uses orbital welding in their process lines and piping systems to make quality welds that will ensure water through the tubes is not contaminated by bacteria, rust, or other contaminants. The nuclear industry also currently uses orbital welding for producing piping welds.

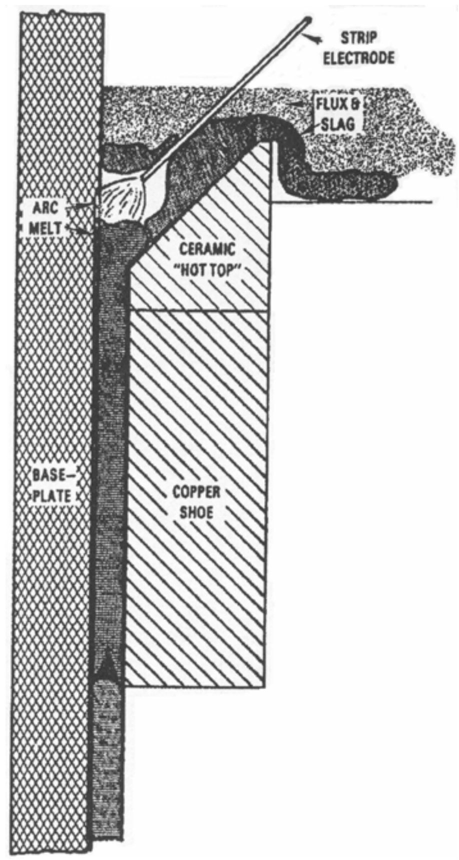

Figure D-5. Vertical Strip Cladding (adapted from Reference 3**)**

SAW is commonly used in steel fabrication for structural shapes, and longitudinal and circumferential seams for pipes, tanks, and pressure vessels of large diameters. Typically, steel plates with thicknesses of 1-in or greater are welded using this process. SAW processes readily weld low-carbon, low-alloy, and stainless steels, but not high-carbon, tool steels, or most nonferrous metals.

Using SAW is traditionally limited to the horizontal position because of the gravity feed of the granular flux. Therefore, when the need for a weld in the vertical position is required, positional welds are usually carried out manually or semi-automatically. Because this method is so time consuming, recent technology has led to submerged arc welding in the vertical position with horizontal electrode feeding. This method is used in shipbuilding, where the joining of large ship sections requires long and mostly straight weld seams in the vertical position under yard conditions. Good mechanical-technological properties of the welded joints are attainable with deposition melting rates of over 4.5 lb/hr.

SAW using gantry units is also used in the construction of various civil structures. Gantry welding units are structural-type frames allowing bidirectional, automatic, or semiautomatic travel. Typically, the welding control units, torches, and power sources are mounted permanently on the unit. A qualified welder can perform vertical-up welding. Gantry welding units can make 5/16-in. horizontal fillet welds at 36 to 40 inches per minute (IPM) in flange-to-web girder welding (approximately 6 ft. of deposited fillet weld per minute). Using this system, fabricators can produce more than 300 ft. of welded girder a day.

SAW with flux-cored wire is being used in field construction of nuclear power plants in Japan. Strip clad welding has been used in the construction of nuclear components overseas.

2. BENEFITS

Advanced GMAW techniques, which include the Rapid Arc and Ultramag processes, have achieved deposition rates of 33-37 lbs/hr in certain applications. Deposition rates as high as 66 lb/hr can be achieved under special circumstances (Reference 1). Typical weld deposition rates are in a range of 4-20 lbs/hr (Reference 2).

The orbital GTAW welding process is an automated welding process. This makes controlling process variables easier and facilitates achieving a consistent and high level of quality. The relatively small size of the orbital welder allows it to be used in locations were personnel access is difficult or impossible. Productivity rates are improved over manual methods because setup is easier and less rework is required. The deposit rate of the orbital process is approximately 1.6 lb/hr. In addition, the relative ease of the welding technique eliminates the need for the skilled welders required with standard methods. Orbital welding is an attractive option for use in construction of a new nuclear power plant in the United States.

For several decades, SAW has been the preferred high deposition rate welding process in many industrial applications (Reference 1). In 1996, deposition rates as high as 33 lbs/hr were reported for standard single wire (i.e., single consumable electrode) subarc welding. For a multiple wire process, deposition rates as high as 100 lbs/hr were reported (Reference 1). SAW used in vertical applications has achieved a disposition rate of approximately 4.5 lb/hr. For comparison, weld processes used in domestic nuclear plant construction were classified as high deposition rate methods when the weld metal was deposited at a rate exceeding 11 lbs/hr (Reference 2). Structural members can be assembled for civil applications using gantry units at rates of 6 ft/min versus a typical rate of 20 in/min.

Flux-cored wire, although having higher material costs, provides significant cost savings due to the associated productivity improvements.

Based on a demonstration performed in 1999, the deposition rates for Strip Clad Welding exceed those of GTAW and SAW. This demonstration also showed superior control of process parameters. A similar demonstration performed in 2000 deposited a total of 486 lbs of weld metal at rates of 26-28 lbs/hr. This weld deposition rate is approximately thirteen times that achieved with GTAW and three times that achieved with SAW.

Subsequent tests indicated superior mechanical and metallurgical properties for cladding applied by Strip Clad Welding. Exceptional tensile and toughness properties were demonstrated for the weld itself, and cross-weld properties (including base metal, heat-affected zone, and weld) were determined to be good. Additionally, the stress profile was noted to be encouraging. Improvements on these characteristics are anticipated in real-world applications.

3. Code and Regulatory Issues

Federal regulations require welding procedures and personnel to be qualified in accordance with applicable codes. Pressure welds are typically required to meet the ASME code and structural welds are typically required to meet the American Welding Society (AWS) code. These standards further require that a welding process be qualified for nuclear grade applications. A novel welding process must be capable of producing welds that have sufficient mechanical properties, and must be capable of demonstrating those properties in testing. In addition, the personnel operating the equipment must also demonstrate that they are trained and competent in the use of the novel technique.

Qualification activities are carried out by the vendor in the field prior to their use. Since each of the technology advances has been demonstrated, their qualification for domestic use is not expected to be a challenge. In addition, several commercially available orbital welding systems have previously been qualified domestically for use in repair of nuclear grade components.

4. Summary

Five technology advances were identified that offer significant potential toward reducing construction period: high deposition rate gas metal arc welding, orbital welding, flux cored submerged arc welding, vertical submerged arc welding, and strip clad welding. Orbital welding and high deposition rate gas metal arc welding are mature and commercially available technologies. Flux cored submerged arc welding, vertical submerged arc welding, and strip clad welding have been demonstrated. Vertical submerged arc welding could potentially be useful in assembling steel-plate reinforced concrete structures in the construction of a new nuclear plant.

No research and development is required. However, DOE should inform the industry of the technology advances in high deposition rate welding through publication of this report and possibly through participation in a conference on advanced construction technologies.

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E
Robotic Welding

A modern robotic welding system is illustrated in Figure E-1. This technology is the most flexible version of automated welding. It involves automated control of the weld head position and the option of automatically controlling certain welding parameters. A typical system consists of a weld head, robot, user interface, and power supply. Robotic welding can be used with most types of welding processes including gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), flux cored arc welding (FCAW), and submerged arc welding (SAW).

Automated welding processes can be divided into two categories: fixed and flexible. Fixed automated welding involves expensive equipment for holding and positioning weldments. It is used for simple weld paths and high volume production. Flexible automated welding involves relatively inexpensive and simple equipment for holding and positioning weldments and can be more easily adapted to complex weld paths. It is suitable for low, medium, or high volume production. Robotic welding is flexible enough to be used as a direct replacement of some difficult manual welding operations.

Figure E-1. Modern Robotic Welding System

Set up activities are required to use a robot in a new welding procedure. The setup includes tooling arrangement and software programming.

1. IMPLEMENTATION EXPERIENCE

In traditional large-scale construction projects, such as nuclear power plant construction, the majority of the welding operations are performed in the field. Field welds are commonly difficult to access with a robotic welding system. In addition, many field weld procedures are repeated only a few times (i.e., small series production). Only processes that require minimal setup time can take advantage of robotic welding systems. This is demonstrated in the construction of fossil power plants where field welds are performed either manually or using automated processes not involving robots (Reference 1).

Modern, multi-unit, modular construction projects benefit from robotic welding systems. These benefits include the following:

- Increased productivity for large series production
- Improved productivity for small series production over early robotic welding systems
- Suitable for shop applications that are typical of modular construction techniques
- Suitable for complex or simple weld paths
- High level of control over welding process parameters
- Compatible with automated quality control processes

Robotic welding systems are commercially available for use in many industrial applications. Robotic welding has been applied extensively in assembly-line applications, such as automobile fabrication. Robotic welding has been applied in shop construction of nuclear power plant components in Japan.

2. BENEFITS

Robotic welding is most suited for shop work where there is a controlled environment and processes are repeated many times (i.e., large series production). As robotic welding systems become increasingly more flexible, they are also useful in small series production applications. Modern construction techniques, which are more modularized and involve increasing amounts of shop fabrication, are well suited for robotic welding. However, this does not reduce the on-site construction duration since shop work is not critical path.

Quality control of welds on nuclear components is time-consuming. One technique that offers cost savings is automated quality control. Robotic welding is compatible with automated quality control techniques and could facilitate their introduction. This benefit is primarily in cost reduction and not schedule reduction and is therefore not discussed in detail in this report.

Employing robotic welding for repetitive welding procedures is estimated to increase productivity by a factor of three over manual welding (References 2 and 3). In applications where a welding robot replaces manual welding, a return on investment is typically achieved in about one year (Reference 3).

3. Code and Regulatory Issues

Federal regulations require welding procedures and personnel be qualified in accordance with applicable codes. Pressure vessel welds are typically required to meet the ASME code, and structural welds are typically required to meet the American Welding Society (AWS) code. These codes generally require that a welding process be qualified for nuclear grade applications.

Appropriate tests will be required to show that robotic welding is capable of producing quality welds. Weld strength may be different for automated welding than for manual welding (Reference 4). Corrosion resistance may also be affected. In addition, procedures must be developed for demonstrating that the personnel operating the equipment are trained and competent in the use of the robotic welding system. Software used with robotic welding does not require NRC acceptance beyond acceptance of the weld produced.

Robotic welding is relatively mature and demonstration of acceptable welds is expected. Robotic welding has been applied in shop construction of nuclear power plant components in Japan. Therefore, pending qualification, the process is likely suitable for nuclear construction in the U.S.

4. Summary

Robotic welding offers cost savings through increased productivity and reduced rework for certain shop applications. As more construction activities are moved out of the field and into the shop, robotic welding becomes increasingly beneficial for large-scale construction applications. However, the main benefit of robotic welding is cost reduction and not construction schedule improvement. Robotic welding has been applied in shop construction of nuclear power plant components in Japan.

No research and development is required. However, DOE should inform the industry of the technology advances in robotic welding through publication of this report and possibly through participation in a conference on advanced construction technologies

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F

3D Modeling

Solid, three-dimensional (3D) modeling software is used in contemporary facility design to provide three-dimensional layouts of the proposed facility. 3D modeling software allows for greater visualization of a project. It is the standard approach for plant engineering. This type of modeling has replaced much of the physical 3D modeling used to support the construction of domestic nuclear generating facilities. Benefits of 3D design occur in all stages of the completion of a plant: conceptual design phase, engineering and detail design phase, construction phase, and operations and maintenance phase. Figures F-1 and F-2 show examples of 3D models. Significant detail, including stairways and platforms has been included in the solid model shown in Figure F-1.

The process of using 3D design software to design a power plant starts with generating a solid model of the plant components. A solid model is a 3D computer-generated model of the components in a system. After the solid model is completed, the 3D design software is used to automatically generate the various plan, elevation and detail views needed to fabricate the plant. There is typically a relationship between the drawings and the model such that any changes made to the model are automatically updated in the drawings and vice versa. In addition to providing a 3-dimensional entity that designers can use to assess spatial relationships between components and structures, the solid model provides all of the dimensional data for the plant in a single database. This approach greatly increases efficiency and reduces the potential for errors.

Future applications of 3D modeling include the possibility of full-scale virtual reality modeling. Japanese vendors are currently experimenting with using a virtual reality environment to move around a virtual plant, trace out coordinates, add or remove components, and track actions. This technology will likely not be ready for use until after 2010.

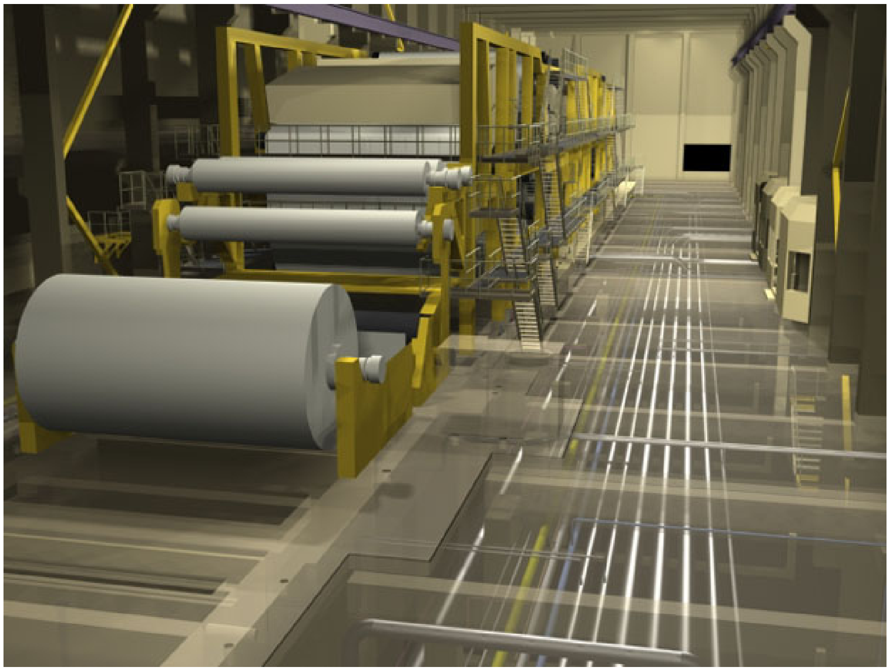

Figure F-1. 3D Model of Paper Coating Line

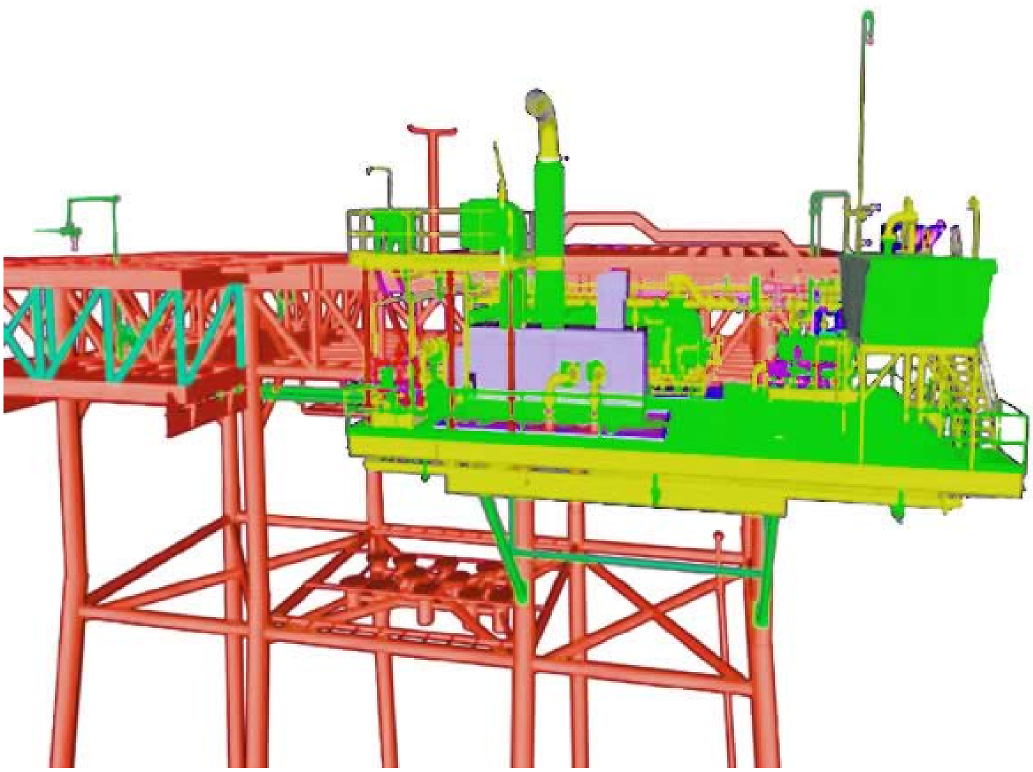

Figure F-2. 3D Model of Offshore Platform

1. IMPLEMENTATION EXPERIENCE

The benefits of the 3D design process are not limited to the design and construction of the plant. Many nuclear plants not designed using 3D processes have generated 3D plant models to increase efficiency of maintenance and outage activities. NSSS vendors and A/E firms have roughly equal capabilities with 3D modeling and can be expected to use this technique based on the reduction in the construction cost. The Oyster Creek Nuclear Plant in New Jersey uses a 3D model of the refueling floor to coordinate, evaluate, plan, visualize, and sequence refuel floor outage activities. The model is also used to generate detailed drawings of the refuel floor during each of the various processes. Use of this model optimizes these processes and reduces outage time. TVA's Browns Ferry in Alabama, another 1970 vintage plant, is evaluating the development of a 3D model which will be tied to the equipment databases. Users could navigate through the 3D model, and, by selecting various components with a click of the mouse, can access the pertinent component design information.

