Agile Manufacturing Development of Castings

Contract N00014-96-3-0001

Final Report

Reporting Period

January 1995–August 2000

Submitted by

Agile Castings Consortium
GE Corporate Research and Development
Building KW, Room D259
One Research Circle
Niskayuna, NY 12309

Submitted to

Office of Naval Research
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800 North Quincy Street
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Executive Summary

The Agile Manufacturing Development of Castings Consortium has demonstrated how the application of functional and collaboration technologies can dramatically reduce the casting acquisition cycle and cost for both industrial and defense-related applications. The Consortium, consisting of members that represent every tier of the castings supply chain, include Atchison Casting Corporation; Clinkenbeard & Associates, Inc.; Denison Industries; GE Corporate Research and Development; K + P Agile, Inc.; and QuesTek Innovations LLC. The Consortium has developed internet-related software that facilitates secure collaboration and distributed project management independent of the physical location of the team members and without the need for software maintenance on the client machines. Working together in an agile manner, the Consortium has been able to reduce the casting acquisition cycle to less than a third of its typical length. as illustrated by cases of the Allison AAAV transfer case, the Sunstrand aircraft pump housing, and the VME subrack. Due to the close collaboration between the Consortium members, the Allison AAAV transfer case development required only 8 weeks versus a normal acquisition cycle of 30 weeks, the Sunstrand housing development required only 19 days versus a normal cycle of 12 weeks, and the VME subrack development required only 14 weeks versus a normal cycle of 40 weeks. The ability to perform with this level has opened business opportunities for the future. Through the experience of this program, the team members have witnessed sufficient benefit to continue to move forward beyond the end of the project. All Consortium members intend to use the software developed to enhance regular business processes. Members will continue to collaborate on a regular basis to provide customers with results similar to those demonstrated.

1. Overview of the Project

1.1. CHARTER

The Agile Manufacturing Development of Castings Consortium was formed in response to a DARPA request to prototype an agile, virtual manufacturing process that enables U.S. manufacturing businesses to introduce new, high-quality castings more quickly and at a fraction of the current cost. Consortium members include: Atchison Casting Corporation; Clinkenbeard & Associates, Inc.; Denison Industries; GE Corporate Research and Development; K + P Agile, Inc.; and QuesTek Innovations LLC. The proposed program leverages integration enablers to demonstrate, among a multi-tier supplier chain, a streamlined castings acquisition process for military and commercial applications.

The manufacturing process development covers all the work performed to reach a production-ready state for a new product design. There are several reasons why the casting manufacturing process dominates new casting development time and cast:

- Typical casting development includes decisions based on intuition and historical precedent
- Tooling design is largely a manual process, highly dependant on the skills of the designers
- Manufacturing process simulation and analysis is frequently omitted
- Pattern acquisition is long and expensive
- Validation is typically carried out in the foundry under extreme time pressure with marginal results

1.2. TECHNOLOGIES UTILIZED

To address these issues, the project focuses on two technology categories—integration technology and functional technology.

To integrate the various supply chain members that play a role in the manufacturing process development, the Agile Manufacturing Development of Castings Consortium has developed *Agile Casting (AC) Notebook,* a robust software system for distributed collaboration and specification management. This Java software facilitates distributed management of product development through the Internet. The software permits secure exchange of technical and other information within a project management structure.

A project leader or principal investigator defines the project phases and the persons or organizations responsible for their timely completion. If signoffs or tollgates are necessary to progress through the development, the software facilitates the electronic signature process. The tasks that are part of the development phases can be assigned to various persons or organizations in the supply chain, and the tasks can be monitored through red/yellow/green status indicators.

Technical information is shared through various electronic documents. A built-in version control mechanism allows documents to be tracked as they change. The specifications needed for each stage of the development process are included in these documents, so that review of specification dependencies can be triggered by built-in mechanisms. This facilitates true concurrent engineering, since the understanding of interdependencies, evaluation of tradeoffs, and resolution of inconsistencies are fundamental elements of agile product development. These web-based tools allow the Consortium to save time and accurately communicate casting design and manufacturing process information.

Functional technologies accelerate and enhance the performance of each of the manufacturing process development stages. They also facilitate quick turn-around of various product development tasks. The functional technologies that have been developed include:

- Algorithms that generate parting-lines and surfaces
- Castings producability analysis
- Parametric definition of casting manufacturing geometry
- Process modeling and simulation methodologies that integrate design geometry and processing conditions
- Low-cost, production-intent pattern prototyping methodologies to refine production tooling
- 3D solid modeling
- Computerized pattern design, high-speed machining
- Computer networking

1.3. TECHNOLOGY DEMONSTRATIONS

The technology development at each stage was exercised through demonstrations. These demonstrations helped the Consortium evaluate its progress on both the integration and functional technologies. Four demonstration reports were published, documenting examples of how the developed technology was used to facilitate the development process.

An early collaborative system prototype was put together using a limited-feature storage and retrieval program called *Basic Support for Collaborative Work* (*BSCW*). In this prototype, the concepts of tollgates, signoffs, and specifications were introduced in rudimentary form. Using this environment as a testbed, one of the early demonstrations of the *Agile Manufacturing Development of Castings* project involved a support structure for the Phalanx missile-targeting radar, installed on U.S. Navy AEGIS-class destroyers and cruisers. This activity can be classified as a fabrication-to-casting (fab-to-cast) conversion, as the existing structure in use was a steel weldment. The goal was to convert a fabricated assembly (steel) to a cast unit, applying the same requirements used on the original design. Analytical tests, such as shock and vibration, were used to validate the prototype casting. A large number of many types of documents were successfully uploaded to the secure server and accessed using conventional Internet browsers from a variety of distributed computers. The shared documents included 3D solid models in proprietary and open file formats, images from process simulations and engineering analysis, and many text formats. In this demonstration, a much larger and more complex casting than originally envisioned went from concept to tooling production in 12 weeks. Based on this work, new mechanisms for access permissions and document signoffs needed to be developed. Also, new mechanisms for security needed to be developed and implemented.

The Consortium also completed the design, fabrication, and validation of tooling for a complex ductile iron casting for a locomotive. The development was accomplished in spite of poor documentation and an evolutionary part design. In so doing, it was successfully demonstrated that an agile manufacturing team can work with customers and suppliers that are not full members of the collaborative team. The prototype collaborative environment was used during agile development of a locomotive casting by the Consortium members and other supply chain members. The Consortium was successful in delivering robust tooling for a challenging casting design against a tight schedule. During the course of the agile development cycle, improvements and enhancements were identified.

Based on the lessons learned in the previous demonstration, codes written in the interpreted language Python were created to enhance the functionality of the BSCW software used by the Consortium. Prior to the completion of this work, the Consortium was tasked by GE Transportation Systems (GETS) with development of the IFE, a complex ductile iron casting for a commercial locomotive that, prior to the Consortium's involvement, had resulted in very few acceptable castings. The prototype specification management software was not available to the Consortium early in the IFE tooling development. Rather than attempt to transition the tooling development documents to the enhanced management system at an intermediate point in the engineering cycle, the Consortium managed the tooling development effort using BSCW without the enhanced specification management features. The development was accomplished, again in spite of poor documentation and an evolutionary part design. In so doing, it was successfully demonstrated that an agile manufacturing team can work with customers and suppliers that are not full members of the collaborative team. The Consortium was successful in delivering robust tooling for a challenging casting design against a tight schedule. During the course of the agile development cycle, improvements were identified. These necessary improvements indicated that BSCW environment enhancements were not sufficient, due to limited functionality, and that long-term viability was a serious risk. The emergence of Java as a viable distributed application language influenced the decision to construct the next-generation prototype in Java.

Based on the lessons learned, a new prototype collaborative environment was created. This system was built using Java and incorporated functionality that facilitated project tracking and synchronous collaboration. It incorporated the creation and maintenance of a hierarchical project structure, specification management, file storage, tollgates, permissions, encryption using SSL (secure socket layer), and a collaborative whiteboard. Because of their experience with modern design and manufacturing integration methods, the Benét Laboratories' Integrated Casting Design Team was chosen to evaluate the capabilities of the prototype, leading a design cycle using the new system. The Benét team managed the conceptual design (with the Consortium members) of an integrated towing bracket/muzzlebrake for a future direct support weapon system. The first prototype was quickly fabricated by modifying and welding some existing components together. Performance of the *AC Notebook* with a muzzlebrake and a removable towing eye was evaluated during simultaneous, distributed group work, demonstrating the stability and robustness of the system. The conclusion was that the methods and tools developed reduced the effort required to effectively communicate detailed business and technical knowledge for cast component acquisition.