2. BENEFITS

3D design technology offers many benefits during the construction of the plant. A large cost savings resulting from using 3D design software is the reduction in rework labor and materials. Field rework labor can cost as much as 12% of total construction labor when using manual methods of design (Reference 1). Due to better visualization of the project and completion of interference checks prior to construction, this number can be reduced to 2% (Reference 1). 3D plant design systems also provide a means to determine job sequencing and craft work, leading to compressed construction schedules. Using the 3D models to convey the plant layout and design visually improves construction sequencing. Off-site fabricators can also get a clearer understanding of their work from the 3D models, minimizing the possible errors made in reading traditional isometric and orthographic views.

3D design programs include databases of the plant design that can produce bills of material and material take-offs automatically. This provides more accurate procurement of parts and materials needed for the construction of the plant. This reduces the amount of material surpluses, and thus reduces the project expenditures.

During the conceptual design phase of a project, 3D design processes can be used to facilitate the economic analysis of alternative plans before project costs are committed. As much as 80% of project costs are committed during a conceptual design phase (Reference 1). By using 3D design processes, designers can complete designs sooner. They can also change the design more efficiently when evaluating design alternatives. The design plans created using 3D design software are easier to interpret and more accurately communicated. This contributes to improved quality and timeliness of a project. Design changes can be made quickly, and all components are updated automatically. All of the physical plant drawings can be easily produced from the original model. Another benefit gained when using 3D design is the ability to communicate design information to non-technical personnel.

There are many advantages of using 3D design software in the engineering and detail design phase. These benefits include improved quality, consistency and standardization of the design, constructability analysis, automated interference checking, improved overall efficiency, and enhanced project control and coordination.

While developing 3D models can be more expensive on an hourly basis than producing similar 2D drawings, the time saved in other areas of design can provide 5% to 10% in overall engineering cost savings (Reference 1). 3D design usually reduces errors and generates higher quality designs than 2D methods. The 3D software incorporates specifications and code requirements in a database which helps to avoid expensive mistakes by recognizing errors and designs not meeting specifications. 3D models can be combined with analysis tools to test the design for mechanical stress, hydraulic analysis, thermal stress, and other factors.

The larger and more complex a system is, the greater the potential savings from using 3D design software. The 3D models help check and fix interference between different design areas, such as piping, electricity, and HVAC. The ability to use 3D design software to evaluate spatial details makes future maintenance easier.

3D design also helps streamline the hazard and operability review (HAZOP) process. Due to the enhanced visualization offered by a 3D model, the time it takes to review a plant can be reduced by one-third. The 3D models improve the quality of the review and the operability assessment.

Recently, 3D models have also been used in the operations and maintenance phase. Maintenance crews can use 3D models to familiarize themselves with work areas. This allows them to plan in advance the placement of electrical or welding outlets, eye wash stations, safe routes, and other activities, thus making the entire process more efficient.

3. CODE AND REGULATORY ISSUES

Requirements for the preparation of a 3D model and drawings are governed by ASME Y14.41-2003. These standards also provide guidelines to improve modeling and annotation practices when using computer aided design software.

4. SUMMARY

The use of 3D design software in the design, engineering, and construction of a plant can potentially reduce costs and construction schedule, and increase quality and efficiency. The 3D models can help communicate the design to both technical and non-technical personnel. The increased visualization of the project design can help reduce field rework and minimize material and labor costs. Creative use of the model after construction to support operation and maintenance activities can also offer significant benefits. Scheduling and cost analyses are facilitated with 3D plant design systems. DOE should inform the industry of these technology advances in the use of 3D design and engineering through publication of this report and possibly through participation in a conference on advanced construction technologies.

5. REFERENCES

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G

Positioning Applications in Construction (GPS and Laser Scanning)

Global Positioning System (GPS) is a worldwide radio-navigation system formed from a constellation of thirty-two satellites orbiting the earth (Reference 1). This system is shown pictorially in Figure G-1. Based on the measurement of the time it takes for radio signals to travel from the satellites to a ground receiver, the receiver calculates its own location in terms of longitude, latitude, and altitude. GPS was created by the U.S. Department of Defense (DoD) in 1973 and declared fully operational in 1994. While it was originally developed for military purpose, it is now available to civilian users free of charge.

GPS has several applications related to the construction and operation of power plants. The applications identified include:

- Site surveys
- Control of earth moving equipment
- Tracking of equipment and material
- Measurement of structural deformation and alignment
- Indoor as-built measurements with laser GPS

A receiver requires signals from four or more satellites at the same time to calculate position, velocity, and time. The receivers automatically choose the satellites that will produce the best estimate of location among the satellites that are in view. Since a line-of-sight to the sky is required, GPS is inappropriate indoors, in areas of dense vegetation, next to tall buildings, and under bridge structures.

The accuracy of measurements is affected by natural phenomenon, electrical failure of elements, and intentional disturbances. The Department of Defense can deliberately downgrade the accuracy of the GPS satellites signals through a process called Selective Availability (SA). They reduce the accuracy available to unauthorized users in times of war or for military action. Authorized users may obtain encrypted information to make corrections so that accuracies are not affected during these times. Other sources of error include clock errors, satellite orbital errors, travel delays through the ionosphere and refraction through the troposphere, and signal reflection off of buildings and lakes. Data processing techniques have been developed to minimize the effects of these errors.

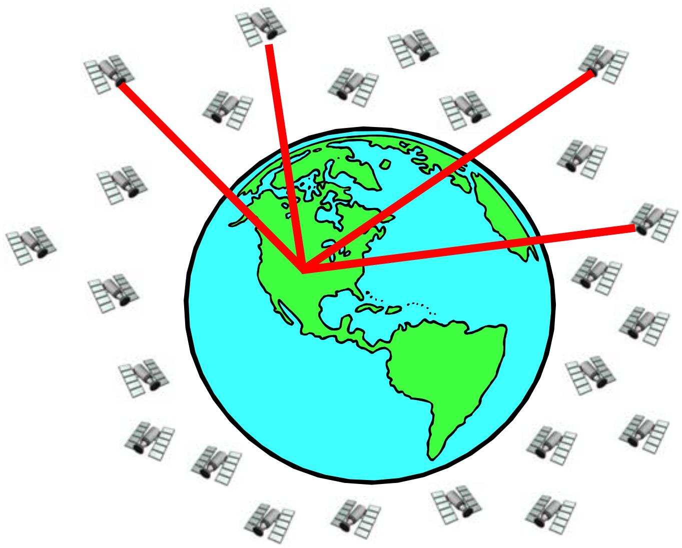

Figure G-1. Global Postioning System Pictoral Representation (Thirty-Two Satellites Orbiting Around the Earth)

1. Implementation Experience

Research into using GPS in construction has been performed by the following organizations:

- United States Army Corps of Engineers
- Construction Industry Institute with Purdue University
- National Institute of Standards and Technology
- Transportation Research Board of the National Research Council
- Most State Departments of Transportation

Most state departments of transportation have purchased GPS equipment within the past several years and are using the systems to perform surveys, assess inventory, and produce maps. Industrialized countries outside of the United States are using GPS similarly.

GPS technology from Trimble Navigation Ltd. and Leica Geosystems Inc. has been used to survey and move earth for roads, airport runways, shopping malls, residential housing, and business parks. Associated software calculates labor, material, and schedule requirements.

Indoor GPS technology, using lasers rather than satellites, has been used in the general construction industry to position walls, ceilings, and floors quickly and accurately. Also, laser technology has been used to align pipe for underground utilities. The most advanced application of indoor GPS has been its implementation in the construction and inspection of aircraft.

GPS equipment used on a construction site includes:

- GPS receivers – On a new construction site, one receiver is set up on a permanent base mounting with an antenna and serves as the reference station. Other receivers are allowed to move around the site and are "roving" receivers. The signals of the roving receiver are corrected by errors calculated at the stationary reference receiver whose position is accurately surveyed and well known

  Stationary reference receivers have been established across the country by government agencies and are available for public use, sometimes making the installation of a site reference station unnecessary.

- Computer – The computer takes the GPS data and translates it into a site plan

- Radios – Information is relayed between receivers and other equipment on the site by a high speed radio network

A single mobile GPS receiver, a roving receiver without a stationary base receiver, is accurate to about 10 yards. If differential GPS is used (DGPS), the receiver is supplied with corrections derived from a GPS base station within 200 miles and the accuracy improves to better than 3 ft. If real-time kinematic GPS is used (RTK GPS), the GPS receiver has more processing power and it is supplied with real-time data from a base station within 13 miles such that the accuracy becomes better than 0.1 ft.

Conversion to GPS requires a substantial initial capital investment that can outweigh the investment in equipment for one-time use applications. Theodolites and alidades tend to be less expensive and more durable than their electronic counterparts. The decision to use GPS is a function of time, cost, required degree of accuracy, availability of equipment, and the design or construction phase involved. An RTK GPS system can cost around $60,000 for a single base unit and one rover (Reference 1). Additional rover units cost around $25,000 each. Less accurate units can be purchased for under $10,000.

Most vendors offer training courses on how to use their equipment. Mastering the GPS unit takes approximately 6 months to a year for a trained surveyor. The greatest amount of training involves learning and understanding the potential sources of error.

2. BENEFITS

Application of GPS technology to field construction has many potential benefits including those discussed below.

Surveying

A primary benefit of GPS surveys versus traditional surveys is reduced costs associated with decreased labor and time requirements. However, to ensure time is saved, a controlled method of planning, organizing, and conducting GPS surveys is required to efficiently and effectively use the large volume of data that is collected.

Another benefit often gained is increased measurement accuracy. Human error is reduced since readings are recorded electronically with minimal human interaction other than selecting the location and typing in the description of the point. A GPS system can record points at least four times faster than conventional methods. Redundancy in some of the measurements provides a means to check the results.

For survey work, a geodetic-quality GPS receiver with centimeter-level accuracy is required (RTK GPS). Industry standards are two centimeter of accuracy for real-time horizontal GPS surveys, exceeding accuracy of conventional methods by a factor of 5 or greater. Vertical accuracy is approximately four centimeters, about the same as traditional methods. GPS may not be accurate enough for the final grade check of surfaces and may require the use of leveling to supplement the GPS established control.

Field operations to perform a GPS survey are relatively easy and can generally be performed by one person per receiver, with two or more receivers required to transfer control. Conventional survey work is generally accomplished using a two or three-person survey crew. According to a National Cooperative Highway Research Program report, common labor reduction ratios for GPS as compared to traditional survey methods are nearly 6:1 for horizontal surveys and 10:1 for elevation surveys (Reference 1).

Another time-saving advantage of GPS is its long-range capability. Once a GPS system is established, measurements can be taken within a 6-mile radius of the base reference station whereas conventional methods would require the surveying equipment be moved about every 600 ft.

As a job progresses, additional surveys are needed to gather more information, to make design changes, and to document completed work. This conventional process is time-consuming and contains numerous opportunities for error. With GPS, the data can be collected in real-time and used to modify plans or a digital terrain model on computers that are in the field.

Earthmoving

Earthmoving equipment, such as bulldozers, motorgraders, scrapers, excavators, can be fitted with GPS receivers and computers that direct operators on the removal or placement of fill dirt to meet the planned site design. Use of GPS eliminates the need for survey stakes to guide the workers. Site design information, in the form of plans or a digital terrain model developed based on a GPS survey data, is downloaded to the on-board computer on the earthmoving equipment. The computer calculates where the machine is and how much cutting or filling is needed by referring to the site grid and the base reference station. The computer makes the decision based on GPS data of the blade location. The information is transmitted to the operator via a monitor or light bars. Instead of being controlled by an operator, the system can be configured so the equipment is automatically controlled via a controller supplied with real time GPS data. Figure G-2 illustrates the use of GPS in earthmoving.

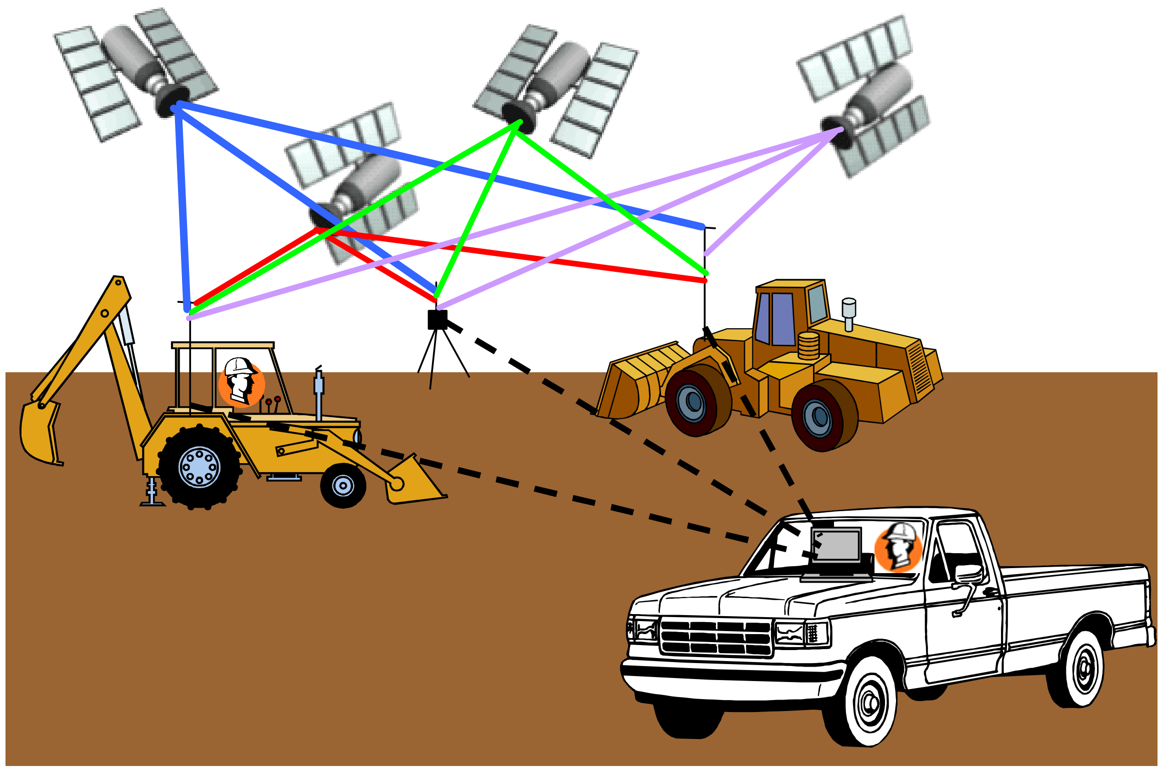

Figure G-2. GPS Information Tracking During Site Land Development

Another advantage of GPS is real-time site monitoring. Progress can be updated by the wireless computer network in real time, allowing the site supervisor to check progress on a computer in the cab of his/her pick-up truck.

In summary, the benefits in applying GPS in site-preparation are as follows:

- Fast and accurate decision and control due to real-time information of position and grade
- Reduction of surveying and grade checking costs and increase of machine utilization
- Faster job cycle - Operators know where the grade is, as well as the locations of design elements, and are able to move more dirt each day. They can work regardless of wind, dust or darkness, finishing jobs faster with less fatigue
- Reduction of rework caused by the lack of correct information in the field

Material and Equipment Tracking

GPS can be used to keep track of construction inventories and equipment location. Since less accuracy is required, less expensive units with meter level accuracy can be used. Man-hours for inventory checks can be reduced and checks on inventory can be performed from a central location or from anywhere on the job-site. It is estimated that a resource grade unit with accuracy on the order of a meter can be purchased for about $10,000 (Reference 1).

Measurement of Structural Deformation and Alignment

GPS techniques can be used to monitor the motion of points on a structure with respect to static structures. This is accomplished with an array of antennas placed on the structure and the static reference structure. Measurements can be made on a continuous basis or on a periodic basis. Measurement precision on the order of 2 to 5 mm is typical (Reference 6). This type of measurement may be used to measure foundation settlement or it may aid in assembly of large structures fabricated off-site.

Indoor Measurement Tools

GPS satellite signals cannot be received inside buildings. Instead, an infrared laser technology that is computationally similar to GPS can be used indoors (Reference 5). This infrared laser technology is often called Indoor-GPS though it employs a localized signal transmission system as a substitute for the global satellite network.

The indoor system requires the set-up of several infrared laser transmitters that send light signals over the area in which position information is desired. During set-up, the relative position and orientation of the transmitters is determined through infrared measurement. When operating, a stationary or roving receiver picks up the infrared signals from at least two transmitters that are in its line of sight. The receiver processes the signal information to calculate its own position based on the known positions of the transmitters. Use of multiple transmitters increases the accuracy of the position calculations. Accuracy on the order of several mils is possible.

Indoor-GPS is used to position large parts for mating, keep track of equipment position and movement, and track part inspection. Inspection and construction tools can be instrumented with GPS technology to do such tasks as keep track of which bolts have been tightened and with what torque.

Benefits of indoor-GPS are greatest when a particular set-up can be reused multiple times. For example, the aerospace industry has found indoor-GPS particularly useful in its manufacturing facilities where it is used for the assembly and inspection of multiple aircraft (Reference 5). Arc Second, Inc. is a major developer of indoor GPS with its Constellationellation$^{3D\text{-}I}$ technology.

In the construction business, infrared technology has primarily been used for surveying purposes and the placement of walls, ceilings, and floors. However, infrared technology has the potential to be a powerful time-saving tool for recording as-built measurements in new nuclear power plants. Furthermore, it can aid the construction process by guiding the placement of equipment and tracking inspections.

3. Code and Regulatory Issues

No issues were identified. In addition, none are expected since the accuracy of GPS surveying methods meets or exceeds that of traditional methods.

4. Summary

GPS technology is currently used to survey, move earth, and grade work-sites. Indoor GPS technology, using lasers rather than satellites, is also available for indoor surveying purposes. These applications are well developed and in current use in the transportation, housing, and office building construction industries. Indications are that they provide significant cost and time savings over traditional techniques. As long as equipment and trained personnel are available, construction of a new nuclear power plant would benefit similarly.

GPS has additional potential benefits to new nuclear plant construction that could be used for plants planned for the generation beyond 2010. These potential benefits include:

- Accurate and time efficient placement of equipment and large structures
- Automation of drawing revisions
- Material and equipment tracking off-site and on-site
- Robotic inspection of critical components
- As-built measurement of piping and equipment

As this technology is being pursued aggressively by industry, DOE-sponsored research and development will probably not be required to enable its use in nuclear plant construction. DOE should inform the industry of technology advances in positioning and measurement applications through publication of this report and possibly through participation in a conference on advanced construction technologies

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H

Open-Top Installation

In previous domestic nuclear power plant construction, the as-built construction schedules from first concrete (FC) to fuel load (FL) were long and few tasks could be completed in parallel. In the open-top installation construction sequence, part of the Reactor Building is built, followed by placing the Reactor, Steam Generators, and other large pieces of equipment in place in the building using large cranes. Once the equipment has been placed inside, the construction of the Reactor Building can be finished while other site workers install piping and electrical systems. Figure H-1 illustrates the open-top installation process.

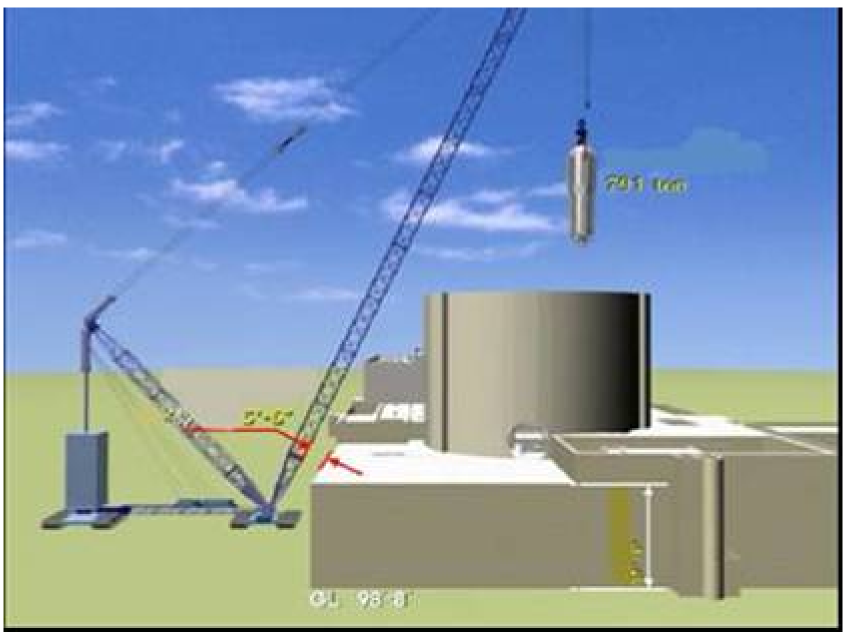

Figure H-1. Open-Top Installation

Since the last generation of plants built in the U.S., the load capacity and reach of cranes has been increased, leading to cranes known as Very Heavy Lift (VHL) Cranes. These cranes are capable of lifting and moving modules weighing up to 900 tons and reaching several hundred feet. The advent of these cranes permits very heavy loads to be placed. This has extended the feasibility of Open-Top construction and allows large-scale use of techniques such as modularization.

1. IMPLEMENTATION EXPERIENCE

This method is used in large-scale construction projects, including nuclear power plants recently completed or under construction in Japan, Taiwan, and China. Using Open-Top Installation and Modularization techniques, these plants have been built in less than 72 months. As a result, construction costs have been reduced 10 to 20%, or approximately $100 million (Reference 2). It is expected that these costs will further decrease as industry experience is gained in using Open-Top Installation in combination with modularization.

2. BENEFITS

There are significant advantages in cost and schedule using Open-Top Installation. It is estimated that Open-Top Installation in combination with modularization techniques can shorten the construction schedule from 10 to 15 years to as few as 4 to 5 years from first concrete to fuel load (Reference 2). Even limiting the use of this technique to the installation of major components can save massive amounts of time.

3. CODE AND REGULATORY ISSUES

There are no identified codes or regulatory issues pertaining to the use of Open-Top Installation. As long as the installation, fabrication, and inspections meet the applicable codes, the construction process does not affect the structure.

4. SUMMARY

There is significant potential for savings in schedule and cost using Open-Top Installation in power plant construction. A review of the regulatory codes and standards has not identified any issues which may affect current rule-making. Open-Top Installation in combination with modularization has been employed in the construction of several plants internationally with great success in cost and schedule reduction.

In order to take full advantage of Open-Top Installation, reactor vendors and construction companies will need to ensure that the design and construction schedule of the plants support Open-Top Installation and modularization. Also, depending on the climate at a site, a constructor should consider installation of a moveable roof to allow work inside the open containment to proceed in all weather conditions.

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I

Pipe Bends vs. Welded Elbows

Domestic nuclear power plants were constructed using welded pipe fittings, such as elbows, in piping systems throughout the plant. Extensive construction materials and labor are required at the construction site to support this type of piping system construction. This method contributes to the long construction period typical of large-scale field constructed projects. Pipe bending is a simple alternative construction technique that can speed up piping system construction and reduce the number of workers required.

Pipe bending technology was available 20 to 30 years ago when the existing domestic nuclear power plants were constructed. At that time, welded-in fittings were a more cost-effective construction method. However, pipe bending can now be performed at a lower cost than welding. Further, the development of portable bending machines allows on-site bending of pipe.

Figure I-1 shows isometric views of a section of piping constructed using pipe bending and welded elbows.

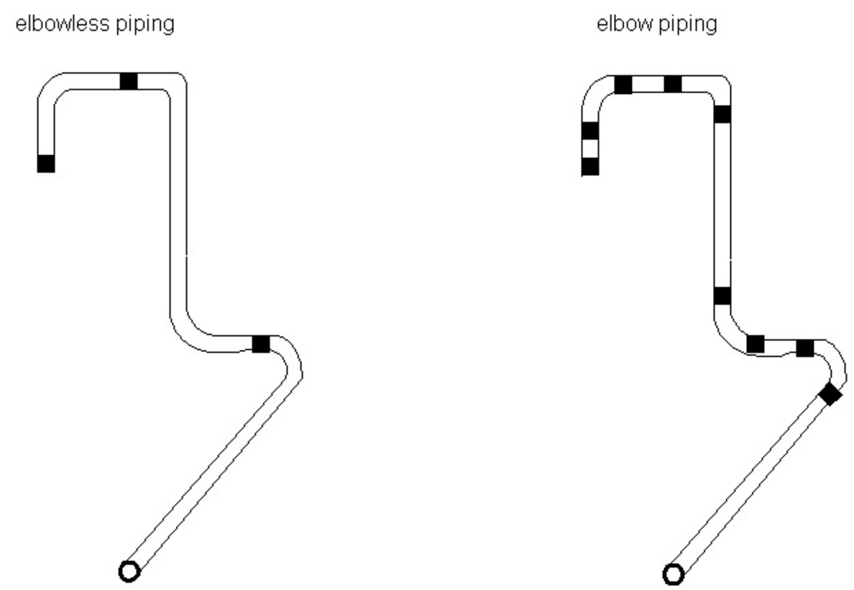

Figure I-1. Comparison of Piping System Construction Pipe Bends vs. Welded Elbows

Several types of pipe bending techniques are currently available. The most common are cold bending, induction bending, and hot slab bending. A brief description of each technique follows.

Cold bending does not apply heat to the pipe segment that is being reshaped. There are several ways to perform a cold pipe bend. The first is to draw bend, or pull, the pipe segment around a circular die to create the desired shape. The second is compression bending, where the pipe is pressed around the die to create the desired shape. The final way is to use a ram to press the pipe into the desired shape (Reference 4). Examples of ram and draw type bending are illustrated in Figure I-2.

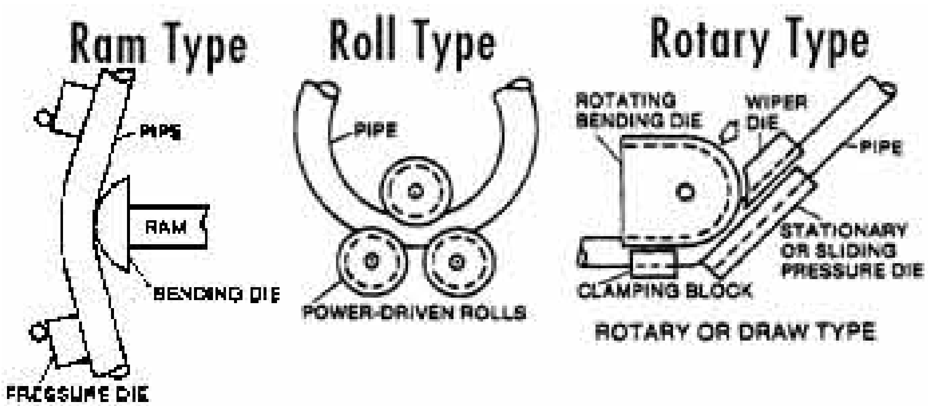

Figure I-2. Types of Cold Bending

Heat induction bending is a technique that uses localized heating in the location of the desired bend. The pipe is pushed through a set of rollers, and then through an induction ring, which is ring shaped to match the contour of the pipe. The induction ring uses electricity to heat the pipe from 800° F to 1200° F. After passing through the induction ring, the pipe is bent and then quenched using water or oil. The radius of the bend is controlled by the radius arm (Reference 4). An example of heat induction bending is shown in Figure I-3.

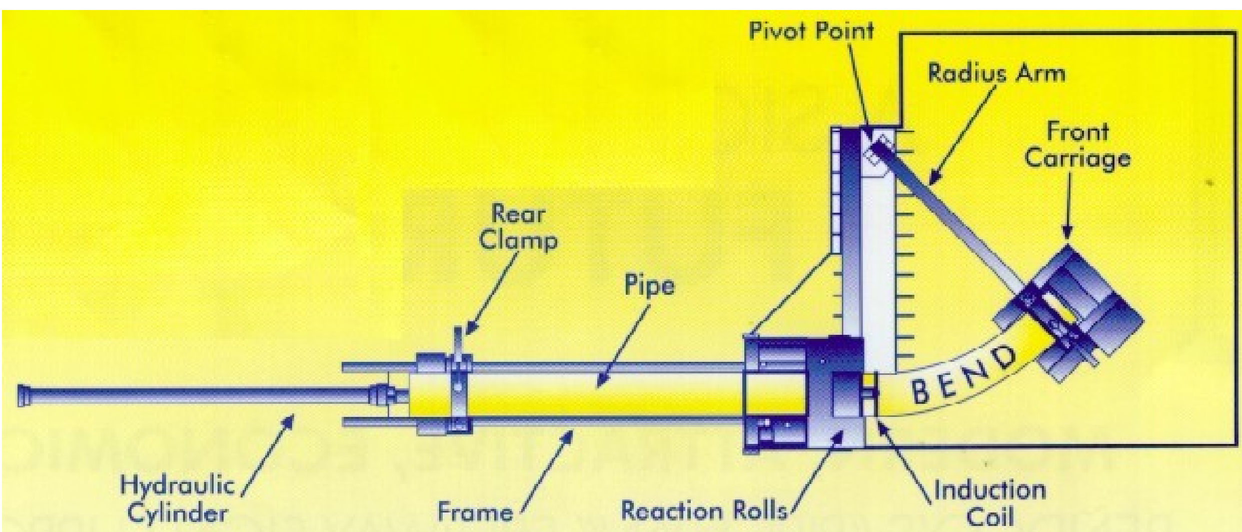

Figure I-3. Schematic of a Heat Induction Bending Machine

The third method of bending pipe is hot slab bending. The pipe is filled with dry sand and placed in a large oven which heats the metal to temperatures near 2000°F. The pipe is taken out of the oven, and secured on a bending table. Cables are attached to the free end of the pipe and pulled by winches to create the desired bend radius and length. This is the oldest pipe bending technique and most common method of bending large bore piping (Reference 4).

1. Implementation Experience

Pipe bending is a proven and commonly used technology. Applications of pipe bending on large construction projects include piping systems at fossil plants, process piping at refineries, replacement pipe in U.S. nuclear power plants, and various piping systems in nuclear power plants in South America and Asia.

Stationary pipe bending machines currently are able to bend pipe sizes in excess of 66 inch outside diameters with wall thicknesses of 5 inches for use in refineries and power plants (Reference 5). Portable bending machines are capable of bending pipe up to 60 inches in diameter (Reference 6). Cold bending is limited to pipes 20 inches in diameter and smaller (Reference 5).

These machines have been commonly used for bending process piping in field fabricated situations.

2. Benefits

There are several advantages to using pipe bends instead of welded elbows in piping systems. The use of pipe bends eliminates a large amount of the field welding required. This will decrease the time required to perform field welding and shorten the construction schedule. The number of welders required on-site will also be reduced. By eliminating welds, the code required inspections for Safety-Related piping are also reduced, reducing the inspection time required during both the construction of the piping system, and throughout the life of the plant. Other construction benefits include the reduction of shoring and scaffolding required onsite. While these construction costs are reduced by increasing the use of pipe bends, there is a small increase in the materials and additional engineering to use pipe bending. Due to wall thinning on the extrados of the bend, larger schedule pipe may be required to ensure that minimum wall thickness requirements are still satisfied.

Bending pipe allows engineers flexibility in locating the weld seams in the piping system. This helps eliminate seams that are difficult to weld, as well as inspect (Reference 3). Typical improvements would be eliminating elbows in close proximity to penetrations, or eliminating several welds in close proximity to one another, such as elbows located close to valves.

Piping in Safety-Related systems require additional inspections throughout the life of the plant. Reducing the number of welds in the plant reduces the number of welds that must be inspected as part of the In-service Inspection (ISI) Plan for the operating nuclear power plant. A typical ASME code inspection of a weld costs approximately $5,000 per weld per inspection. Eliminating welds from the inspection program can save tens of thousands of dollars per outage. Additionally, plants must apply for exemptions when it is not possible to inspect welds, such as those that are difficult to access or those where the local pipe geometry cannot provide accurate inspection results. Eliminating welds that are difficult to inspect reduces the paperwork and other difficulties that plants may face when ISI exemptions are required. Reducing the number of welds that must be inspected will also reduce the radiation exposure to personnel who perform the inspections.

While architect/engineers can use pipe bends to replace welded elbows in many or most applications, not all welded elbows can be replaced by bends. There will be circumstances where a pipe run will require use of a welded elbow rather than a bend in a long run of pipe in order to allow installation or to allow access to other components during construction. A combination of pipe bends and welded elbows is likely to be used in construction.

The disadvantages of selecting pipe bending over using welded fittings are:

- Welded fittings use a standard 1 ½ D radius for elbows. Standard bend radii for bent piping are between 2D and 5D depending on the nominal pipe size and schedule. These bends require more space than welded fittings (Reference 4).

- Bending at elevated temperatures can change the microstructure of the pipe near the bend and result in lower strength and susceptibility to stress corrosion cracking (SCC).

- Cold bending can leave residual stresses in the pipe that make the bend more susceptible to SCC or creep in systems operating in excess of 500°F.

3. Code and Regulatory Issues

The present regulatory codes are based on the ability of the pipe to withstand against internal or external pressure. Since the current codes permit the use of curved pipe, there are no identified unresolved issues.

4. Summary

Potential savings in both construction schedule and cost are available from using pipe bending instead of welded fittings in the construction of piping systems. A review of regulatory codes and standards has indicated that there are no unresolved issues that need to be addressed with future rule-making. This technology is currently being used both domestically and internationally in nuclear power plants.

Since pipe bending is a mature and proven technology, no additional development is needed. Due to the potential benefits of this technology, both during initial construction and throughout the life of the plant, pipe bending should be employed as determined to be optimally cost-effective in the construction of new nuclear power plants. DOE should inform the industry of technology advances in the use of bends rather than welded elbows through publication of this report and possibly through participation in a conference on advanced construction technologies.