1.4. SUCCESSES

With the help of the integration and functional enablers that were developed or used, the Consortium provided castings for both government and commercial applications were able to provide solutions to hard technical problems that customers could not get anywhere else. The examples of the Allison AAAV transfer case, Sunstrand housing and the VME subrack are clear illustrations of this.

For the AAAV transfer case, which was a large complicated casting measuring 29" × 42" × 20" and requiring 34 cores, under normal acquisition cycles a total of 30 weeks would have been required to get the first casting. The Consortium, however, was able to provide the first casting in 8 weeks despite many additions and changes.

In the case of the Sunstrand housing a normal cycle would have required 12 weeks. The Consortium was able to cut this to 19 days and the quality of the part exceeded the casting requirements.

The VME subrack, a fab-to-cast conversion, went from concept to delivery in only 14 weeks meeting all functional requirements versus a 40 week normal cycle. The product unit cost was reduced by 40% and the component is lighter than the fabricated part it is replacing.

Benchmarks of the typical casting cycle for parts that were not as complex were undertaken as part of this project by the American Metal Castings (AMC) Consortium and the USAF. For a GETS locomotive casting that the Agile Manufacturing Development of Castings Consortium undertook, the conventional development cycle would have tooling development complete at 26–28+ (AMC) weeks and first part machined at 30+ (AMC) weeks. The Consortium was able to have tooling development for the locomotive casting completed at 13 weeks and the first part machined at 18 weeks. Similarly, for the AEGIS Tower, the conventional development cycle would have tooling development complete at 17 weeks (AMC) to 70 weeks (USAF). The Consortium was able to have tooling development for the AEGIS casting completed at 8 weeks.

1.5. CONCLUSIONS

Through the experience of this program select team members have witnessed sufficient benefit of applied results that they are working for longer-term collaboration. They developed internet-related tools that were able to shorten the cycle among the members and that have application beyond the casting area. The program has helped insert and demonstrate agile practices within this diverse supplier chain.

2. Activities

2.1. PROGRAM ACTIVITIES

The Agile Castings program focused on increasing the manufacturing agility for dual-use casting acquisitions between distributed design and manufacturing facilities and service providers. The goal of the program was to demonstrate the ability to obtain high-quality, production-ready, sand-molded castings in periods as short as two to four weeks. The core team members, which collectively formed the Agile Manufacturing Development of Castings Consortium, were selected to achieve a complete thread through the design, prime manufacturing and supplier tiers that are needed to complete the development cycle for new castings in both commercial and military environments. The following is a summary of the role for each team member:

GE Corporate Research and Development was the lead team member for the Consortium and directed the management of the program through the Consortium's Executive Committee. GE was also responsible for overall technical management and acted as the system integrator for the program. In this role, GE was responsible for the design, development and implementation of all software-based integration tools, and for the development of functional technologies supporting producibility analysis, casting and pattern design, and validation analysis.

Atchison Casting Corporation was one of two casting suppliers participating as a dual-use casting house. Atchison's St. Joe division performed the role of the vertical integrated steel foundry. In this role, Atchison interacted with the prime component manufacturers and then initiated and coordinated networked interaction and services from the Consortium's second tier suppliers to produce high-quality steel castings.

Clinkenbeard & Associates, Inc. was one of the Consortium second tier suppliers responsible for tooling and rapid prototyping in support of nontraditional pattern fabrication. Clinkenbeard provided network services for pattern making in support of the steel and aluminum foundries and worked closely will all team members on the validation of patterns and castings.

Denison Industries was the aluminum casting supplier for the program. Denison acted as team leader on two major demonstrations of the Consortium's web-based engineering and design tools: the AEGIS Tower (a fabricated steel supporting structure) with General Dynamics being the prime contractor; and a complex aluminum transmission case design and development demonstration with prime contractor Allison Transmission.

General Dynamics/Lockheed Martin participated as the Consortium's military prime manufacturer. General Dynamics acted as the prime contractor in a complex demonstration to apply techniques for rapid and robust manufacturing development to the creation of a large sand-mold casting. Using the AEGIS Tower, the Consortium members successfully conducted a collaborative fab-to-cast conversion demonstration.

K + P Agile, Inc. was another of the Consortium's second tier suppliers and provided network casting process design, analysis, and prototyping. K + P Agile, Inc. was the principal modeler of component parts and provided finite element analysis (FEA) and process simulation results for the team's consideration.

Northwestern University acted as the program's integrating subcontractor during the initial two years of the program, handling finances, communications and reporting for the Consortium.

QuesTek Innovations LLC assumed the role of integrating subcontractor in the last year of the program. In addition to handling finances, communications and reporting, QuesTek's software developers worked closely with GE Corporate Research and Development in the redesign and implementation of next-generation integration tools.

U.S. Army Benét Laboratories joined the Consortium team in the third year of the program. Benét Lab and Watervliet Arsenal have the collective mission of designing and acquiring castings, which will be manufactured into large caliber cannon components. Benét Labs Integrated Casting Design Team participated with the Consortium in demonstrating the capabilities of the program's web-based collaboration system by directing a simulated military component design request and casting acquisition.

The program was authorized on September 16, 1996 under Contract No. N00014-96-T-0001. The total contract value was established at $14,123,880 with an estimated cost to the government of $7,328,932. Table 1 sets forth the program funding allocation for each Consortium member. After award of the contract, both NIFM and Keokuk resigned from the Consortium. NIFM's scope of work and its funding obligation of $210,000 was primarily taken by Benét Lab ($190,000), and the balance of $20,000 was evenly distributed between

K + P Agile, Inc. and Northwestern University. The only other member to resign was General Dynamics. The balance of its scope of work and funding obligation was taken by Clinkenbeard & Associates, Inc. ($67,105) and K + P Agile, Inc. ($67,000).

Table 1 Program Funding Allocation

Consortium Member (* Original)	Original Contract Value	Adjusted Contract Value	Adjusted Funding
GE CRD *	$8,038,715	$8,038,715	
K + P Agile, Inc.	2,113,050	2,190,050	77,000
Clinkenbeard & Associates, Inc.	1,423,140	1,490,245	67,105
Atchison Casting Corporation	655,419	655,419	
Denison Industries	655,419	655,419	
General Dynamics	542,000	407,894	(134,106)
Northwestern University/QuesTek Innovations LLC	359,230	369,230	10,000
National Institute for Flexible Manufacturing (NIFM)	210,000	0	(210,000)
Benét Laboratories	0	190,000	190,000
Keokuk	16,079	16,079	
Total	$14,013,051	$14,013,051	

The total cost to the government for this program is $7,328,932 or 47.7%. Through the completion of the technical effort, Consortium members' cost sharing totaled 48.6%. Final program reconciliation will take place after the completion of this last Payable Milestone.

2.2. TECHNICAL ACTIVITIES

2.2.1. History of the software development

The software industry is perhaps one of the most rapidly changing industries in history. This fact makes the development of a multi-generation software development plan, such as was required for this contract, an extremely difficult task. As the state of the art has changed, so has the technology used in this software development effort. The collaborative software used in this program has gone through four major phases.

The initial software system presented to the Consortium members was a third-party application called BSCW (Basic Support for Collaborative Work). This application provided the ability for users to share documents via the Internet by uploading them to a central server, hosted at GE Corporate Research and Development. The limited capabilities of this system provided an adequate starting point for discussions about other requirements of a collaborative software application.

The next phase of the software development was to prototype some of the additional required features identified by the consortium. The decision was made to build on the capabilities already provided in BSCW by adding components directly to the existing system. The features added to the software were primarily designed to enhance the workflow-type capabilities of the system. The concept of tollgates enabled project leaders to specify points in a casting acquisition at which key members of the team must sign off. This supported project monitoring activities and built a degree of accountability into the system. A specification management component was added to track the critical inputs and outputs for the documents stored on the server. By storing the relationships along with the documents, the system was able to assign a status to each document indicating whether or not the data in that document was up to date. These new features, along with the original document storage and retrieval functionality, provided the basic capabilities required for collaborative work.

After the creation of this initial prototype, the software team paused development activity to reevaluate the current state of Internet technology. Java was beginning to emerge as the programming language of choice among web application developers. In addition, the authors of BSCW had announced that they no longer intended to support or enhance BSCW. As a result, the decision was made to cease work on the BSCW-based system and focus on development of a new, Java-based system.