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J

Precision Blasting/Rock Removal

Early in the construction phase of a nuclear power plant, excavation work is required to construct the foundations for the Reactor Building, Turbine Building, and other associated support buildings. For domestic nuclear power plants, excavation has traditionally been accomplished through the use of drilling and mechanical methods. In many cases, months were required to excavate the foundations for the Reactor Building alone, adding significant time to the construction schedule and cost.

An alternative to these construction techniques is precision blasting. Precision blasting for excavation involves drilling a series of shafts in an engineered pattern in the area to be removed. The shafts are filled with explosives and a detonation cord is run to a central location at the site. The charges are set off in an order designed to maximize the excavation with minimal amounts of debris and sound damage to the immediate area. Precision blasting is a complicated science, requiring extensive training and knowledge. It requires the use of a specialty contractor to design and control the blasting.

1. Implementation Experience

Since the 1800's, blasting has been used for several applications. Blasting was used to create railroad tunnels and cuts through otherwise impassable land. Blasting is used extensively in mining applications. Since its introduction, precision blasting has become a common means of excavation on large-scale projects such as constructing channels, roadways, and foundations for large structures.

Precision blasting has been successfully performed in the construction of the foundations for domestic nuclear power plant sites. The foundation for the Reactor Building at Millstone Unit 3 was excavated using precision blasting techniques. This is a notable success since the construction was performed while Millstone Unit 1, located only 900 ft away, was operating and Millstone Unit 2, less than 600 feet away, was late in the construction phase. The blasting techniques did not disrupt activities at either unit (Reference 2).

2. Benefits

Some large-scale projects that would require months for excavation have been completed in a few weeks using precision blasting techniques. The exact savings in the schedule are dependent on the type of rock and other geological features of the area, as well as the size and depth of the foundation excavated.

Precision blasting costs are approximately 1/3 the costs of traditional mechanical excavation methods, such as drilling and digging. Part of the cost reduction is due to the ability to remove or loosen a significant portion of the rock for the desired foundation in a short time. Blasting also reduces the personnel and equipment (and associated maintenance costs) required on-site during the excavation process.

Improperly controlled blasting has the potential to initiate problems if performed at a site with a currently operating unit. Seismic activity can result, which may cause the operating unit to shut down. Other concerns include damaging the equipment at the other unit or damaging footings or other concrete work that is being performed nearby. Improperly performed blasting has the capability to change the stability of the local geology, potentially leading to cracking or ground openings.

Regulations are in place to ensure that individuals and companies performing blasting are properly trained and certified. As a result, blasting is routinely performed, and the effects of poorly performed blasting are rare.

3. CODE AND REGULATORY ISSUES

Regulations have been developed to govern this method of construction due to the risks imposed on the personnel and structures close to the construction site. Both federal and state regulations must be followed prior to and during the blasting process. Specific regulations vary state to state. Once a site is selected for construction, the local regulations will need to be reviewed to determine if blasting is permitted for that location and what, if any, restrictions may apply.

4. SUMMARY

The selection of precision blasting as the method of excavation is impacted by the site geology, structure design, and the type of foundation required. Other factors, such as the federal and state regulations governing blasting, will also influence the acceptability of this construction technique. If precision blasting is applicable as the means of excavation, it can result in a significant savings in cost and schedule. Experience indicates that blasting can be used for construction at sites with existing units without disrupting their operation.

Since precision blasting is a mature and well understood technology, no further research or DOE action is required. DOE should inform the industry of the previous experience in successful use of precision blasting near an operating nuclear power plant through publication of this report and possibly through participation in a conference on advanced construction technologies.

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K
Cable Pulling, Termination and Splices

There have been several advancements in the field of cable pulling, splicing, and termination since construction of existing U.S. nuclear power plants. These advancements can potentially reduce overall plant construction time.

6. ADVANCES IN CABLE INSTALLATION TECHNOLOGY

Cable Pulling

Cable pulling broadly refers to the installation of cables in cable trays or conduits (also referred to as raceways) to connect the electrical loads of the plant to power sources. It is also commonly referred to as cable laying.

A cable or group of cables is pulled through the cable tray or conduit using a pulling rope, which is first routed through in the reverse direction. A lubricant is commonly applied to the cables to reduce friction, thereby allowing a longer cable length to be pulled. A pulling device is used to pull the pulling rope and the cables.

Three advancements in the area of cable pulling involve reducing the coefficient of friction between the cable and raceway or conduit. This allows longer cables to be pulled and allows them to be pulled more quickly, thereby saving time. The advancements that provide a reduced coefficient of friction (COF) are:

- High performance lubricants
- Cable tray rollers
- Cable tray sheaves

Other advancements in cable pulling include:

- Automatic lubricant application. The usual method of applying pulling lubricants is by hand. The lubricant is either poured into an upturned conduit or patted onto the advancing cable jacket throughout the pull. Construction crews who regularly install large amounts of cable are interested in ways to automatically apply pulling lubricant. Automatic application achieves a more uniform application of lubricant and reduces manpower requirements (Reference 7). This method uses a pump and flow regulator operated in concert with the cable pulling equipment.

- Assisted pulling devices. The most common method of pulling cable is with the use of an electric winch or tugger. Pullers are generally rated between 4,000 and 6,500 pounds and provide a direct tension readout as the pull progresses. If an installer is faced with a design calling for a long length of cable to be installed without splices, a second, or assist puller can be used. This assist puller method is accomplished by strategically placing an additional puller and pulling line in a straight section of pull. By pulling the slack cable using the assist puller, the pulling tension and sidewall pressure are reduced. The lead or the main puller will have less load to pull, thereby reducing pulling tensions and sidewall pressures. To safely distribute the pulling stresses on the cable, an assembly called a mare's tail is recommended; otherwise the area of the cable under grip should be wrapped with several layers of friction tape. This approach is discussed in IEEE Std. 576-2000, section 10.4. (See References 6 and 8)

Cable Splicing

Cable splicing is the joining of the two free ends of two cables together. The objective is to make a joint that is electrically equivalent to the cable. Performance characteristics for cable splices are required to conform to IEEE Std. 576-2000 and IEEE Std. 404-2000 (See References 1, 5, 9, 10, 11).

The commonly used methods of splicing are as follows (Reference 1):

- Cold Shrink: A tube or a series of tubes which are expanded to several times their diameter are placed over the conductor and allowed to shrink in diameter over the cable without the use of heat. When cold shrink products are stretched and then allowed to shrink on the cable, they exert a continuous inward pressure on the cable as they try to shrink back to their original diameter, less the permanent set. This inward pressure provides an environmental seal and improves electrical performance

- Heat Shrink: A tube or a series of tubes are applied over the conductor and reduced in diameter over the cable with the use of externally applied heat

- Premolded: The joint is factory molded and is installed by sliding it over the cable. The use of heat is not a part of the installation procedure

Cable Termination

Cable termination describes the treatment of a cable end which is connected to the electrical load or power source. Cable terminations are installed over prepared shielded power cables where a portion of the insulation has been removed. The function of a typical termination is to provide a cable end seal, electrical stress control, and external insulation covering. The cable end seal protects the cable from moisture. The electrical stress control is needed to prevent a dielectric breakdown. External insulation covering must limit leakage current and resist both tracking and erosion from exposure to the environmental conditions in a strong electric field. The commonly used methods of cold shrink, heat shrink, and premolded preparation described above for cable splicing also apply to cable termination.

7. Implementation Experience

High performance lubricants and cable tray rollers and sheaves are being routinely used by cable laying crews in the U.S. and other countries. Automated application of lubricants is gaining acceptance and becoming more common primarily due to the reduction in manpower. It could not be determined whether these techniques have been used at recently constructed nuclear power plants.

Assisted cable pulling is also used when necessary for long pulls of cable to save time. It could not be determined whether this technique has been used at recently constructed nuclear power plants. Given that there are few cable pulls of over 1,000 feet in length at nuclear power plants, it is not likely that this technique has been widely used in the construction of new nuclear power plants.

High performance lubricants and assisted cable pulling devices have been used at existing U.S. nuclear power plants during construction, for repairs, and for installing modifications. Examples include: all cable replacement work for restart of Browns Ferry Unit 1, completion of construction at Grand Gulf and Comanche Peak, and replacement of damaged underground cables at Diablo Canyon

Cold shrink technology is mature and has gained industry acceptance for use in splices and end terminations. It could not be determined whether this technique has been used for cable repairs or replacement at U.S. nuclear power plants or for construction of new plants outside the U.S. Heat shrink technology is the standard, and has been used for both repairs and cable replacements at U.S. and foreign nuclear power plants. Preformed fittings are also commonly used for both repairs and cable replacements at U.S. and foreign nuclear power plants. They are simpler to install than heat shrink or cold shrink, but do not allow the flexibility of those techniques and proper fittings may not be available for every situation.

The maturity and improved reliability of splices has led to installation of fully fitted cabling in preassembled modules with over 90% of work completed. Sufficient length of cable is left in a coil at the module boundary so that at the time of installation, each cable is run to a cable splice junction box where numerous cables are spliced for ease of inspection and maintenance in the future. This technique is being used in the U.S. and overseas in construction of ships, fossil power plants, and oil and gas drilling platforms. It is being used in the U.S. in construction of the latest class of nuclear-powered submarines. This concept has not been used in the civilian nuclear industry.

8. Benefits

Cable Pulling

High Performance Lubricants

When cables are pulled in cable trays or conduit, an upper limit of the length of cable pulled is calculated to avoid exceeding the maximum cable tension allowed to prevent damage. A key variable in the calculation of maximum allowable tension on the cables during cable pulling is the frictional coefficient measured between the cable jacket and the conduit wall. One of the more significant factors affecting coefficient of friction (COF) is the presence and the type of lubricant.

Over the past twenty years, the clay slurry lubricants common in power cable installation have been replaced by lower friction, water soluble organic polymer lubricants based on polyethers, polyalcohols, polyamides, and/or neutralized polyacids. Recently, silicone oil polymers (dimethyl polysiloxane) which are not water soluble, have been emulsified in water systems and used in cable pulling lubricants, usually in combination with other polymer systems.

Tests performed by the American Polywater Corporation (a manufacturer of silicone oil polymer lubricants) indicate that high performance polymer lubricants result in COF ranging from 0.10 to 0.20 (References 2 and 3). A silicone oil supplement further lowers this COF. This improvement is on the order of 10%, (i.e., 10% lower tensions on straight pulls, or longer pulls with the same tension). When the pulls include multiple bends, the COF is calculated exponentially, therefore tension is further reduced. The test result data indicates that the COF used in EPRI EL-5036, "Power Plant Electrical Reference Series, Volume 4: Wire and Cable," (Reference 4) may be conservative in calculations when high performance lubricant is used. This conservatism could result in more expense in splicing and conduit access than necessary.

The benefits of using high performance cable pulling lubricants is lower tensions on straight pulls and longer pulling distances for the same tension. Longer pulls reduce the need for splicing and speed the overall cable pulling process. Also, lower dynamic COF of the cable would reduce the cable pulling time.

Cable Tray Rollers and Sheaves

The proper use and location of rollers and sheaves will greatly reduce the necessary tension required to pull cable into the tray. Rollers are used to support the cable in the straight run of the cable tray. When the tray changes direction, sheaves should be employed to satisfy the maximum allowable sidewall pressure limits and minimum bending radii requirements of the cable.

According to IEEE Std. 576-2000, section 10.3.1 (Reference 5), "Field data indicate that an effective coefficient of friction of 0.15 will account for the low rolling friction coefficients of well designed rollers and sheaves in good operating condition."

Use of rollers and sheaves reduces the COF, thereby reducing the cable pulling tension and cable pulling time. This would be noted during the cable pull process as a lower tension indicated on winch instruments, allowing faster pulling, and does not require regulatory or code review.

Automatic Lubricant Application in Cable Pulling

Automatic lubricant application during cable pulling ensures uniformity in application of the lubricant, which reduces the cable COF, and thereby increases cable pulling length and speed and reducing cable installation time. This would be noted during the cable pull process as a lower tension indicated on winch instruments, allowing faster pulling, and does not require regulatory or code review.

Assist Pulling Device

An assist puller allows for pulling longer lengths of cable at one time, which will reduce the time needed to pull longer cables. This would be noted during the cable pull process as a lower tension indicated on winch instruments, allowing faster pulling, and does not require regulatory or code review.

Cable Splices and Terminations

Cold Shrink Technology

Cold shrink technology has become popular in splicing medium-voltage cables over the past 20 years. Cold shrink technology is available for insulation rated from 600V to 35kV. Some of the benefits of the cold shrink technology include:

- No heat, flames, or special installation tools
- Minimal training required
- Easy, fast, and safe installation
- Symmetrical cable cutback dimensions
- Allows transition of different cable sizes within a splice range
- Low temperature handling
- One piece splice body design
- 100% factory tested

The amount of training and skills required for cold shrink is much less compared to the requirements for proper use of other types of splicing and termination technology. It tends to be more reliable than heat shrink, because it provides a constant, even pressure around the conductor and is not dependant on the need to apply heat uniformly, like heat shrink. It does not do a good job of resisting hard objects, though, which is one reason it is not used for direct burial.

A considerable amount of installation time is taken in securing the site safety requirements, applying uniform heat, allowing the splice/terminations to cool down, and transporting the heat torch in making a heat shrink splice/termination. The preparation of conductor in the cable for splice/termination is the same for both cold and heat shrink terminations.

Consolidated statistics from past nuclear power plant construction (Reference 12) indicate that the average man-hour (MH) requirement for a single power termination (pre-molded or heat shrink) is 2.5MH. Use of a cold shrink termination takes no more than 1.0MH for completion and could be done in as little as 0.5MH. This translates into at least a 150% reduction in time for each termination/splice by using cold shrink technology over heat shrink or pre-molded technology. Considering the number of cable terminations in a typical nuclear plant, a considerable reduction in cable installation time can be achieved through use of this technology.

Cable Splices Enable Modules to Be More Finished

One of the emerging technologies in the area of shipbuilding or other modular construction projects is the extensive use of cable splices to enable fully outfitting a module and testing its installed equipment prior to delivery to the project. For example, ships are built in modules and these modules are finally assembled side by side and welded to their neighbors. In the past, long lengths of cable were pulled through many sections of a hull after welding of modules had been completed (Reference 13). Raychem (a manufacturer of cable insulation products) is marketing a family of thick-wall shrink-fit wraps for cable splicing that allow each prefabricated steel module to be fully fitted with all cabling prior to joining to its neighbors. This water-proof splice joint has been approved by Lloyd's Register, American Bureau of Shipping, and Det Norske Veritas (an independent foundation whose services include safety and quality certification of ship designs).

Modules installed in the latest class of submarine have cable pre-installed with coils of lengths needed to reach a cable splice junction box. The cable coils are arranged out of the way of module lifting equipment and hull sections to prevent damage to the cable during transport or installation of the module. This also minimizes safety issues with personnel or equipment entanglement with cable coils on modules to be moved. General Dynamics Electric Boat and Northrop Grumman Newport News developed specifications and tests to prove the splices meet performance requirements. They also developed special tools that apply proper heat and pressure simultaneously for the required amount of time, to speed the splicing process.

This use of cable splicing can be applied to nuclear power plant construction as it makes more use of modularization. For example, piping is being modularized wherever possible, equipment is being pre-installed, cable tray and tray supports come pre-installed inside the modules. This reduces the site work and shortens project completion time. If cables can be preinstalled in modules and connected to cable sections in the neighboring modules using splices, the reduction in construction time could be substantial. Extensive use of splices for nuclear power plants is a new concept and more studies should be done to analyze its benefits and life-cycle costs.

9. CODE AND REGULATORY ISSUES

Cable Pulling Lubricants

The methods set forth in EPRI EL-5036, "Power Plant Electrical Reference Series, Volume 4: Wire and Cable," have been the de facto standard for nuclear power plant cable pulling since it was issued in 1987. While this report addresses the use of some modern lubricants for cable pulling, it has not been updated to include the reduced COF of more advanced lubricants and the longer pulling lengths described in IEEE Std. 576-2000. There should be no regulatory issues with applying the COF estimates based on the use of new lubricants to the calculations in EPRI EL-5036.

Increased Pulling Tension Limits

IEEE Std. 576-2000 (Reference 5) has increased the maximum allowed pulling tension of three-conductor or multi-conductor cables from 6,000 lbs. (in IEEE Std. 576-1989) to 10,000 lbs. (Reference 7). As a result of this change, the maximum allowable pulling tension in EPRI EL-5036 differs from that in IEEE Std. 576-2000 for multicore cables. This increase in allowable tension enables pulling longer cable lengths. There should be no regulatory issues with applying the limit in the latest IEEE standard to the calculations in EPRI EL-5036.

Use of Cold Shrink Splices and Terminations

Raychem heat shrink tubing type WCSF(N) has been used by most domestic nuclear plants for cable splicing. This type is qualified to design basis accident conditions per U.S. Nuclear Regulatory Commission Regulatory Guide 1.131, "Qualification Tests of Electric Cables, Field Splices, and Connections for Light-Water-Cooled Nuclear Power Plants (for Comment)" (Reference 15). The more recently developed cold shrink splices and cable terminations need to be qualified for design basis accident conditions for use in nuclear power plant construction in accordance with applicable regulations.

Use of Splices to Enhance Modularization

The NRC currently recognizes that cable splices are unavoidable, but does not allow their general use. This is stated in regulatory position 3 of U.S. NRC Regulatory Guide 1.75 proposed Revision 3 (December 2003) as follows: "NRC recognizes that cable splices in cable trays cannot be avoided. Field splices should be strictly limited to special circumstances. Cable splices in raceway should generally be avoided to the extent it is practical" (Reference 15). This is a change from the earlier regulatory position. Regulatory position 9 of U.S. NRC Regulatory Guide 1.75, Revision 2 (September 1978), states "Cable splices in raceway should be prohibited" (Reference 14).

10. SUMMARY

Extensive use of the most up-to-date cable pulling methods and systems has the potential to reduce bottlenecks and reduce time and cost for the overall construction schedule of a new nuclear power plant. Given the number and quantity of cables installed in a typical nuclear plant (over 20,000 cables totaling over 6,500,000 lineal feet for a typical single-unit PWR), the potential for time savings is considerable.

Information concerning the use of advanced cable lubricants and other techniques to speed cable pulling such as automatic lubricant pumps and integral cable tray rollers should be disseminated to potential users through publication of this report and participation in a nuclear plant construction method workshop. These technologies do not pose any new code or regulatory issues.

Information concerning the potential for reduction in construction schedule through use of cold-shrink cable splice and termination technology should be disseminated to potential users through publication of this report and participation in a nuclear plant construction method workshop. DOE should encourage EPRI or a manufacturer to perform the necessary environmental qualification testing to qualify cold shrink products for nuclear safety-related system applications.

The use of cable splices as part of modular construction is estimated to shorten new nuclear plant construction schedules by approximately 1 month out of a 66-month construction schedule (see Appendix N for details of this estimate). Therefore, the feasibility and desirability of using this technology should be investigated. MPR recommends that the following actions be taken as part of a nuclear industry-sponsored effort:

1. Perform environmental qualification testing of cold-shrink splices. This could be based on the application of splices found in use in construction of nuclear-powered submarines and the testing used to certify cold-shrink splices for use on commercial ships. The testing should be planned with NRC participation to ensure it addresses potential regulatory concerns.

2. Perform testing, possibly at a national laboratory such as Sandia or Brookhaven where cable insulation aging has been extensively studied, to show that aging of splices does not degrade overall cable performance. The testing should be planned with NRC participation to ensure it addresses potential regulatory concerns.

3. Make results of this work widely available for use in efforts to change industry and NRC standard practice that restricts the use of splices, with the goal of the NRC revising regulatory guidance to incorporate results of performance testing and accepting the use of splices to enhance modular construction. This will support envisioned application of a modularization strategy incorporating splices in new domestic nuclear plant designs and construction plans.

These activities could be co-sponsored by DOE if DOE and industry determine that making this technology available as a construction technique would be a worthwhile effort. The long lead time to adopt splicing technology as industry practice will probably result in its not being available within the next 5 years for the next nuclear plant construction in the U.S.

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L

Advanced Information Management and Control

Nuclear power plant information must be maintained throughout the life of the facility - from requirements definition, project planning, and design to procurement, construction, and operational handover, and throughout facility operation, maintenance and ultimate disposition at the end of its useful life. Information management and control consists of acquisition, storage, retrieval, and manipulation of the plant information. This appendix discusses the current state of the art and future technologies that could be applied for information management and control for future nuclear power plant construction projects.

1. IMPLEMENTATION EXPERIENCE

New Attack Submarine Deployment by General Dynamics Electric Boat

Electric Boat credits part of its success in the development of the Navy's newest submarine class (New Attack Submarine or NSSN) to the use of advanced information management and control technologies (Reference 1 and 2). This project has many parallels to a nuclear power plant construction project. The submarine has a nuclear reactor and related machinery that requires design effort and quality assurance. Also, the boats are built in limited quantities and the engineering and construction effort is a large and complex undertaking.

The first boat in the new submarine class, the USS Virginia, was christened in August 2003. Prior to beginning the design for NSSN, Electric Boat initiated a study to identify the most cost effective and efficient techniques for the new submarine project. Electric Boat concluded that the construction and operating costs for a new submarine were almost entirely determined during development; therefore, improvements in the development process would decrease life cycle costs. The result of the study was the implementation of a program called Integrated Product and Process Development. The intent of this program was to team the designers, builders, life cycle support personnel, quality personnel, and cost personnel within Electric Boat. In addition, the team included the customer (the Navy) and outside equipment suppliers. The goal was to have all stakeholders provide input early in the project, where it would have the greatest impact.

Computerized design databases made the teamwork possible by ensuring that all parties had access to information at all times. Central control of the information ensured that all parties worked to the same baseline. The databases were tools used during initial design and construction. Further, they will provide information throughout the life of every submarine in the class. The use of electronic tools allowed the shift from paper to electronic design information. Two technologies were key in the new submarine project: data modeling and management systems and video telecommunications.
Electric Boat used CATIA, a program developed by Dassault Systems and supported domestically by IBM, for data modeling and management. CATIA provided three-dimensional

CAD capabilities, and data management capabilities. In addition to the existing CATIA capabilities, Electric Boat required extensive customization to achieve process efficiencies for data management. The information in the design models were used to create drawings, parts lists, work orders, and in some cases were used in computer controlled manufacturing.

Video telecommunications allowed continuous involvement of all the relevant parties from an early point in the design. Key decisions could be made rapidly that did not require co-location or extensive travel. Specially built rooms at various sites allowed real time transmittal of 3-D model information, in addition to voice and video. Weekly electronic video teleconferences in these rooms allowed meetings to occur remotely but interactively between various parties. Questions were resolved immediately or in greatly reduced times compared to previous practice. Shipyard workers saw the power of 3-D visualization in meetings with designers and requested that a similar room be installed in the shipyard. Shipyard workers have come to question the need for two dimensional drawings in the future.

CANDU

A recent nuclear power plant construction project in China, known as the Quinshan CANDU project, used several advanced information technologies: the Asset Information System and TRAK databases, the CANDU Material Management System, and the Integrated Electrical and Control Database (Reference 3).

The Asset Information System (AIM) and TRAK databases provided all project participants with access to design and construction documents. It provided the baseline to ensure proper information was used for design and construction, and will be used during operation of the plant.

For the CANDU project, the computer aided design and drafting system (called CADDS) was linked to systems for controlling and managing materials and documentation. In the CANDU Material Management System (CMMS), material management began as soon as design elements were created in CADDS and continued through procurement, storage, and issuing materials at the job site. The CMMS was used to generate requests for quotes for material supply, purchase orders, and to accurately identify materials on-site. Bar codes applied to materials on-site allowed tracking their location with CMMS. CMMS will support operation and maintenance once the plant is on-line.

The Integrated Electrical and Control Database stored all information associated with the design and as-pulled data for wiring, cables, and connectors. The database also integrated with the systems for controlling and managing materials and documentation.

FIATECH

The flow of information is important during all phases of capital projects' life cycles. Figure L-1 illustrates the information flow between the phases of a capital project.

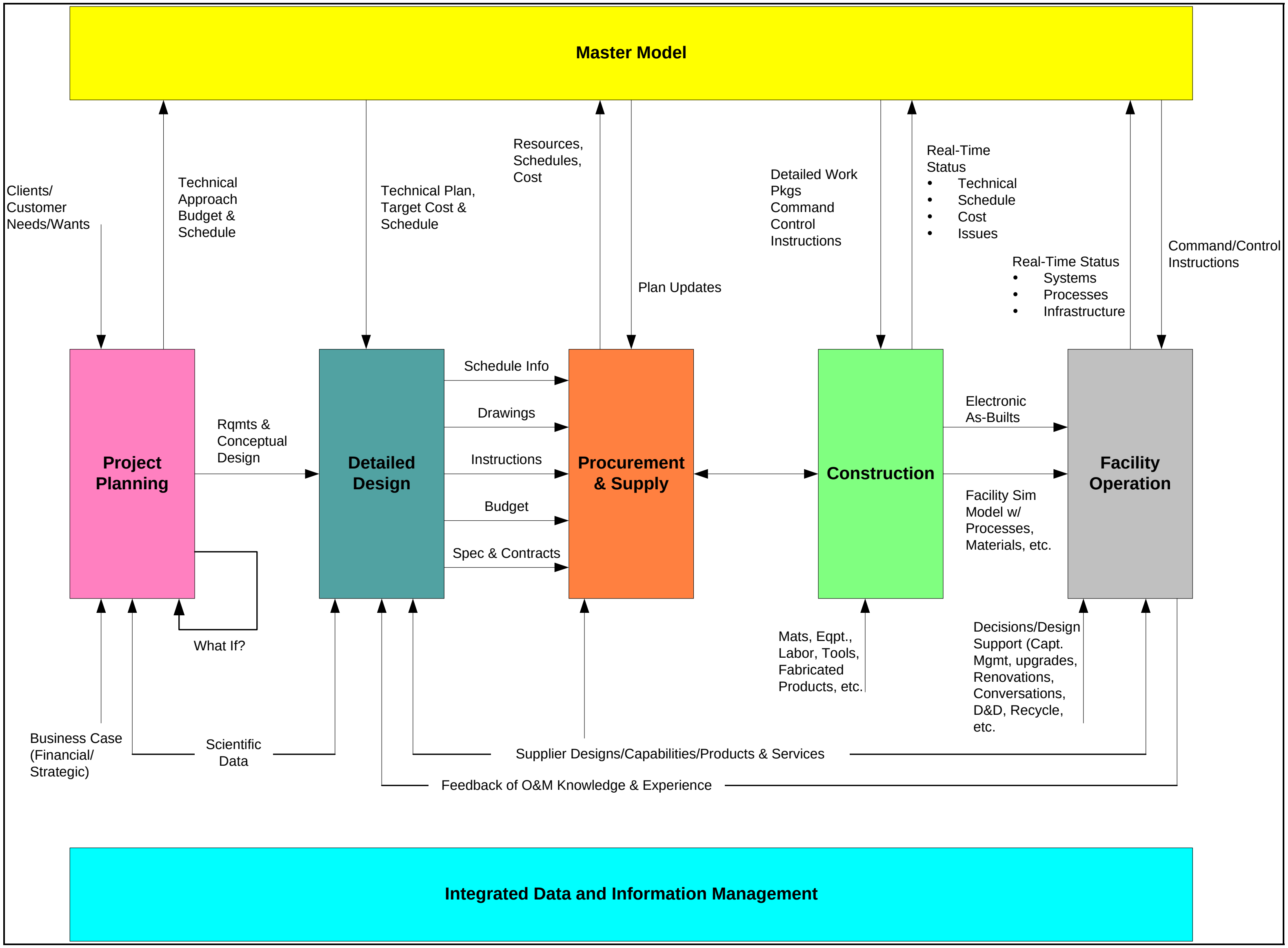

Figure L-1. Schematic of Capital Project Information Flow (largely based on FIATECH, Reference 4)

During project planning, requirements are articulated by the owner/customer. What-if scenarios and the choice of a conceptual design require input from outside sources of information. The financial plan and a high level schedule are created during project planning, but they support decisions made later in the project. The requirements and conceptual design from the planning phase are passed to the detailed design phase.

During detailed design, information provided by vendors and subcontractors for materials, equipment, and subsystems is used to finalize the details of the design. Lessons learned from previous designs (construction, operations, maintenance) guide decisions. The detailed design phase produces drawings, specifications, and instructions for use in procurement and during construction. The detailed design also updates and provides greater detail for the project schedule and budget.

While equipment and materials are procured and supplied, numerous parties must interface with suppliers and shippers. Again, the schedule and budget are updated as this phase progresses.

During construction, on-site personnel require information to efficiently receive materials and equipment. The constructors require work packages from designers. As they progress, the constructors have information to update the schedule and budget. Also, they produce as-built drawings that can be used in operation and maintenance of the plant.

Once plant operations begin, lessons learned can provide valuable feedback for future projects.
In addition, the owner's management of the facility requires a two-way flow of information.

Since all phases of capital projects are interrelated and interdependent, further integration of information flow can improve these projects. There is a need for more effective information management, and standards are needed to support interoperability across the project/facility life cycle.

A partnership named FIATECH aims to build a fully integrated information system for projects and industries. FIATECH, which stands for Fully Integrated and Automated TECHnology, is a partnership of the National Institute of Standards and Technology, industry (including major construction companies, software vendors, oil companies, and utilities), and other government organizations (Reference 4). FIATECH's mission is to direct industry and government appropriations for research and development of new construction technologies. FIATECH is also addressing new materials, new construction methods, and workforce issues that are not addressed in this appendix.

The FIATECH vision for the future of information management and control technologies includes the following:

- Information available on demand to all parties, with appropriate security

- Integration of systems and processes. Project partners and functions can instantly and securely communicate irrespective of geography, culture, and technology preferences

- Interconnected, automated systems and processes that reduce the time and cost of planning, design, and construction

- Collection of tools (software) that are totally interoperable with each other and perform their own function flawlessly while supporting the needs of the other functions. The tools are integrated but flexible to meet the needs of the different stakeholders

- Construction processes that take advantage of the available information technologies to assure conformance with design and regulatory requirements

- Information technology delivering better facilities that are optimized for post-construction operation. The resulting facilities are simplified, and less costly to operate and maintain. Information that was created when the facility was in planning through completion of construction gives the capability to adapt to changing business demands

2. BENEFITS

The benefits are time savings, cost savings, and overall improved project control.

In the future, potential benefits include integrating real-time plant process instrument and control data and 3D computer models for process monitoring and optimization. By combining 3D geometry data and operations data, real-time simulation and analysis of plant processes are possible.

FIATECH

According to FIATECH, the benefits of advanced information flow include:

- Up to 8% reduction in costs for facility creation and renovation

- Up to 14% reduction in project schedules

In addition, FIATECH estimates that improving the interoperability of software used for capital projects would result in savings of $1 billion per year for industry.

CANDU

The CANDU project benefited from the use of advanced information management technology in the following ways:

- The material management system allowed for accurate identification of materials, smoothing the process for materials that required quality assurance and traceability. This is an important improvement for a nuclear power plant

- The electronic data management system ensured that the project team did not have to recreate information for purchase orders

- The electronic data management system will be the basis for inventory, operation, and maintenance once the plant is on-line

Electric Boat NSSN

According to Electric Boat, applying Integrated Product and Process Development (IPPD) to the NSSN has resulted in:

- Drawings issued on schedule and with fewer re-issues as compared to previous submarine classes.

- Drawings for the new submarine were issued on average 2.5 years earlier relative to the start of construction than for previous classes of submarine.

- Construction man-hours are 40% lower for the lead ship (Virginia) as compared to the two previous classes' first ships.

- Virginia was delivered at quality and cost levels that compare to the third ship in class for previous programs.

Electric Boat credits its success to the overall process (IPPD), not just the electronic tools. However, the process was facilitated by the new technology now available for construction projects.

3. Code and Regulatory Issues

Advanced information management and control technologies must be implemented properly to avoid regulatory issues during construction and operation of a new nuclear power plant. Regulations focus on ensuring accuracy, accessibility, and proper documentation of information. No specific limits on the use of electronic systems were identified; however, all requirements of standard information management and control systems would also apply to an electronic system. Proper use of advanced technologies is expected to help plant constructors and operators comply with appropriate codes and regulations. The increased availability of information should facilitate proper oversight scope, scheduling, and verification.

4. Summary

Advanced information management technology is currently in use in the construction industry. The Qinshan CANDU project has integrated some design and parts tracking information and utilizes project databases that provide a baseline for all parties. General

Dynamics Electric Boat has used advanced information technologies in developing the New Attack Submarine. Current information technology has demonstrated success.

Future technologies promise to facilitate communication that was not possible in the past. These technologies, when coupled with the appropriate processes for teamwork, should aid successful development of a new nuclear power plant.

The major hurdle to integrating the project phases is the lack of software compatibility. Currently, software is available for specific functions in support of each project phase. There is no standard for direct flow of information from one program to another. In general, information flow is either a manual process or it does not occur. It is important to note that if generic industry-wide standards are not specified prior to the first utility committing to construction of a new nuclear plant, then problems could arise based on compatibility of the information management systems between the nuclear vendor and the A/E firm.

Another barrier to further information portability is a working environment with multiple companies with disparate goals involved in the design, build, and operations of power plants. Implementation of advanced information management and control technologies will require a major commitment from all parties involved. Support from the users is necessary for the tools to be useful. Companies must be convinced that the significant costs associated with implementing new information technologies will result in schedule and cost reductions of comparable value.

The vendors responsible for new nuclear plant construction will need to perform a study on the processes to be used in a new nuclear plant project. This system should start with project planning and extend through construction to start-up and operation. This study will require input from owners, designers, constructors, operators, and the regulator. The results of the study will guide the development of the appropriate information technologies.

The FIATECH program sponsored by NIST is working to advance the integration of information between the phases of capital projects. Use of advanced information management and control is also explicitly recognized and required in the US Advanced Light Water Reactor (ALWR) Utility Requirements Document. This technology does not require DOE research funding. However, the nuclear industry (e.g., NEI) should obtain information on FIATECH from NIST and conduct an investigation to assess the applicability of this project to improving project coordination for new nuclear plant construction in the U.S.