The first Java prototype was produced very quickly as a "strawman system," which could then be used to obtain more feedback from the consortium members. The system was built by borrowing code from other GE Corporate Research and Development projects as well as third-party software. This incarnation of the system was demonstrated to the Consortium, and a new-requirements gathering phase was begun in which each consortium member was asked individually for suggestions and comments. The feedback provided by the Consortium members was used in development of the fourth and final version of the software.

When the *AC Notebook* was in its alpha phase it was hosted on GE's external web server. The third-party code, as well as code from other GE Corporate Research and Development projects, had been replaced by code written by members of the Agile Castings software team. This allowed the team to address the specific needs of the consortium better, and it also improved the commercialization potential of the software by removing the need for license agreements with outside parties. The system was also tested at each of the consortium member sites, and adjustments were made to the code to improve system performance and ensure correct operation at each location.

The types of data stored in the *AC Notebook*, as well as the relationships among these data types, were decided upon based on numerous discussions among the Consortium members. The software attempts to represent many different kinds of information: the organization of activities within a project; the flow of information from one document to another; and the progress of each project phase. These data are intended to assist a project team in a successful collaborative effort.

The software was then provided to QuesTek Innovations LLC and made available to the other Consortium members. Questek successfully installed instances of the server and, as part of the commercialization phase, added some functionality with regard to the permissions model. With regard to commercialization, Questek plans to use the software as a testbed for further development beyond the end of the project.

2.2.2. Demonstrations and development

AEGIS Tower description and demonstration

The Consortium chose for its first, full casting development activity a component currently fabricated by steel sheet welding. A successful conversion of the part to an aluminum casting would result in a large reduction in the acquisition cycle time, as well as a significant reduction in the piece part cost, based upon current orders for the component. The selected component is the majority of the support structure for the AEGIS targeting radar, installed on the AEGIS-class destroyers and cruisers operated by the U.S. Navy.

This development can be considered a fab-to-cast conversion, although the effort is complicated by the substitution of aluminum for steel. In addition to satisfying a number of specific performance requirements, the part is expected to be a direct replacement for the weldment, including the interface attachment, during assembly.

Description of Part and Customer Requirements

The AEGIS Tower is the supporting yoke for a shipboard targeting radar dish and gyroscopic stabilization hardware. The base houses delicate waveguides and cables, protecting them from incidental and environmental damage. Figure 1 shows this fabrication. In addition to the specific shock, vibration, flexural, and environmental requirements, the casting will be lighter in weight and present a reduced radar cross section compared with the current fabrication.

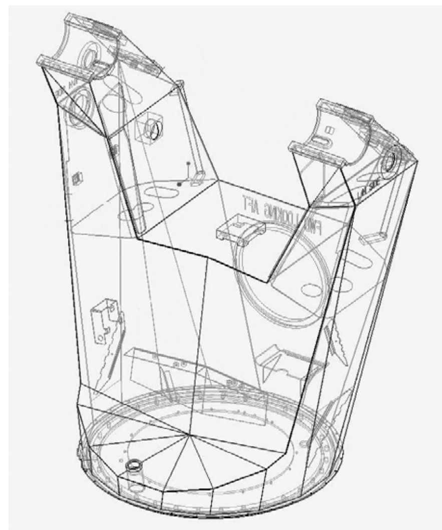


Figure 1. AEGIS Tower fabrication.

Goals of the acquisition (in addition to production volume and delivery terms) were provided to the Consortium by General Dynamics and are enumerated below. The first three goals are product advantages inherent in the conversion from a steel weldment to an aluminum casting. These improved attributes will be used to sell the advantages to General Dynamics' ultimate customer, the U.S. Navy. Items numbered 4–7 are requirements to allow the casting as a direct replacement for the current tower.

1. Reduce weight from 750 to 525 pounds
2. Reduce radar cross section
3. Reduce costs in comparison to the weldment
4. Maintain tower envelope dimensions to IAW weldment specifications
5. Retain tooling points used for production of the weldment
6. Maintain interior passages for cables, waveguides, air ducts, and pipes
7. Meet shock, vibration, and environmental qualifications

Roles of the Consortium members

The AEGIS Tower agile development demonstration encompasses the design and manufacture of tooling for the AEGIS casting. This acquisition is intended to be similar in most respects to conventional casting acquisitions, with some exceptions:

- The principal suppliers are predetermined to be the members of the agile development team, rather than being chosen by competitive selection
- The supplier companies and part customer are expected to communicate using collaborative software tools maintained by the Consortium, when such use is the most appropriate method available
- Documentation of the activities of each Consortium member is to be extensive enough that desirable and undesirable characteristics of the applied development methods and tools can be identified

The entire demonstration cycle, from initiation of conceptual design through final machining of the second viable casting, was estimated to require approximately 13 months (a complete timeline of the casting development cycle prediction listing all functional tasks is given in Figure 2 and Figure 3.)

Prior to composition of this report, the Consortium planned to complete the following tasks:

- Create several casting geometric concepts, and select the most promising for conceptual design
- Pass a formal concept design review at General Dynamics
- Prove through finite element simulation that the concept model casting (less detailed features) would perform acceptably under expected mechanical loadings and thermal conditions
- Completely define the internal and external geometries of the casting
- Create a layered object model (LOM) of the casting design
- Verify through finite element simulation that the proposed design will possess acceptable vibration characteristics and mechanical strength
- Verify through finite element simulation that the proposed design can be assembled and will operate successfully over the possible range of temperature
- Design casting rigging, risers, and gates; and validate with casting process simulation

Atchison Casting Corporation. Atchison Casting Corporation was expected to provide foundry process advice during design reviews. No detailed casting process development work by Atchison Casting Corporation was required, because the AEGIS Tower demonstration casting was not being founded by them.

Clinkenbeard & Associates, Inc. Clinkenbeard & Associates, Inc. were responsible for development of the mold and core patterns for the AEGIS Tower casting, including patterns for the metal feeding system. Included in the pattern development activities during this demonstration phase were the following:

- Selecting and ordering pattern materials
- Programming machining equipment
- Machining, hand-finishing, and mounting patterns (to 80% complete)
- Devising pattern assembly method, including core prints
- Creating scale physical models of the part for review by Consortium members

The final step in pattern development was for Clinkenbeard & Associates, Inc. to validate core fits and ship the equipment to Denison Industries.

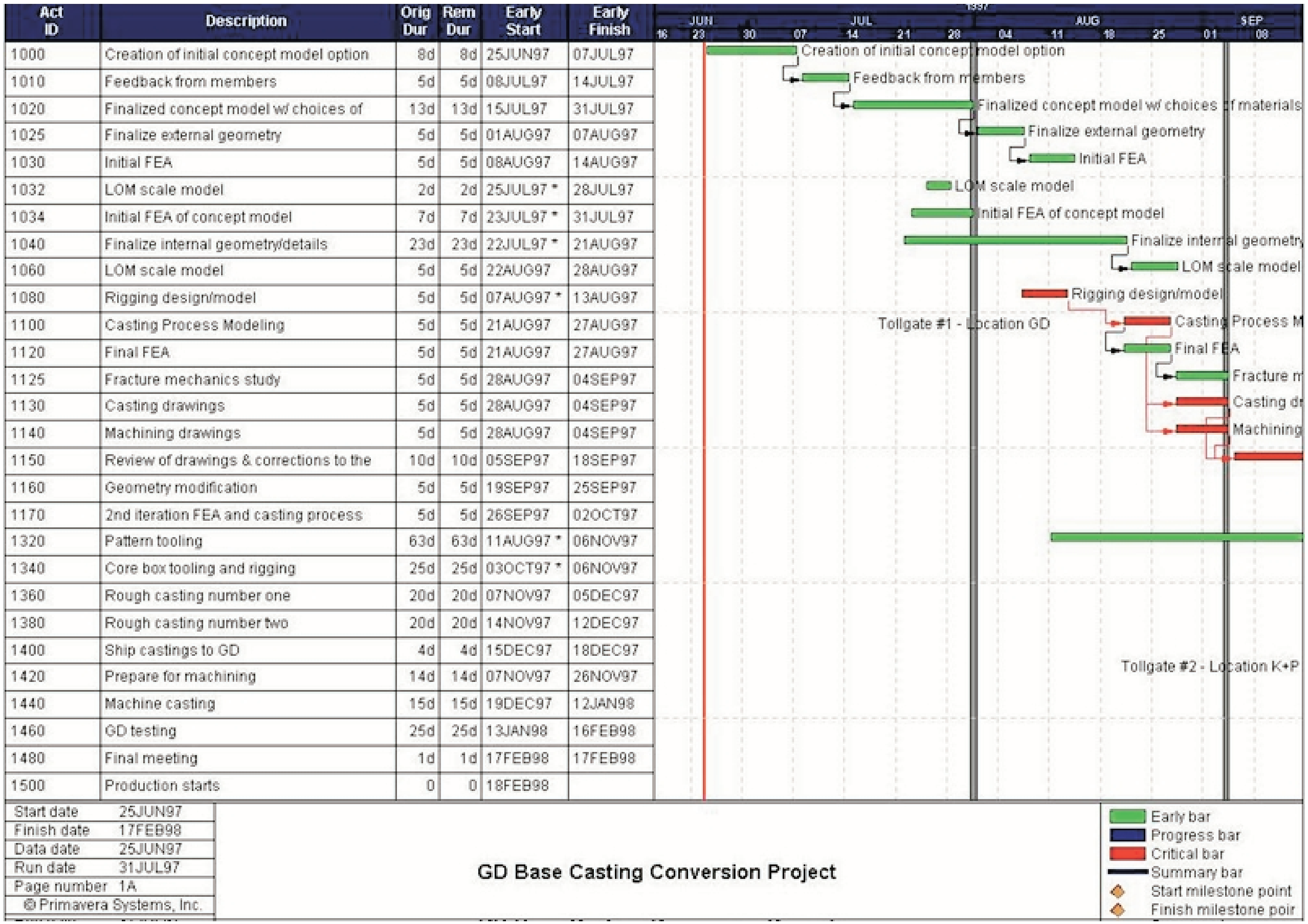
Denison Industries. Denison Industries had principal responsibility for the design of casting processes capable of producing the AEGIS Tower casting and execution of the foundry processes resulting in two viable castings. For this demonstration phase, Denison Industries:

- Design the metal feeding system, with support from K + P Agile, Inc.
- Collaborate with Clinkenbeard & Associates, Inc. in the design of the cores and molds
- Devise a method for melt handling

In addition to the traditional foundry development activities required, Denison Industries communicated casting development information using the collaborative tools of the Consortium, where appropriate, and expend additional effort to maintain a history of communications that are not captured automatically by the software environment (such as telephone and paper facsimile).

General Dynamics. As the customer for the AEGIS Tower casting, General Dynamics was responsible for defining the performance requirements and dimensional constraints imposed on the part, and for establishing acceptance criteria against which the casting can be measured. General Dynamics devised a method for finish-machining and inspecting the finished component and will contract with an appropriate service provider to test the dynamic mechanical behavior of a casting.

General Dynamics provided to the Consortium members relevant documentation describing its internal and external design, development, and procurement processes. These documents are intended to aid General Dynamics' Consortium partners in preparing content for design reviews, as well as formatting casting, machine, and tooling drawings.



Act ID	Description	Orig Dur	Rem Dur	Early Start	Early Finish
1000	Creation of initial concept model option	8d	8d	25JUN97	07JUL97
1010	Feedback from members	5d	5d	08JUL97	14JUL97
1020	Finalized concept model w/ choices of	13d	13d	15JUL97	31JUL97
1025	Finalize external geometry	5d	5d	01AUG97	07AUG97
1030	Initial FEA	5d	5d	08AUG97	14AUG97
1032	LOM scale model	2d	2d	25JUL97 *	28JUL97
1034	Initial FEA of concept model	7d	7d	23JUL97 *	31JUL97
1040	Finalize internal geometry/details	23d	23d	22JUL97 *	21AUG97
1060	LOM scale model	5d	5d	22AUG97	28AUG97
1080	Rigging design/model	5d	5d	07AUG97 *	13AUG97
1100	Casting Process Modeling	5d	5d	21AUG97	27AUG97
1120	Final FEA	5d	5d	21AUG97	27AUG97
1125	Fracture mechanics study	5d	5d	28AUG97	04SEP97
1130	Casting drawings	5d	5d	28AUG97	04SEP97
1140	Machining drawings	5d	5d	28AUG97	04SEP97
1150	Review of drawings & corrections to the	10d	10d	05SEP97	18SEP97
1160	Geometry modification	5d	5d	19SEP97	25SEP97
1170	2nd iteration FEA and casting process	5d	5d	26SEP97	02OCT97
1320	Pattern tooling	63d	63d	11AUG97 *	06NOV97
1340	Core box tooling and rigging	25d	25d	03OCT97 *	06NOV97
1360	Rough casting number one	20d	20d	07NOV97	05DEC97
1380	Rough casting number two	20d	20d	14NOV97	12DEC97
1400	Ship castings to GD	4d	4d	15DEC97	18DEC97
1420	Prepare for machining	14d	14d	07NOV97	26NOV97
1440	Machine casting	15d	15d	19DEC97	12JAN98
1460	GD testing	25d	25d	13JAN98	16FEB98
1480	Final meeting	1d	1d	17FEB98	17FEB98
1500	Production starts	0	0	18FEB98	

Start date	25JUN97
Finish date	17FEB98
Data date	25JUN97
Run date	31JUL97
Page number	1A

Figure 2. Project planning schedule for acquisition of the AEGIS Tower casting, sheet 1.

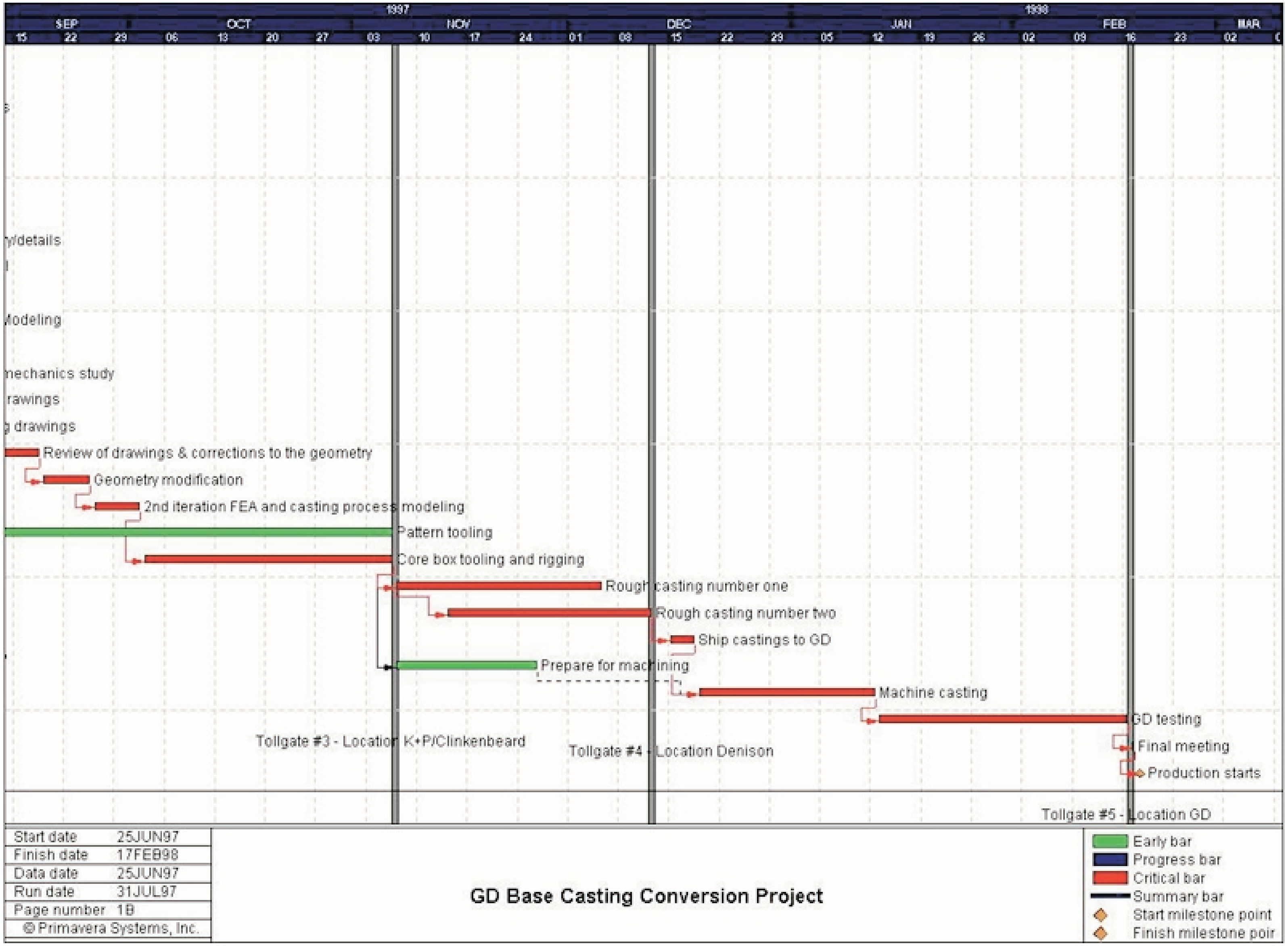


Figure 3. **Project planning schedule for acquisition of the AEGIS Tower casting, sheet 2.**

GE Corporate Research and Development. GE Corporate Research and Development was charged with maintaining and enhancing the collaborative software environment and secure server computer used by the Consortium, as well as administering established and new user accounts. GE was also responsible for capturing design, engineering, and business information "best-practices" recognized by the Consortium, for incorporation in the collaborative software environment and the associated castability database.