Also, the investigation could assess the applicability of the FIATECH project to improving communications between the plant construction team and the NRC throughout construction. The investigation should determine steps needed to resolve any NRC concerns about safety-related electronic documentation and safeguarding any sensitive information related to plant security. The NRC is developing its own Construction Inspection Program Information Management System (CIPIMS) to track inspection, test, analysis, and acceptance criteria (ITAAC) during construction of new nuclear power plants. An assessment of the NIST project is recommended because it could improve the process of inspections and approvals by NRC during plant construction, in addition to increasing efficiency during construction. Industry should conduct this assessment and invite NRC to participate.

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M

Prefabrication, Preassembly, and Modularization

Prefabrication, preassembly, and modularization are construction techniques that are being utilized in many industries, including nuclear power plant construction. These construction techniques will find application, in some form, in any new construction of nuclear power plants.

Prefabrication is a manufacturing process, generally performed at a specialized facility, where materials are joined to form a component part of a final installation. Prefabrication components often involve the work of a single craft, like piping.

Preassembly is a process by which various materials, prefabricated components and/or equipment are joined together at a remote location for subsequent installation as a unit. Preassemblies typically contain portions of systems and require work by multiple crafts.

A module results from a series of remote assembly operations, possibly involving prefabrication and preassembly. Modules are often the largest transportable unit or component of a facility. A module in its most complete form is a volume fitted with all structural elements, finishes, and process components which are designed to occupy that space. Modules can be constructed remotely or constructed at the work site and then placed in position.

There are many motivations for the use of these new construction techniques. A lack of adequate materials or labor at the worksite leads to moving the work to where the labor and materials are located. Difficult site locations can also motivate the creation of new worksites with better conditions (for example, the construction of the international space station or earthbound constructions of an offshore oil rig). The functional characteristics or need for speed and ease of erection of projects may lead to the use of these techniques. Relocation and reuse of a facility may be possible if constructed using modularization. Quality requirements may result in the need for work to occur in a shop rather than the field.

Prefabrication, preassembly, and modularization all allow decoupling sequential activities into parallel activities, providing for possible improvements in the construction schedule. The resulting economics and time savings spur the move to more productive work environments. Technological developments in project planning, design, and materials are enabling the use of these construction techniques.

This section discusses prefabrication, preassembly, and modularization experience and how it can be applied to future nuclear power plants.

1. IMPLEMENTATION EXPERIENCE

Prefabrication has been used in the building industry for structures such as precast concrete buildings, metal buildings, walls, and space frames. Preassembly has been used in buildings and industrial construction. Skid-mounted pumps and dressed vessels are typical equipment preassemblies. Stairs, catwalks, and instrument panels are small preassemblies, while pipe racks with pipes installed are an example of large assemblies. Modularization has been used by the petrochemical industry to address cold weather challenges in Canada and Alaska. Large modules have also been used for offshore platforms. The following section discusses the use of modularization in shipbuilding, civil works, fossil power plants, and in nuclear power plants.

Northrop Grumman Newport News Shipyard

Newport News shipyard implemented modularization in increasing proportions of the construction of each successive Nimitz class aircraft carrier over the last thirty years. Currently, the shipyard assembles 100-ton modules into 300 to 600-ton “super lifts” (see Figure M-1) that are placed onto ships in drydock (Ref. 1). Newport News is planning to implement modularization even further for the new CVN-21 class. They project that the new ships will include over 60% pre-outfitted building blocks and superlifts.

Newport News is also implementing modularization in the construction of new submarines in conjunction with Electric Boat (discussed more below). Newport News assembles the module structures, and then outfits them with coamings for pipe and cable runs, pipe hangers, and light fixtures. They do not install long electric cables in modules due to a safety concern. Cables are pulled after modules are installed. Newport News uses preassembled pipe as much as possible. They use as-built measurements made by laser to ensure pipe lengths and bends are manufactured correctly to fit (e.g., into bulkhead penetrations).

General Dynamics Electric Boat

Electric Boat is using a modularization concept for constructing the newest class of submarines for the Navy (the first boat is the Virginia) in conjunction with Northrop Grumman Newport News Shipyard. Electric Boat has also used modules in submarine construction for past submarine designs, specifically in hull sections i.e., slices of the boats in the form of cylinders, truncated cones, and end domes as illustrated in Figure M-2. The hull sections are outfitted with internal structures, pipes, and cables installed.

Electric Boat’s submarine assembly yard is located in Groton, Connecticut. The hull sections are constructed in an enclosed plant at another facility at Quonset Point, Rhode Island. Hull sections, weighing up to 1400 tons, are transported by barge from Quonset Point to Groton. For the Virginia class, hull sections will also be transported between Electric Boat and Newport News.

The use of modularization has increased the level of completion of the boats at pressure hull closure, from 58% on the Seawolf to 85% complete for the Virginia (Ref. 2). The first hull section of the Virginia was 1100 tons and was 98% outfitted prior to joining to adjacent sections.

Figure M-1. Lifting the Island for the USS Ronald Reagan, CVN 76
(excerpted from www.nn.northropgrumman.com/photogallery)

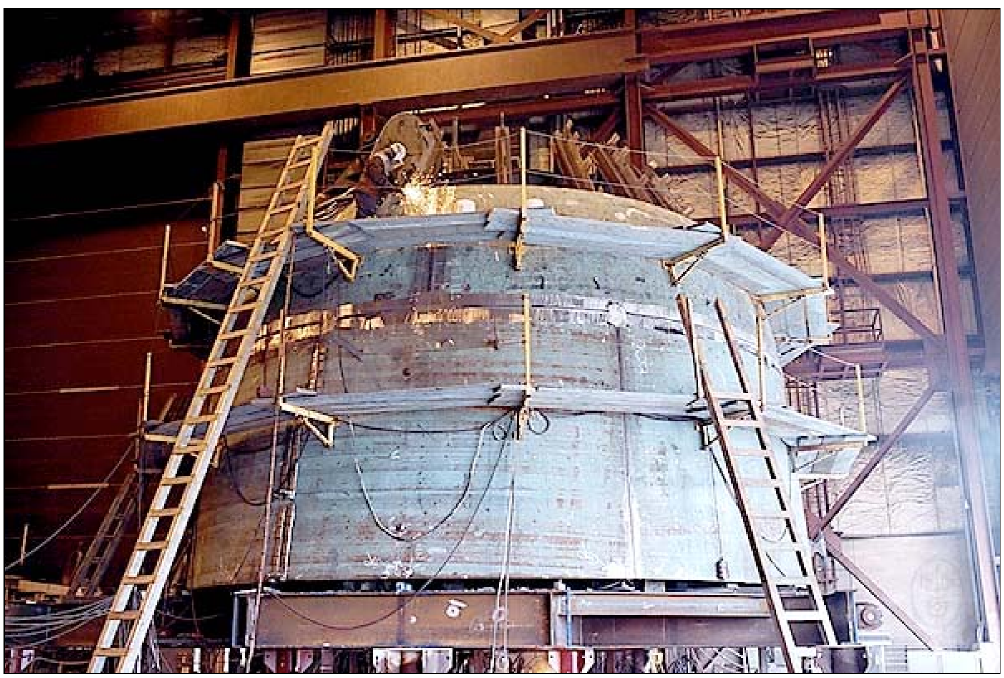

Figure M-2. A Submarine Hull Section
(excerpted from www.nn.northropgrumman.com/photogallery)

Boston's Big Dig

The Ted Williams tunnel in Boston's Big Dig incorporated modularization. Tunnel sections were made of steel tubes that are 40 feet in diameter and 300 feet long. The tubes were built in Baltimore and transported to Boston via barge (see Figure M-3). The tunnels were sunk into trenches that had been dredged in the harbor floor. Twelve tubes were connected to make a ¾-mile tunnel. The tunnels were finished with tiles and lighting after they were sunk into place. Similar construction was used on the Baltimore Harbor Tunnel and elsewhere but with less complete structure.

Figure M-3. Tube Sections for the Ted Williams Tunnel
(excerpted from www.bigdig.com)

Nuclear Power Plants

Modularization has been proposed for use in the construction of the four Generation III+ reactor plants being evaluated by MPR for the DOE NP2010 program.

AECL ACR-700

The modularization techniques proposed for the ACR-700 are based on the experience and established work processes of recent CANDU projects. Four CANDU units were built in the 1990's: Qinshan Phase III Units 1 and 2 went into service in 2002 and 2003, and there are two other units currently under construction. Like previous plants, AECL plans to use Hitachi machine shops and satellite offices located in Japan, Canada, and the U.S. for the ACR-700.

The approach for modularization of the ACR-700 involves the use of four module types:

- Multi-discipline modules with process equipment, piping, cable trays, ducting, civil structures, instruments, etc.
- Process equipment and piping modules with equipment, piping, and structural frame
- Piping modules with piping, supports, and structural frame
- Instrumentation, Controls, and/or Electrical (ICE) modules with panels, cabinets, racks, and cable trays

The design packages for the modules of the ACR-700 will be prepared through a process that improves on the methods that were used at Qinshan. The Qinshan design packages were produced by area (location) and by different engineering groups (civil, mechanical, piping, etc.). AECL plans to produce the design packages for the ACR-700 modules in two parallel paths: for construction divided by module with collaborative input from all the engineering groups and for construction divided by volume with input from the engineering groups.

AECL plans four alternative methods for module production:

- Modules completed in a factory and shipped to site
- Sub-modules completed in a factory, shipped separately to the site with final module assembly in an onsite facility
- Components fabricated in a factory, with modules fabricated in an on-site facility
- Major equipment shipped separately to site (a piece of major equipment is considered a module).

The transportation methods available to the construction site will affect the module types used in the plant construction.

AECL states that the construction schedule duration will be reduced since modules will be produced in parallel with site civil work. In addition, the reactor building design is simplified and will require significantly less time to construct in part due to the integration of floors with the modules (floors will be poured in structures integrated with the modules as they are installed). In the proposed ACR design, over 80% of the reactor building is modularized.

GE ESBWR

The structural modules planned for adaptation and use in the GE ESBWR have been used successfully on the ABWR to significantly reduce construction time. The modularization planned for the ESBWR results from the simplification of the systems and structures in the new plant design. Modules will be lowered into position once the floor elevation on which they sit is complete.

GE plans three modularization methods for the ESBWR:

- On-site assembly and modularization of equipment
- Equipment manufacturers providing components that are complete and assembled more than usual
- All equipment provided to a central facility for assembly and installation into modules

The modules may be massive and require special transportation methods.

There are fifteen module types:

- Reactor building (RB) and auxiliary fuel building (FB) precast stair tower/elevator shaft modules
- RB, FB, and control building (CB) structural steel/metal deck modules
- RB, FB, and CB prefabricated rebar mat modules
- RB upper base mat rebar/embedment module
- RB bottom Reinforced Concrete Containment Vessel (RCCV) liner module
- RB RCCV wall rebar modules
- RB RPV pedestal module
- RB RCCV diaphragm floor liner module
- RB upper RCCV wall liner module
- RB drywell equipment and piping support structure (DEPSS)
- RB RCCV top slab liner module
- RB and FB pools liner modules
- RB and FB roof truss structural steel modules
- RB, FB, and CB general area rebar modules
- RB, FB, and CB forms and supports modules

The DEPSS consists of the RPV shield wall, the DEPSS structural steel, and integrated piping duct and electrical components. It is the heaviest and most complex of the modules and, if implemented, provides the most benefit to the construction schedule.

The majority of the module types are civil works. GE acknowledges there may be advantages to development of modules for mechanical and electrical components. It should be noted that GE's ABWR design includes equipment modules in addition to civil modules. GE plans to maximize modularization benefits during the detailed design phase.

In GE's modularization plan the major benefits to shorten the schedule will come in the areas of: reactor building structures, the reactor vessel and connected piping and valves, equipment-like control rod drives in the reactor building, the Reactor Water Cleanup System, and the Shutdown Cooling System. The modularization of the DEPSS will permit the RPV shield wall assembly to be constructed concurrent with other RCCV work, saving significant critical path time. Additional smaller benefits are anticipated in the fuel and control buildings. GE anticipates reduced or no benefit from modularization of activities that are not on the critical path.

Westinghouse AP600

Modules are an integral part of the AP600 design concept. There are approximately 600 modules in the design. All the major pipe areas are modularized. Large modules carry 90% of the pipe, valves, and instruments for containment systems. Of all the pipe welds inside containment, 65% will be made in shops and shipped in modules.

There are five types of modules planned:

- Mechanical Equipment modules- equipment on a common structural frame along with interconnecting piping, valves, instruments, wiring, etc.
- Piping modules- pipe and valves and associated instrumentation on a common structural frame.
- Electrical Equipment modules- electrical equipment on a common structural frame.
- Structural modules- liner modules, wall modules, super floor modules, heat sink floor modules, turbine pedestal form modules, stair modules, platform modules, structural steel modules, space frame modules.
- Wall, basemat, and floor reinforcement modules.

Some of the modules will be shop-assembled, some will be assembled on-site.

Westinghouse states that the total impact of modularization on the construction schedule has not been defined, but that the single largest driver of schedule reduction is modularization.

Many critical path activities are planned to be shortened through modularization. The key components in Westinghouse's construction schedule are:

- On-site fabrication and lifting of completed reinforcement and structural modules into place.
- A modularized containment vessel as opposed to piece-by-piece installation in a congested area.
- Liner modules that can be pre-assembled in parallel with other construction activities.
- Major piping and equipment modules in containment, which are on critical path.
- Any mechanical or electrical modules that must be installed before the floor steel above.

The information presented here is based on the modularization plan for the AP600; however, since the AP1000 is largely the same design, the information is considered applicable.

Toshiba ABWR

Toshiba plans to apply modularization to critical path activities to reduce construction times for the ABWR. Since the critical path is the reactor building, modularization will figure highly there. In addition, modularization is planned for areas that will require large amounts of mechanical and electrical commodities that may become critical path if delayed.

The types of modules planned for the ABWR are based on experience gained in ABWR construction in Japan. The modules are similar to those described in the GE ESBWR section, but additionally the ABWR literature lists the following modules:

- Cable tray modules
- Large bore piping modules
- Large equipment modules (e.g., the condenser)

The RCCV modules are the most important features for maintaining the ABWR schedule. These are modules for: central mat, RCCV lower shell, RCCV diaphragm floor, DEPSS, and top slab. Like the other designs, the ABWR construction schedule relies on modularization for shorter durations.

2. IMPLICATIONS OF PREFABRICATION, PREASSEMBLY, AND MODULARIZATION

The decision to use modularization must be made during the conceptual design stage to maximize its benefits and minimize the detrimental impacts. The ramifications of modularization will impact almost every subsequent decision. Prefabrication and preassembly also require some level of early decisions, although not to the degree required for and resulting from modularization. A summary of the implications of making extensive use of PPM in a construction project is provided in Table M-1.

Table M-1. Significant Changes Required to Implement PPM in Construction Projects

Change	Discussion
Earlier Final Decisions	1. The decision to use PPM must be made during the conceptual design stage to maximize the benefits of its use and minimize the detrimental impacts of the implications of this decision. 2. In order to support design completion, equipment selection, arrangement, pipe and cable layout, etc., must be decided sooner in the engineering process. 3. Equipment and materials will need to be procured earlier than in traditional projects. Project financing must allow for the cash flow required for equipment and module procurement much earlier in the process than for projects without PPM.
Efforts to Optimize Modularization	1. PPM is not beneficial to cost or schedule in every case. Finding the optimum degree of modularization is a tradeoff between such factors as transportation capabilities, lift capabilities, costs, and constructability. The Construction Industry Institute has produced a tool to aid in deciding what level of prefabrication, preassembly, or modularization to use (see Reference 5). 2. Successful use of modularization requires early participation of all disciplines in the module design. The detailed design may require splitting the designers into multidisciplinary module teams. 3. Design and construction teams must be integrated to effectively use modularization. 4. Life-cycle maintenance should also be considered when dividing a facility into modules and arranging equipment and interfaces within modules. This may be of greater concern to the buyer than the builder.
Design Requirements Differ	1. Modular design will require additional structural engineering for each module to be self-supporting as well as supporting the entire structure once assembled. The design of modules will have to consider the rigging requirements, like inclusion of lifting lugs. Center of gravity calculations (for transportation) may impose design constraints that otherwise would not exist. 2. The use of modularization requires choosing how to divide the plant (see Reference 4 for a quantitative method). The detailed design will have to consider laying out the plant in a modular arrangement. 3. Designers will have to consider how to arrange the equipment in the modules to ensure interconnections will function.

Change	Discussion
Increased Reliance on Information Management	1. Computerization in the design process is the key to modularization because of the enormous amount of data generated, processed, and shared between different groups involved in the engineering of modular plants. Information technology and computer-aided design both play a role. 2. Mistakes in procurement must be minimized since they have more significant impacts on cost and schedule for modular projects.
Design, Engineering, and Planning Must Be Completed Earlier	Increased up-front planning is required due to the interdependency of the parts that will make up the new plant. Design and engineering must be completed in time to allow construction planning and final issue of module fabrication specifications. Project financing must allow for more man-hours of engineering and planning effort earlier in the process.
Team Integration and Organization Is More Important	The use of modularization requires a higher level of control and organization during design and procurement than for traditional projects. For the most part, this translates into a need for a high level of information transmittal between organizations and teams. The level of involvement between the project team and the vendor procurement activities will likely be set by the contractual relationship set up between the parties involved.
Transportation Access Affects Design	Modularization requires consideration of transportation issues. The must be adequate site access to deliver large modules. The maximum module size and weight must be considered. The project team will have to survey the transportation routes for oversized module transport.
Standardization Affects Design	If multiple units are to be built using modules, the designers need to tailor the design of overall plant to site and customer requirements, but retain as much in common as possible between plants. One strategy is to divide plants into modules so that site-specific requirements affect the fewest modules, with minimum impact on other modules that can thus be standardized.
Reliance on Module Fabricators	There needs to be a high level of interaction between the project team and module suppliers to ensure all requirements are met. The dependence on suppliers for equipment for the modules and the modules themselves requires a rigorous qualification of bids. The project team will have to try to seek shops with experience in producing modules, or provide appropriate oversight for new processes. Fabricators must ensure dimensional control so that interfaces align between modules.