K + P Agile, Inc. K + P Agile, Inc. was responsible for delivery of two viable AEGIS Tower castings to General Dynamics within the schedule agreed to by the Consortium. In addition, K + P Agile, Inc. was charged with verifying by simulation that the design conceived will be capable of meeting static and dynamic mechanical loads imposed during normal operation and during exposure to percussive shock. The company was also required to aid Denison Industries in refining and validating the gating, risers, and rigging designs through casting process simulation.

The ultimate capability of the current tower weldment was not always known or specified. For example, thermally induced stresses at the bolt-ring interface with the ship deck mount were not an issue for the welded tower, as the interface is of similar materials. The aluminum tower base, however, requires stress analysis at mounting and use temperature extremes to demonstrate capability of the design.

In addition to performing the engineering analyses, K + P Agile, Inc. was also charged with proving that the software and modeling techniques applied were accurate. A scaled layered object model (LOM) was produced to validate design intent by K + P Agile, Inc. They chose to achieve this by modeling the dynamic and static loading responses of the current AEGIS Tower, and comparing these predictions with those made previously by General Dynamics.

Use of the Basic Support for Collaborative Work (BSCW) Environment

No specific organizational structure was imposed on the BSCW collaborative software environment for use during the AEGIS Tower casting development. The Consortium members were allowed to create groups ("workspaces") nested in any fashion desired, and to add and remove documents to any workspaces to which they had been invited by the workgroup creators.

As the number of contributors and contributions to the repository grew, some use patterns emerged, but were not universal. A number of the Consortium members' contributors organized their files under branching workspace hierarchies, with layers of nested groups, while others created a number of workspaces in the main page that might have contained as few as one file. It was nearly universal practice that users did not insert documents in workspaces created by those in other organizations, or even by others in their own organizations, opting to create new workspaces instead. It was usually true that the documents contained within a given workspace were uploaded by the workspace creator, or members of the same organization as the workspace creator. An example of the BSCW main workspace viewed with the Netscape browser, captured during the AEGIS Tower development activity, is shown in Figure 4. Even to those not accustomed to BSCW, it can be seen that the level of detail employed by workspace creators in naming and describing the workspaces varies; in many cases, the optional explanation field used to impart additional information to the viewer is not used.

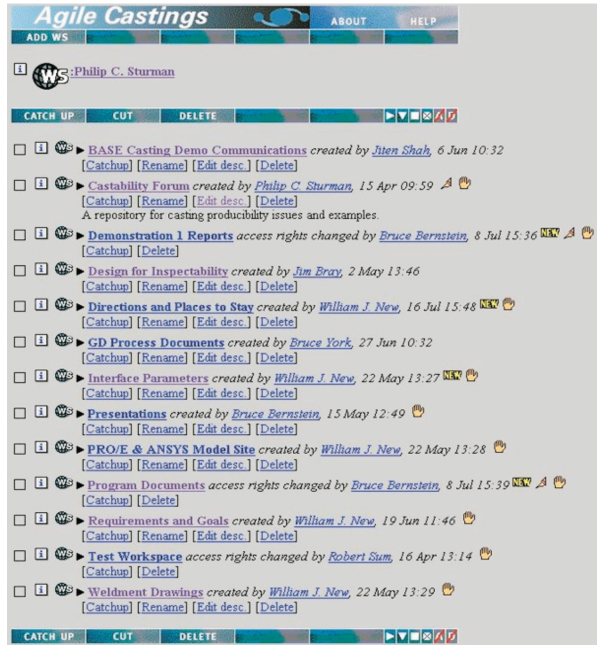


Figure 4. Example of the BSCW main workspace.

K + P Agile, Inc. generated five distinct casting geometry concepts, which were uploaded to the BSCW collaborative environment in 2D graphical interchange file format (GIFF), stereolithography (STL) format, and in the proprietary file structure used by Solid Concepts' Solid Player engineering visualization software. The concept geometries were reviewed by the Consortium, and the castable design concepts that met General Dynamics' objectives was selected for refinement. The latter format allows file viewing without purchasing an engineering analysis or visualization application. Graphics for describing details of the concepts could be annotated easily, and some computations could be performed within the application—especially useful during review of a conceptual model. The five concepts are given in

Figure 5, captured from the solid model viewer. Short descriptions of the concepts are listed below.

AEGIS Tower Casting Concepts

- Option 1—Single-piece aluminum casting, requiring a very large core
- Option 2—Two shell castings of nearly equal size, requiring butt-welding to join
- Option 3—Upper and lower castings, the upper fully enclosed, the lower composed of load-bearing beams wrapped with a sheet metal skin
- Option 4—Two upper shell castings and one lower casting to be butt-welded together
- Option 5—Two upper casting with full skins, to be welded together and attached to a lower composed of load-bearing beams wrapped with a sheet metal skin

The design option finally chosen (option 1) casts the bulk of the tower as a single piece, excluding some small features, such as a foot step and hand rails used to gain access to the interior and upper portions of the tower. When the supplier companies had the opportunity to review the concept, and cooperate remotely to clarify gross aspects of the design, General Dynamics scheduled the concept design review.

Concept Design Review

The concept design review is the first formal, collective opportunity to assess the practicality of a proposed design. It results in one of two outcomes:

- Decision to terminate the product development
- Decision to continue development contingent upon successful resolution of a list of issues, with an associated schedule for resolution

Prior to assembling the product development team, it was necessary to educate members, generate preliminary schemes for development of the casting, and refine the options generated to a narrower product concept. The nature of the efforts required for preliminary design activities depends upon the type of development (new product, fab-to-cast, reverse engineering, or redesign). The demonstration casting is intended to replace an existing product, fabricated of welded plate steel. Relevant documents defining the known performance requirements and geometry of the current product were uploaded to the BSCW collaborative workspace by General Dynamics, along with a list of issues considered critical for the viability of a cast replacement. Discussions were principally by telephone conference, supported by engineering analysis results and computer model representations shared in BSCW. After review of the known requirements and supplier capabilities, the most promising concept for replacement was chosen for review.

Preparation for Concept Design Review

Prior to the concept design review, each casting development team member organization submitted a list of tasks for which it would be responsible during the development. Each task included the expected duration, the requirements for initiation and completion, and a description of what the activity created. The task list was compiled into a preliminary schedule using commercial project management software and shared in BSCW. An agenda for the concept design review was created by General Dynamics that addressed all major concept elements that required resolution to successfully pass the design review.

A physical model of the concept geometry was created by K + P Agile, Inc. and Clinkenbeard & Associates, Inc. to aid discussion during the review sessions. The part was created with layered object model (LOM) equipment from an electronic representation of the concept design. Although many details of the part geometry could not be represented until completion of the structural design, the part interface constraints and approximate envelope were known.

Dynamic and static loading simulations of the current product were performed by K + P Agile, Inc. with conditions already simulated by General Dynamics. The results obtained by K + P Agile, Inc. were the same as those generated by General Dynamics, providing confidence that the mechanical simulation software and methods used in the casting development were free from fundamental error.

It was determined that Denison Industries would provide two casting rigging designs to K + P Agile, Inc. simultaneously. One concept was to be more conservative, with the highest likelihood of producing a defect-free part; the second was to be the most economical, although carrying a greater potential for casting defects.

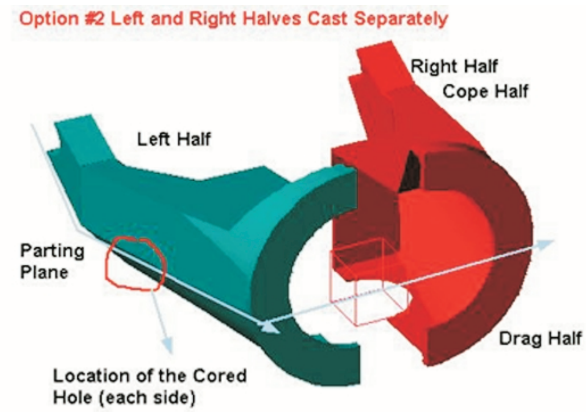
Participants of Concept Design Review

The following disciplines and organizations were immediately represented in all or a portion of the concept design review, which spanned most of three contiguous days:

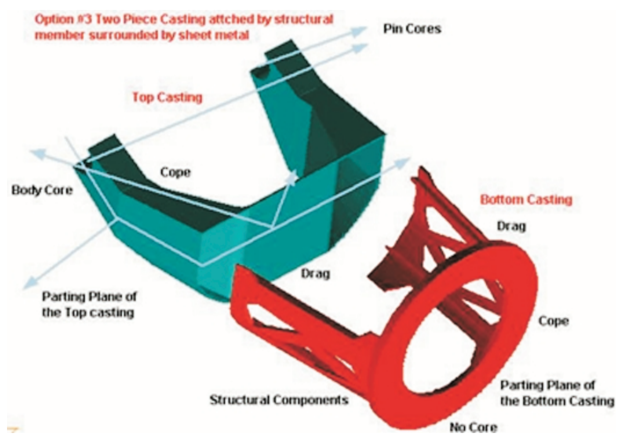
- Product management
- Conceptual design
- Mechanical design
- Foundry process engineering
- Interfacing systems
- Casting quality inspection
- Process simulation
- Patterning technology
- Finish Machining

This level of face-to-face collaboration is not always necessary. Due to the complexity of the part, its size, and

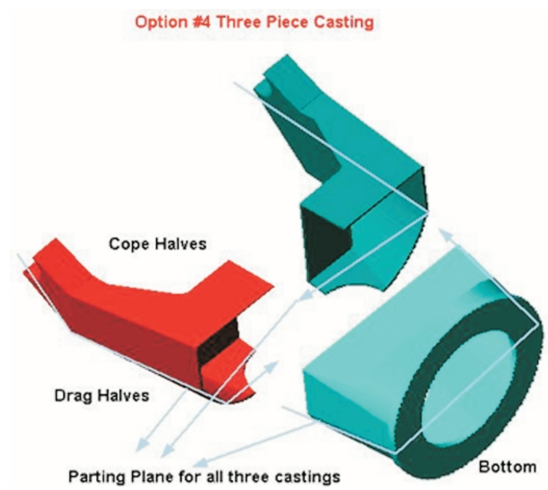
Option 1. The part concept selected for demonstration. Fine part features are not included in this preliminary model.



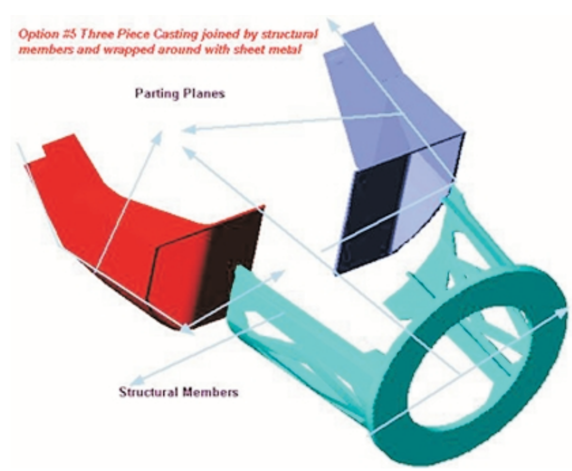
Option 2. A two-piece casting that would have reduced the size of each casting pour. The pair of castings would be poured separately and welded. This instance would have required that a hole be allowed in each piece to support a large core in the trunnion arm. The holes would be covered during assembly by welding.



Option 3. A tower concept composed of an upper shell casting and a lower truss casting to be welded together. The lower truss would be wrapped with sheet metal to enclose.



Option 4. Three-piece shell concept. Although this design would significantly reduce the complexity and risk of the casting, it would require considerable welding during assembly.



Option 5. Two shell arm castings attached to a base truss casting. Although the casting challenge is much reduced, assembly effort is even greater than that in Options 3 and 4.

Figure 5. K + P Agile, Inc. distinct casting geometry concepts.

the need for seamless integration into the current product, the team required was large. For other types of development activities (new product, reverse engineering, etc.), the participants would likely be different.

Activities of Concept Design Review

The duration of the concept design review meeting (three days) was justified by the constraints imposed on the component targeted for casting. The product is required to remain within stringent long- and short-term deformation limits under a number of transient and static mechanical and thermal loads. Specific mechanical vibrations must be limited. In addition, the part environment is corrosive, and a particular appearance is desired. A complication of fab-to-cast conversions is the expectation that the cast replacement will not deviate in performance from the original part, even when the performance criterion is not formally defined. These requirements necessitated extensive collaboration among the consortium members.

The first two days of the concept design review were dedicated to defining and refining the state of the fab-to-cast concept. This involved multidisciplinary discussions, prepared presentations, and observing and documenting a current part in operation. After the development team reviewed the major areas of concern and reviewed experiences from completed fab-to-cast conversions, specific issues were addressed by subgroups in short sessions:

- Performance validation by mechanical simulation
- Process capabilities versus part requirements
- Interface, finish machining and assembly requirements
- Dimensional validation of casting

At the end of the second day, a formal assessment of the known risks was performed, and an abatement scheme was formulated to reduce the risks. The final day was used to refine the development technical specification using the conclusions of the technical subgroups. A formal presentation of the status of the development was made to General Dynamics product management, resulting in a decision to continue the casting development, contingent upon completion of a few tasks.

One foundry process requirement was not resolved during the concept design review. It was not known whether Denison Industries had the capacity to cool the AEGIS Tower casting by air quenching. Foundry air quenching was assessed by Denison Industries after the review. It was resolved after the review that the foundry was capable of processing the part; this conclusion was posted to the BSCW collaborative environment by Denison Industries.

Tooling Design Review

On August 19 a portion of the Consortium met to refine the patterning and foundry process designs. By this time, a flexible rigging concept was selected that allowed considerable alteration of the gating without requiring tooling or process modification. Approaches were discussed for handling fine part features, and details of the patterning and core geometries were decided. The rigging design was communicated to K + P Agile, Inc., along with the foundry pouring conditions. K + P Agile, Inc. built a combined part and rigging software model for simulation of mold filling and metal solidification, to be analyzed with FDM (finite difference method) commercial code. The results were used to guide refinements to the gate and riser positioning to improve the actual casting quality.

Shock

The analyses performed on the steel fabrication included ANSYS analysis of the structure prior to any physical test and a second round of analysis after physically testing the first assembly on a shock table. The scope of the analysis for the aluminum casting was initially laid out to use the measured shock levels and impulse shape as the input for analysis. The goals for the analysis were—

- Ensure that the stress levels stay within the allowable stress levels for the aluminum
- Determine the natural frequencies
- Modify the structure to increase the natural frequencies to above a threshold level

Three iterations of the design were performed in an effort to reduce stress levels at critical areas of the casting.

The basic methodology was to examine output from the finite element shock analysis to determine the areas of high stress (Figure 6).

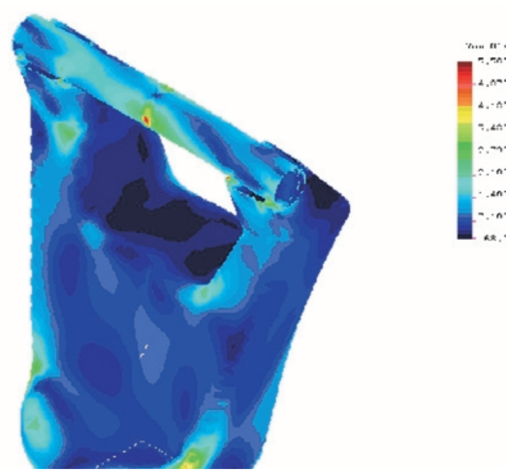


Figure 6. Stress on a deformed shape at time = 0.049 s (deformation plotted to a scale of 10x).