3. BENEFITS

Prefabrication, preassembly, and modularization increase the number of locations at which work can be performed and shift many of these to a shop environment rather than in the field, reducing construction cost and schedule. Parallel paths for work lead to schedule compression. The total construction duration can be reduced through careful planning. Weather-related challenges and associated downtime can be reduced by moving work from the field into shops. Modularization has the most dramatic effect on the manpower curve for the construction of a nuclear power plant of any of the construction techniques discussed. More effort is shifted into planning, design, and procurement. The manpower required at the construction site is leveled throughout the project.

The project costs from incorporating prefabrication, preassembly, and modularization are affected in different ways, not always resulting in reduction of costs. More engineering is required for these construction techniques, increasing design costs. More materials are required for modularization and the transportation costs are increased. There should be a reduction in construction time since field time is replaced by shop time, which is more efficient. Also, field time should be more efficient in assembling modules than traditional construction techniques. Inspection, calibration, and testing could occur in the module fabrication facility prior to module shipment to work sites. Due to the compact design of modularization, however, maintenance issues at the work site could be harder to resolve. As discussed above, more activities can occur in parallel, shortening construction schedules. Shorter construction schedules typically lead to .lower costs from interest on financing for the project.

Prefabrication, preassembly, and modularization should result in better quality control since more work is performed in the shop than in the field. A related benefit should be that most work is performed in a safer environment than a construction site. Quality control should be tighter since inspections and tests will be easier to perform in the shop than in the field.

4. CODE AND REGULATORY ISSUES

There should be no code impact to the use of modularization, preassembly, or prefabrication since all designs will have to meet existing requirements. The requirements will not change due the use of these construction techniques. Some improvements in the regulatory process may be possible if inspections and tests can be performed while modules are in shops. Conversely, regulatory changes during the project will be even more detrimental since scheduling of the modules will be so integrated and essential to project completion.

5. SUMMARY

Prefabrication, preassembly, and modularization (PPM) have been applied in many and varied construction applications and are certain to be applied in any new nuclear power plant construction in the U.S. The schedule should be compressed using these construction techniques and costs should be reduced, primarily by reducing the costs of financing interest during construction. Careful planning will be required to choose the proper level of application of prefabrication, preassembly, or modularization. Successful implementation will also require consideration of the organization of the project team, the schedule, and transportation issues.

Given the extensive recent use of this technology for fossil power plants and for nuclear powered aircraft carriers and submarines, the issues that will affect use for nuclear plant construction in the U.S. are the application of commercial nuclear power quality standards, ensuring non-U.S. module fabricators can produce the required quality and meet tight schedule demands, and maximizing the cost-effective incorporation of this technology into new plant designs and construction plans. DOE should disseminate information concerning the use of modularization by NSSS vendors through a nuclear plant construction method conference attended by vendor, constructor, and utility representatives. The key prerequisites for successful modularization as described in Table M-1 should be emphasized.

Modularization relies heavily on fabrication capability and transportation infrastructure, and the existing infrastructure may not be adequate for nuclear power plant modular construction in the areas of size, weight, complexity, and quality control.

- Industry should assess module manufacturing capability, define gaps in capability under various construction demand scenarios, determine whether capabilities exist to fabricate the modules needed, define any gaps in capabilities or barriers to their use, and develop approaches to overcome the gaps.

- Industry should assess the impact of 10 CFR 50 Appendix B QA requirements on the availability and feasibility of using PPM. Options for development of new QA methods or programs should be investigated. The findings of this review could be presented to the NRC to discuss measures to resolve the obstacles to increasing the number of domestic and foreign suppliers that meet QA requirements.

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N

Construction Schedule Improvement Analysis

1. PURPOSE

Estimate the reduction in construction schedule for domestic nuclear power plants attributable to advanced construction methods.

2. SCOPE

The potential reduction in construction time is quantified for the technologies recommended for further industry-sponsored research and development. The following technologies were evaluated:

- Cable Laying, Splicing, and Termination
- Modularization

Additionally, the potential schedule savings from the use of steel-plate reinforced concrete structures was evaluated.

The level of accuracy of the estimated reduction in nuclear plant construction schedule is considered sufficient for prioritizing the recommended research and development efforts. The estimates should be used to compare the potential schedule benefit of each construction technology, but as they are based on 1970's-era construction schedules, these estimated time savings are not directly applicable to more recently proposed plant construction schedules.

3. RESULTS

Table N-1 summarizes the estimated improvement in the overall nuclear plant construction schedule provided by each construction method. These estimates are focused on the construction schedule reductions expected between first structural concrete activities ("first concrete") and fuel load. Any benefits derived during the engineering design or other phases of the nuclear plant development are not included in the estimates.

Table N-1. Estimated Construction Schedule Improvements

Construction Method	Appendix	Estimated Schedule Reduction (Months)
Steel-Plate Reinforced Concrete Structures	A	2.3
Cable Splicing	K	1.3
Modularization	M	5

4. UNIVERSAL INPUTS

4.1. Benchmark Project

The benchmark construction project duration used as the basis for estimating the benefit from the advanced construction methodology is 66 months. This value, measured from construction permit issue date to fuel load, is the average construction project duration for 43 domestic nuclear power plants completed by 1979 (Reference 1). Use of this benchmark omits the complicating effects of the regulatory changes following the 1979 accident at Three Mile Island Unit 2. Construction duration was 73 months from groundbreaking to fuel load.

The commodity installation rates for man-hour (MH) requirements to place a unit quantity of cable, pipe, concrete, etc., are given as a high and low value in Reference 1. The low (best) rate is used in this analysis, resulting in conservative estimates of the schedule reduction.

The low (best) rates were selected since the worst-case numbers reported were affected by factors that will be mitigated in any future nuclear plant construction project. Examples of these factors include:

- Labor strikes
- Lost labor man-hours due to waiting for material
- Lost labor man-hours waiting for engineering drawing changes to account for unexpected interferences
- Lost labor man-hours waiting for engineering approval of field routing of pipe
- Lost labor man-hours due to re-work caused by regulatory changes, late design revisions, or failed inspections

4.2. *Critical Path Analysis*

Construction schedules are reduced by shortening the duration of critical path activities. The maximum schedule reduction for a specific critical path activity occurs when a different activity becomes critical path.

Schedule improvements estimated in this appendix consider only reductions in critical path activities that reduce the overall plant construction time.

It is assumed that construction of the portions of the plant outside containment is not on critical path.

5. CALCULATIONS

5.1. *Steel-Plate Reinforced Concrete Structures*

Result

The construction schedule for a nuclear power plant is potentially reduced by 71 working days, or a 30% reduction of the postulated 225-day concrete schedule, when steel-plate reinforced concrete (SC) is used during construction. This 2.3 month schedule improvement translates to an approximately 4% reduction in the overall plant construction time of 66 months.

Inputs

Inputs to this calculation are summarized in Table N-2. Additional assumptions regarding the overlap of concrete activities is illustrated in Figure N-1.

Table N-2. Inputs for Steel-Plate Reinforced Concrete Structures

Quantity	Value (see note 1)	Source
MATERIALS		
Amount of materials used to construct concrete walls Concrete (yd^3) Rebar (ton) Embedments (lbs) Formwork (ft^2)	 12,239 3,107 377,147 210,845	Nuclear Industry Experience
LABOR		
Craft hours for structural concrete in a plant Concrete (hr) Rebar (hr) Embedments (hr)	 33,635 76,890 89,410	Nuclear Industry Experience
Formwork (hr)	95,651	
Percentage of concrete craft hours dedicated to removing formwork (%)	40	Assumption
Space requirement of single laborer (ft^2)	300	Assumption
Average work day duration (hr)	10	Assumption
REACTOR BUILDING CHARACTERISTICS		
Shape Diameter (ft) Height (ft)	Cylinder 130 100	Assumption

Note:

1. The values for the information in this table were obtained from information pertaining to construction of a nuclear safety-related concrete building. That information is proprietary, so only the values are referenced here.

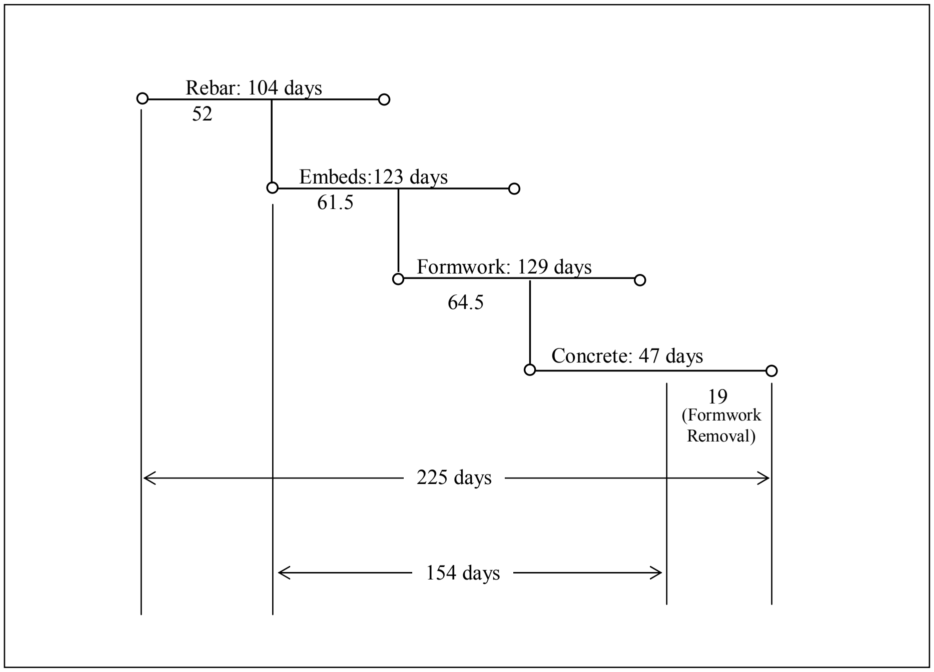

Figure N-1. Construction Schedule Estimate for Reinforced Concrete Inside Reactor Building

Approach

The schedule reduction due to the use of steel-plate reinforced concrete is estimated based on two areas with the potential for substantial time savings:

- Rebar placement
- Formwork removal

Steel-plate reinforced concrete arrives at the construction site in modules. Therefore, no placement of rebar is required. Secondly, these modules are self contained, that is, the steel plates are permanent structures. Therefore, no form work needs to be constructed or removed to support the concrete installation. However, based on the limited industry experience with this technique, there is no construction schedule reduction expected due to replacing formwork assembly with module placement. In addition, time savings associated with scaffolding is not expected since scaffolding will still be required for welding access. Figure N-2 illustrates the differences in the construction activities required.

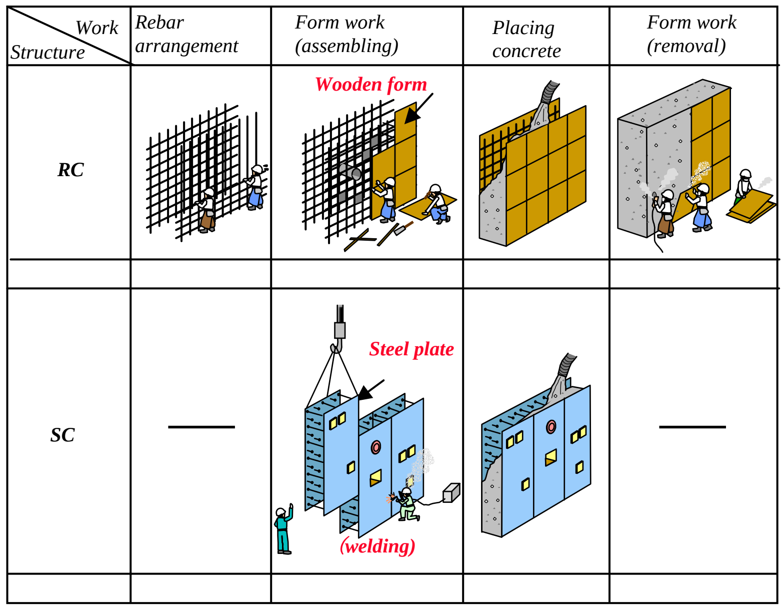

Figure N-2. Comparison of Construction Activities Reinforced Concrete (RC) vs. Steel-Plate Reinforced Concrete (SC) Structures

Calculation

The quantity of materials and labor hours for each material were obtained from past experience in constructing nuclear plant walls. Table N-3 summarizes the quantity of materials used for concrete, formwork, embedments, and rebar. The labor hours needed to place these materials are also listed. These provide the bases for determining the unit effort required to install each material.

Table N-3. Construction of Reinforced Concrete Walls-Material Quantities and Man Hours

Material	Quantity	Units	Construction Labor	
			(MH)	(MH/unit)
Concrete	12,239	yd^3	33,684	2.8
Rebar	3,107	ton	76,890	25
Embeds	377,147	lbs	89,410	0.24
Formwork	210,845	ft^2	95,651	0.45

Using the assumptions in Table N-2 concerning the size of the reactor building and assuming that the amount of concrete needed for the SC structures inside the reactor building is approximately 15 percent of the total containment volume, the concrete volume is calculated as:

$$ConcreteVolume = (0.15) \cdot \pi \cdot \frac{D^2}{4} \cdot H = (0.15) \cdot \pi \cdot \frac{(130)^2}{4} \cdot (100) = 199{,}098 \text{ ft}^3$$

Converted to cubic yards, the Concrete Volume ≈ 7,500 yd^3.

The quantity of rebar, embedments, and formwork required to construct the walls is calculated from the ratio of these materials to concrete using the values provided in Table N-3. Table N-4 summarizes these ratios.

Table N-4. Ratio of Material Quantities to Quantity of Concrete

Material	Unit	Ratio to Concrete
Concrete	yd^3	1
Rebar	ton	0.25
Embeds	lbs	30.8
Formwork	ft^2	17.2

The ratio of the material to concrete, multiplied by the amount of concrete gives the quantity of material needed for the construction of the walls inside the reactor building. Using these values, the total man-hours needed for construction of each material is calculated. Given the dimensions of the reactor building above, the cross-sectional area of the building is:

$$Area = \frac{1}{4} \cdot \pi \cdot D^2 = \frac{1}{4} \cdot \pi \cdot (130)^2 = 13{,}273 \text{ ft}^2$$

Assuming that an average worker requires 300 square feet of space to work, then work in containment is limited to 45 workers. Therefore, it will be assumed that the crew working on the SC structures consists of about 45 workers. Assuming a work day of 10 hours, the total number of working days to complete the SC structures for each material is also given in Table N-5.

Table N-5. Total Man Hours and Working Days for Each Material

Material	Quantity	Units	MH/unit	Total MH	Working Days
Concrete	7,500	yd^3	2.8	21,000	47
Rebar	1,875	ton	25	46,875	104
Embeds	231,000	lbs	0.24	55,440	123
Formwork	129,150	ft^2	0.45	58,118	129

The overlap in the schedule of construction activities when installing each material is illustrated in Figure N-1. It is assumed that the process of building the walls is scheduled such that each new activity begins approximately halfway through the previous activity. The overall time to construct the walls inside the reactor building is approximately 225 working days.

Because SC structures require no rebar, this will save 52 days off the overall schedule. Since no formwork needs to be removed once the concrete is set, the overall schedule will be shortened further. The amount of time it takes to remove the formwork was included in the concrete material schedule. It is assumed that approximately 40% of the labor hours dedicated to concrete were allotted to stripping the structure of its formwork. Therefore, this is a time saving of approximately 19 working days. Consequently, the overall time savings due to the employment of SC structures in the reactor building is approximately 71 working days, or about 30% of the 225 day concrete construction time. For a 66 month total construction schedule, this 2.3 month schedule improvement translates to an approximately 4% overall schedule savings.

5.2. Advanced Use of Cable Splicing

Result

The schedule reduction achievable by advanced use of cable splicing technologies is estimated to be at least 1.3 months.

Inputs

The inputs for calculating the schedule reduction related to cable splicing are provided in Table N-6.