Next, a vibration analysis was performed to determine how the structure deformed. Since the areas of highest deformation coincided with areas of high shock, the structure was modified to eliminate the areas of highest deformation. Then the shock analysis was performed again to verify that the local high-stress areas were eliminated.

Figure 7 and Figure 8 illustrate the deflections that occurred when the structure was in the first and second modes of vibration. In these illustrations, motions are exaggerated. In both figures, the portion of the casting marked “A” is the location of the highest stress level in the shock analysis. Surface deformation is obvious in this area in the illustration. Additional material in the form of gussets and brackets was added to stiffen the areas of high deformation and carry the higher stresses from the skin of the casting to the base ring.

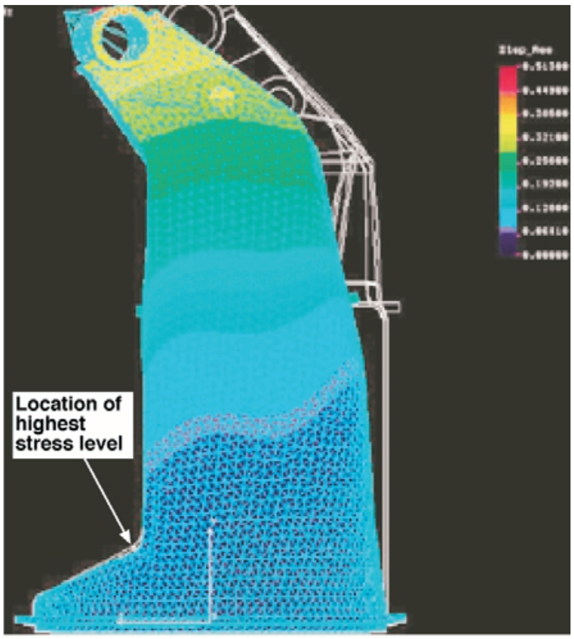


Figure 7. Distortions at high-stress areas (side view).

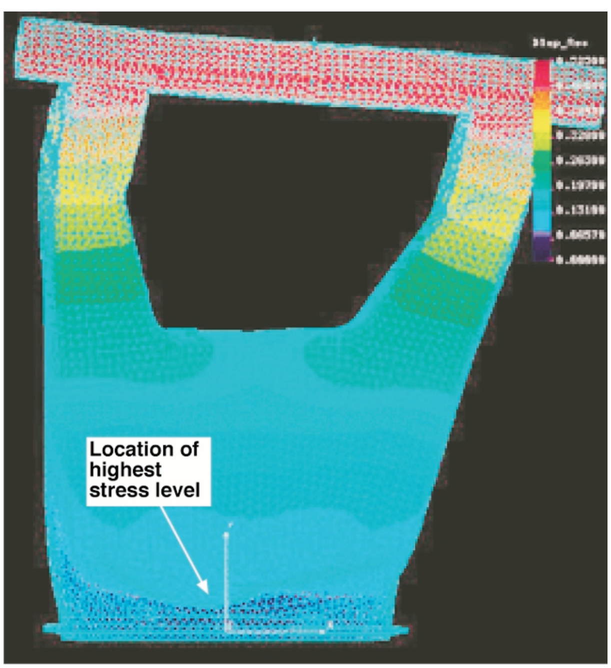


Figure 8. Distortions at high-stress areas (front view).

Since the analysis software is capable of much more detailed stress analysis, as compared to the software used in the original (1970–80) analysis, local areas of high stress were subjected to additional analyses. These areas included bolting details in the upper area (trunnion) and in the lower area (in the vicinity of the base ring).

The increased capability of the modern software led to a much more detailed analysis than the original work. In this demonstration, the scope of the analysis increased significantly during the design process.

Vibration

The goal of the vibration analysis was to analyze the cast structure and modify the design to make the first several fundamental frequencies greater than a specified value. Several iterations of the design were performed, and major changes in the design were incorporated in an attempt to stiffen the structure to achieve higher natural frequencies. The natural frequencies finally achieved were higher than the original design but did not meet the goal.

Additional work was performed to determine what characteristics of the tower controlled the natural frequency. The results of this analysis indicate that the high mass of the structure that the tower supports, combined with the elastic modulus of the aluminum and the geometric constraints, limit the stiffness of the structure in response to vibration. While the design did not achieve the goal, with respect to lowest fundamental frequencies, during tollgate reviews, it was decided by the General Dynamics that the natural frequencies were considered acceptable and that consequences of these lower frequencies would be evaluated further during the test phase.

One of the features of the finite element analysis software is the ability to animate displacement transients. This allows easy visualization of distortions at areas of high stress. Figure 7 and Figure 8 are slides from the animation at the points of maximum deflection. The animation makes the distortions much clearer than the static picture.

Thermal

Concern was raised early on about the ability of the aluminum casting to maintain tight alignment requirements through the range of environmental conditions required for the system. To calculate the ability of the structure to meet the requirements, thermal models were analyzed using the finite element program with the goal of maintaining a radial alignment of ±0.5 min. of arc measured at the location of equipment supported by the tower. In addition, there was a concern that thermally induced stresses may cause unacceptable stress levels at some locations on the casting.

Results of thermal strain analysis, illustrated by Figure 9, indicate that the alignment criteria are maintained throughout the entire range of required temperatures. Thermally induced stresses illustrated by Figure 10 are also found to be very low except in the base ring area.

The increased capability of the modern software allowed a much more detailed analysis than the original work. Detailed stress analysis of the boundary between the tower and the base ring, highlighting the thermally induced stress in this area, was performed. The need for this analysis had not been anticipated when the plan had been laid out. This additional task was performed within the schedule allotted.

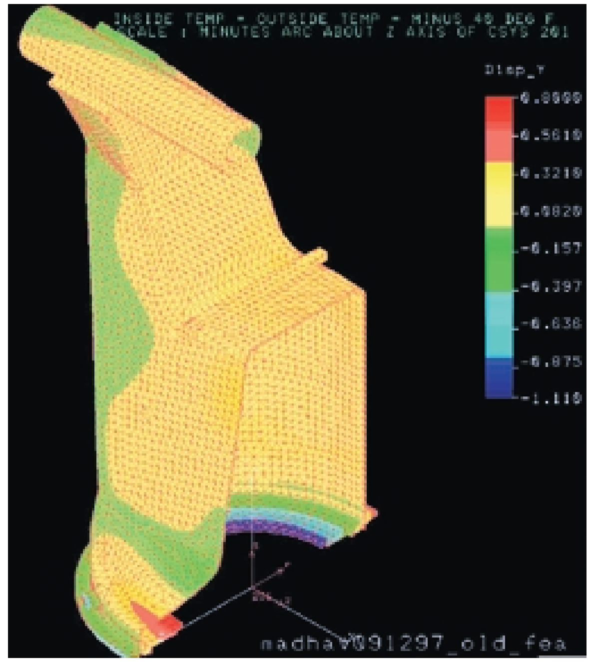


Figure 9. Thermal stress analysis results.

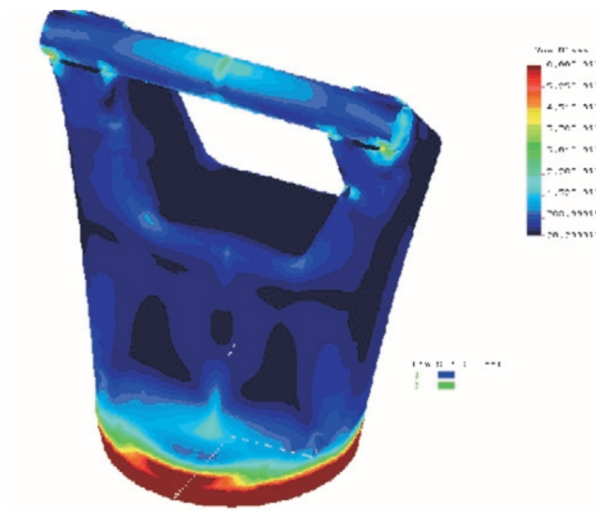


Figure 10. Stress results for combined gravity and thermal loading (initial temp = 55 °F final = 160 °F) scaled down to get better resolution.