Table N-6. Inputs for Advanced Cable Splicing

Quantity	Value	Source
MATERIALS		
Combined quantity of power and control cable in a single-unit PWR or BWR	6,500,000 LF	Based on industry experience and review of new plant design data.
Combined quantity of power and control cable in reactor building	2,500,000 LF	Based on industry experience and review of new plant design data. (some new plant designs have greatly reduced the quantity of cabling in the reactor building to approximately 15-20% of this value)
Quantity of cable as percentage of total Power Control	 30% 70%	Assumption
Reactor building cable quantity on critical path as percentage of total	50%	Assumption based on 25% critical path overlap with prior and subsequent construction activities
LABOR		
Manpower Requirement Cable laying– Power Cable laying– Control	 High – 0.30 MH/LF Low – 0.10 MH/LF High – 0.09 MH/LF Low – 0.05 MH/LF	Reference 1
Cable laying crew size (No. of laborers)	10	Assumption
Space requirement of single laborer	300 ft^2	Assumption
Work day duration	10 hr	Assumption
REACTOR BUILDING CHARACTERISTICS		
Shape Diameter Height	Cylinder 130 ft 100 ft	Assumption

Approach

Cable splicing adds flexibility to the construction process, which saves time by allowing more activities to be performed in parallel. There are many ways to implement cable splicing in combination with modularization. One possible approach is illustrated in Figure N-3. Here two modules are shown located inside containment, each with one load (E) and one cable terminal box (D). Each load is wired to a motor control center (MCC), located outside containment (A).

Three splicing locations are illustrated. The first, at location B, allows the power cable from the MCC to the common splicing location outside containment to be installed off critical path and independent of the installation of loads. A second location is on the module itself at the module cable terminal box (D). Cables from loads on the module would be routed to this common location. The cable terminal box on the module would be located so as to simplify installation of the module and subsequent power, control, and instrumentation cable connections. This allows the module to be prewired and tested off-site. The third splice location is a cable splice junction box inside containment (C) where several cables from the junction box outside containment (B) will be pulled and spliced to cables from the modules (D). Alternatively, the cables from loads on the modules can be made long enough to reach the cable splice junction box inside containment and modules would be installed with these cable lengths coiled and ready.

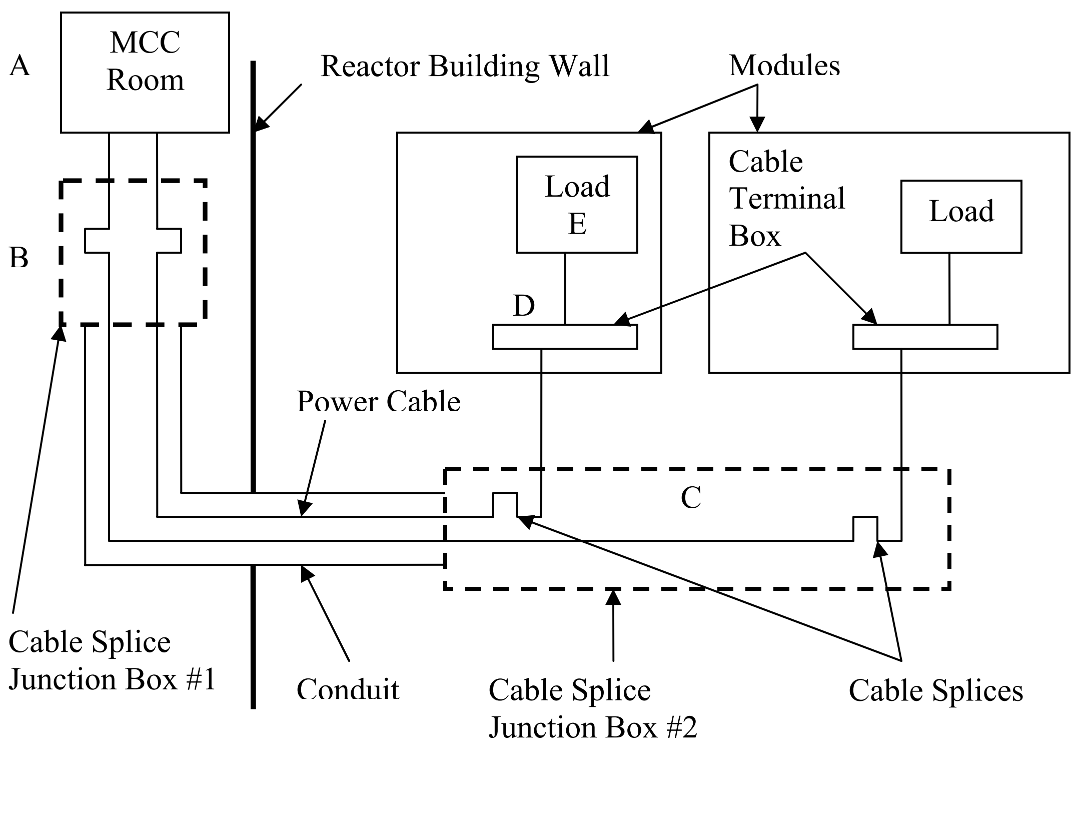

Figure N-3. Conceptual Cable Connections to Modularization

The construction schedule reduction from using splices depends on how much cable is removed from critical path, for example:

- The power cable from the load or module terminal box to cable splice junction box #2 can be pre-wired and coiled inside the module

- The power cable from the MCC room to cable splice junction box #1 is removed from critical path since it can be pulled independent of the reactor building work schedule

Thus, the overall power cable pulling time on critical path is reduced by the percentage of cable due to the use of splicing in combination with modularization. This estimate excludes any schedule reduction achieved as a result of the following:

- Cable pulling using splices are centralized at modules, cable splice junction boxes, and MCCs or switchgear. This would save time in the setup/breakdown of cable pulling equipment and other preparation by craftsmen to perform cable pulling

- Modules have cables and equipment tested in advance of placement in containment to reduce the time needed for post-installation testing

- Separate segments of cables can be installed at different times. This allows rescheduling of installation of segments at times when interferences can be avoided in the work area

Calculation

Power cable and control cable are treated separately because of the difference in man-hours required. The quantity of power and control cable associated with a critical path is calculated based on the following:

- The quantity of cable associated with the schedule critical path in the reactor building (50% of the total), results in 1,250,000 ft of critical path cable

- The breakdown between power and control cable of 30% and 70% of total critical path cable, results in 375,000 ft of power cable and 875,000 ft of control cable on critical path

The schedule reduction due to advanced use of cable splicing technology is calculated as shown in Tables N-7 and N-8.

Table N-7. Power Cable Schedule Reduction Calculation

Estimate	Cable on Critical Path (ft)	Available Labor per Crew (MH/crew-day)	Cable Pulling Rate (ft/day/crew)	Duration of Critical Path (months)	Schedule Improvement (months)
High	375,000	100	333	11	1.3
Low	375,000	100	1000	4.7	0.6

Table N-8. Control Cable Schedule Reduction Calculation

Estimate	Cable on Critical Path (ft)	Available Labor per Crew (MH/crew-day)	Cable Pulling Rate (ft/day/crew)	Duration of Critical Path (months)	Schedule Improvement (months)
High	875,000	100	1111	9.8	1.2
Low	875,000	100	2000	5.5	0.7

The following steps are involved in calculating the schedule reduction:

4. The amount of cable on critical path, calculated above, is listed in Column 2

5. Column 3 lists the maximum labor effort available from a single ten-man cable pulling crew in one ten-hour day

6. Column 4 contains the maximum cable pulling rate for a single crew. An example calculation (for the low estimate for power cables in Table N-6) of this value is:

   (100 MH/crew-day)/(0.10 MH/ft) = 1000 ft/day/crew

7. Column 5 contains the duration of critical path effort required for cable installation. An example calculation (for the low estimate of power cable) of this value is:

   (375,000 ft)/(1000 ft/day * 4 crews) * (1 month/20 working days) = 4.7 months

   The use of four crews is based on the assumption that an average worker requires 300 ft2 of space to work. The total working area in containment is 13,273 ft2 (see steel-plate reinforced concrete structure subsection of this appendix for area calculation). The number of workers in containment is therefore limited to 45. The crew size of 10 limits the number of crews working to 4

8. The length of cable removed from critical path due to pre-installation on the module is estimated to be 2% of the total length. The length of cable removed from critical path due to pre-installation from the MCC to the cable splice junction box outside containment is estimated to be 10% of the total length. Therefore, the reduction in cable length on the critical path is 12%, which also reduces the critical path cable installation effort by 12%

9. The number of months listed in Column 6 is 12% times Column 5

The schedule reductions shown in Tables N-7 and N-8 can be added since the activities would be performed in series, as presented in this analysis. The minimum total schedule improvement associated with advanced use of cable splicing technology is estimated as 1.3 months.

It should be noted that this is a conservative estimate since the improvement can be increased by (1) bundling cables to allow installation of multiple cables in a single pull, (2) pre-installing multiple cables from a MCC to a cable splice junction box, and (3) by taking into account other improvements to the overall project schedule as noted in the Approach discussion.

5.3. Prefabrication, Preassembly, and Modularization

Result

Based on reduction in on-site pipefitting, the construction schedule could potentially be reduced by at least 5 months when modularization is used.

Inputs

The assumptions used in the estimate of the schedule reduction achieved by using modularization are as follows:

- During construction of existing domestic nuclear power plants, the majority of mechanical-related construction man-hours are in three categories:
    - Large bore piping
    - Large bore pipe hangers
    - Small bore piping (which includes pipe hangers)
- Modularization could achieve a reduction of 50% in construction time associated with piping. This overall construction schedule reduction is based on the reduction in the number of field welds, a reduction in the number of hanger installations, and an increase in productivity due to less congested working conditions.

Further inputs to this calculation are provided in Table N-9.

Table N-9. Inputs for Pre-Fabrication, Preassembly, and Modularization

Quantity	Value	Source
LABOR		
Average unit man-hours for pipe fitting for one and two unit nuclear plants of size 800-1150 MWe per unit (man-hours/ft)	High - 13.8 Low - 3.35	Reference 1
Space requirement of single laborer (ft^2)	300	Assumption
Labor reduction due to modularization (%)	50%	Assumption
MATERIALS		
Length of piping (≥ 2.5 in. diam.) required for two-unit nuclear power plant of size range 840-1300 MWe (ft)	170,000 to 275,000	Reference 1
Piping quantity (≥ 2.5 in. diam.) in new plant designs as a percentage of past (%)	Maximum: 90% Minimum: 50%	Assumption
Piping quantity in reactor building relative to total (%)	20-30 %	Assumption
REACTOR BUILDING CHARACTERISTICS		
Shape Diameter (ft) Height (ft)	Cylinder 130 100	Assumption

Approach

This calculation estimates the improvement in the nuclear plant construction schedule based on the pipe installation duration only. It also uses only the low (best-case) value for achieved pipe installation productivity rate (MH/ft) from Reference 1, as previously discussed in Section 4.1 of this Appendix.

Modularization improves the productivity of workers on the job site by reducing the congestion of the work areas. In past nuclear plant construction, congestion slowed work as pipe fitters, electricians, and other trades needed to perform work in the same area (referred to as “stacking trades”). If the modules used include piping and hangers, the majority of pipe welds and hanger installations will be made in a shop. Pipe fitters will only have to make the field welds necessary to connect piping between modules. MPR estimates that the reduction in the number of welds, the reduction in the number of hanger installations, and the increase in productivity due to less congested working conditions could shorten the construction time associated with piping by 50-80%.

Calculation

The calculation of construction schedule reduction due to modularization is shown in Table N-10. The source of the parameters used in Table N-10 that are not calculated is provided in the Inputs subsection.

The schedule improvement calculation in Table N-10 is described as follows:

- The total length of piping used in existing domestic nuclear power plants as determined in the inputs is listed in Column 2
- Column 3 lists the ratio of piping length in the reactor building (critical path piping) relative to the total length for the plant
- Column 4 contains the number of man-hours needed to install 1 ft. of piping
- Column 5 lists the percentage of total piping length in a new nuclear plant (Generation III) relative to total piping length in existing domestic nuclear plant
- Column 6 provides the assumed credit (i.e., percent schedule reduction) due to modularization
- Multiplying the parameters in Columns 2-6 gives the calculated parameter in Column 7

This estimate of the schedule reduction due to the use of modularization is converted to overall schedule reduction by dividing Column 7 by the number of pipefitter man-hours available in one month, provided in Column 8.

The number of pipefitter man-hours available in one month is calculated based on the assumption that an average worker requires 300 ft^2 of space to work. The total working area in containment is 13,273 ft^2 (see steel plate reinforced concrete structure subsection of this appendix for area calculation). Under this assumption, work in containment is limited to 45 workers. Assuming a work day of 10 hours, the maximum personnel effort available for pipe fitting in a month is limited to 9,000 man-hours.

As shown in Table N-10, the schedule improvement due to reduction in pipe installation time is estimated to be between 5 and 61 months. The 61 month reduction used the very low productivity rate of 13.8 MH per foot, and is not a credible value for a 66 month overall schedule. The conservative estimate of 5 months is used in this report. Note, however, that this analysis does not account for the impact of modularization due to higher off-site labor productivity, pre-installation of equipment and instruments, etc.

Table N-10. Calculation of Construction Schedule Improvement due to Modularization

Estimate	Total Length of Piping for Existing Nuclear Plant (ft)	Piping Quantity in Reactor Building Relative to Total (%)	Unit Man-Hours (MH/ft)	Piping Quantity in New Plant Designs Relative to Existing (%)	Credit for Schedule Reduction Due to Modularization (%)	Savings in Pipe Installation Man-Hours thru Use of Modularization, (MH)	Pipefitter Man-Hours per Month (MH/mon)	Time Savings (Months)
Low	170,000	30%	3.35	50%	50%	42,712	9,000	5
High	275,000	20%	13.80	90%	80%	546,480	9,000	61

6. References

1. Budwani, Ramesh. N. "Important Statistics on Engineering and Construction of Nuclear Power Plants." In Nuclear Power Plant Construction, Licensing, and Startup: American Nuclear Society Topical Meeting, Los Angeles, California, September 13-17, 1976, pp.I.5-1--I.5-14. La Grange Park, Illinois: American Nuclear Society, 1976

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Glossary of Acronyms

ABWR Advanced Boiling Water Reactor

ACR Advanced CANDU Reactor

ACRS Advisory Committee on Reactor Safeguards; an independent committee to the that reviews and provides advice on nuclear reactor safety

A/E Architect/Engineer

AECL Atomic Energy of Canada Limited

ALWR Advanced Light Water Reactor

AP1000 Advanced PWR 1000

ARC Advanced Reactor Corporation; a consortium of operating electric utilities to oversee the development of advanced plant designs

ASL Approved Supplier List; the list of approved nuclear vendors for safety-related purchases and procurements

BEA Bid Evaluate and Award

BOP Balance of Plant; all systems, structures, components, and facilities of the plant not a part of or included in the nuclear island

BWR Boiling Water Reactor

CED Contract Effective Date

CIPIMS Construction Inspection Program Information Management System

COL Combined Construction and Operating License; a phase in the new reactor licensing process as described in 10CFR Part 52

CP Construction Permit

CSTA Calandria and Shield Tanks Assembly

DC	Design Certification; a phase in the new reactor licensing process as described in 10CFR Part 52
DOE	U.S. Department of Energy
EPC	Engineer-Procure-Construct
EPRI	Electric Power Research Institute
ESBWR	Economic Simplified Boiling Water Reactor
ESP	Early Site Permit; a phase in the new reactor licensing process as described in 10CFR Part 52
FC	First Concrete
FL	Fuel Load
FOAK	First-of-a-Kind
FOAKE	First-of-a-Kind Engineering; the effort required to integrate never before used technology from a certified design to a level at which they can be incorporated during the construction stage of a plant. Analysis or testing may be required to prove to the licensing organization that the new design or method conforms to strict requirements that ensure reliability and the ability of the plant to safely operate and shutdown under both normal and abnormal conditions.
FWP	Feedwater Pump
GE	General Electric
HVAC	Heating, Ventilation and Air Conditioning
I&C	Instrumentation and Control
ITAAC	Inspection, Tests, Analysis, and Acceptance Criteria
K-6/K-7	Kashiwazaki-Kariwa Units 6/7
LOCA	Loss of Coolant Accident
LOOP	Loss of Off-site Power
LWA	Limited Work Authorization
LWR	Light Water Reactor

M&E	Mechanical and Electrical
MCC	Motor Control Center
NOAK	Nth-of-a-kind
NP2010	Nuclear Power 2010; a program established by the DOE to deploy new nuclear power plants in the U. S. by 2010
NRC	U.S. Nuclear Regulatory Commission
NPP	Nuclear Power Plant
NSP	Nuclear Steam Plant
NSSS	Nuclear Steam Supply System
NTDG	Near Term Deployment Group; a group established by the DOE to examine prospects for deployment of new nuclear plants in the U. S. in this decade and to identify obstacles to deployment and provide action for resolution
O&M	Operation and Maintenance
OL	Operating License
P&ID	Piping and Instrumentation Diagram
PCS	Passive Containment Cooling System
PHT	Primary Heat Transport
PSAR	Preliminary Safety Analysis Report
PWR	Pressurized Water Reactor
QA	Quality Assurance
RCCV	Reinforced Concrete Containment Vessel
RFC	Release for Construction
RFF	Release for Fabrication
RIP	Reactor Internal Pump
RPV	Reactor Pressure Vessel

SIT	Structural Integrated Test; a test to measure strains in the containment structure
SSLC	Safety System Logic Control
TEPCO	Tokyo Electric Power Company
URD	Utility Requirements Document; a document prepared by the ALWR program team that outlines requirements for future Light Water Reactor designs
VHL	Very Heavy Lift (crane)
W	Westinghouse Electric Company
WBS	Work Breakdown Structure