Detail Stress

Concerns were raised about the ability of the aluminum material to deal with relatively high local stresses where the tower is bolted to its support and where the trunnion is bolted at the top of the tower. The General Dynamics project manager designed threaded bushings to be inserted in the aluminum casting at these critical areas and local stresses were analyzed in detail in these areas. This type of analysis was beyond the capability of the software available at the time of the original design. Local stress analysis had not been considered a task that was required at the time the program plan and schedule were laid out. However, the analyses were accomplished in time to meet critical milestone dates in the program.

Dimensional Validation

Dimensional validation occurred in two stages. In the initial stage, an existing three-dimensional model of the fabrication was used to develop the faired casting model. The fabrication was "on screen" in one color, and the cast part was built superimposed, so geometric discrepancies "showed through" the part.

The efforts to produce the machine drawings to the same criteria as the original fabrication required detailed verification of the geometry. A plethora of datum planes were required for the machining operations. Resolving the dimensional tolerances and references to datums effectively ensured that the cast part was fully compatible with the part it was replacing.

Both validations were necessary, and neither was sufficient without the other.

Interference

The brackets and gussets inside the casting are significantly different from the support structure inside the original steel fabrication. Several studies were undertaken to ensure that machining and assembly of components inside the casting could be successfully performed with the new arrangement of brackets.

Wireways and waveguides are located inside the tower (Figure 11). Supports for these systems in the fabricated structure tie to features necessary for the structural design of the fabricated tower. Documentation was not available describing the geometry of these internal

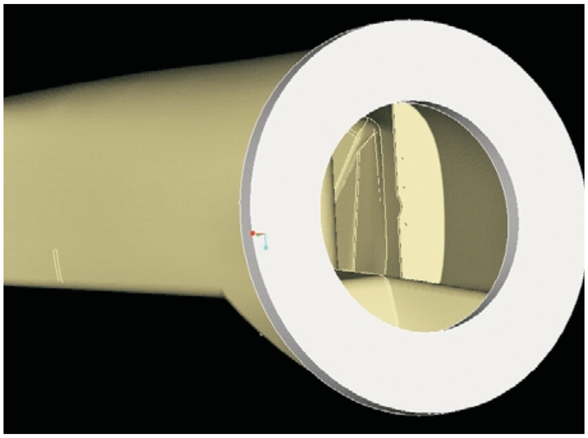


Figure 11. Wireway and waveguide configuration design.

components sufficient to allow design of new support brackets. Support of these components was provided by adding shelf structures inside the tower designed to coincide with support bracket locations in the original design. These shelf structures would likely not have been present had this been an original design. They were required to make the casting fully compatible with the steel assembly it was designed to replace.

Design of Casting Rigging

In parallel with the stress analysis, mold filling and solidification were modeled in order to design the rigging for the pattern by K + P Agile, Inc. Two iterations were required in the gate and riser design in order to achieve satisfactory filling and solidification. Figure 12 is typical output for this analysis.

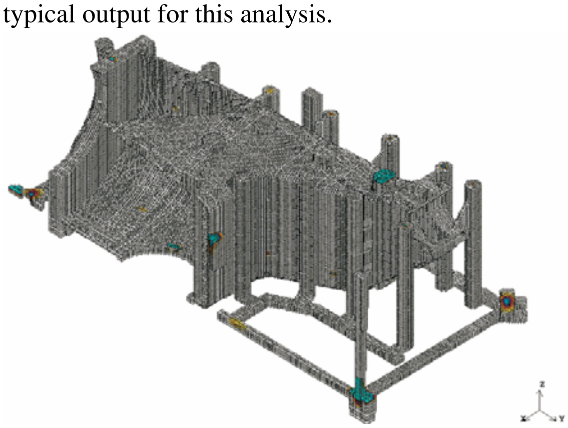


Figure 12. Process simulation model showing rigging approach.

Several meetings using the electronic forum and three meetings face-to-face among the analysis house, pattern shop, and foundry were required to agree on casting details such as parting line, orientation of the casting in the mold, pour rates, and other details of the casting. Results of these meetings were incorporated into the master model and affected the ongoing stress and thermal analyses as well as the mold fill and solidification analyses. The way the master model was employed allowed these parallel efforts to proceed while incorporating ongoing changes in the structure and geometry of the model.

Prerelease/Final Design Review

A prerelease/final design review was held at K + P Agile, Inc. on Oct. 17, 1997. During this review, the decision was made to release the design and commit to tooling.

Release Pattern for Production

The major tollgate to allow start of the pattern fabrication required completion of the technical analysis. This decision required concurrence from a large number of people at the General Dynamics project manager's location. A package was prepared, commented on, and made available to the Consortium members using BSCW. The presentation and signoff of this tollgate occurred at the General Dynamics project manager's location, with representatives from each participating party.

Pattern Development

After approval to proceed, the majority of the team effort focused on pattern construction. A limitation in the processes for exchange of data using electronic media was found. To review fine details of the pattern effectively, it was necessary for a representative of the foundry to see the pattern (Figure 13 and Figure 14).

Several critical issues that affected machining drawings and part geometry were uncovered during these reviews:

- The datum scheme, which appears on the drawing and is the basis for acceptance of the casting, and later for machining the casting, was modified significantly during this phase of the project
- Several paths were added to facilitate handling the casting after "shakeout" (i.e., removal of a part from the sand)
- A feature penetrating the base of the casting was found to be undesirable for the foundry to cast. This feature was modified during the pattern development, and the modification was fed back to the master model

The datum scheme used three cast on pads as the baseline for the scheme. Upon review of the pattern design, Denison Industries recognized that there were sight line interferences to two of the pads, where other parts of the casting interfered with a slight line.

A parallel effort was under way at K + P Agile, Inc. to produce the machine drawings. Other datum issues arose at nearly the same time, which also were resolved simultaneously with the resolution of the pad location. The machine drawing effort was originally to be performed by General Dynamics. This effort was moved to K + P

Figure 13. AEGIS Tower tooling.

Figure 14. AEGIS Tower tooling and layered object models (LOM).

Agile, Inc. to take advantage of the modeling efforts under way there, and to ensure compatibility between the as-cast and the as-machined drawings. Not originally anticipated, this turned out to be a fortuitous decision. Several foundry issues were resolved simultaneously with the datum location issues.

Resolution of the datum issues required major technical decisions, which brought to the table the machine shop at General Dynamics, a new player in the process. The resolution of all the related datum issues followed an iterative process during which K + P Agile, Inc. gained guidance and insight into preparing military-grade documentation. Minor geometry changes to the pattern were required to add or modify material in several areas. In addition, this detail work located errors in the 1972 machine drawings for the fabrication that had not previously been corrected.

AEGIS tower technical accomplishments

Denison Industries

Denison Industries is intimately involved in aspects of the AEGIS Tower casting design that influence foundry methods. Early interaction with K + P Agile, Inc. and General Dynamics helped define the most readily castable option for the AEGIS Tower. Additional refinement was accomplished during the preparation for and duration of the concept design review (CDR). The concerns resulting from the review that were ascribed to Denison Industries were subsequently answered after an internal assessment of foundry capability. Prototype rigging and riser designs were presented by Denison Industries at the subsequent tooling design team discussion hosted by K + P Agile, Inc.

Denison Industries submitted a list of tasks at the concept design review for which it would be responsible during the AEGIS Tower casting development. Each task description included the expected duration and the requirements for initiation and completion and described what the activity created. The task list was compiled into a preliminary schedule using commercial project management software by K + P Agile, Inc. and shared in BSCW. Denison Industries relayed to General Dynamics a list of design unknowns that required resolution during the concept design review to pass the design review successfully.

Denison Industries contributed to refinement of the AEGIS Tower casting concept during the second and third days of the concept design review. Details of the functional requirements and geometric definition were learned by observation of a functioning tower assembly in the General Dynamics test facility. Denison Industries recommended, and General Dynamics agreed, that a number of small protruding features of the current weldment would not be cast directly, to reduce the complexity of the casting.

Denison Industries attended the August 19 tooling design review for the AEGIS Tower casting hosted by K + P Agile, Inc. Denison Industries provided foundry rigging, gating, and riser geometry recommendations for K + P Agile, Inc. to use in casting process simulations. Filling and solidification behavior predictions were later passed from K + P Agile, Inc., and were used to refine the rigging design ultimately to be employed for the first tower casting.

Atchison Casting Corporation

Atchison Casting Corporation contributed foundry process advice during the Concept Design Review. No independent casting development work has been necessary, as the AEGIS Tower demonstration casting is not the responsibility of Atchison Casting Corporation.

K + P Agile, Inc.

Prior to the three-day concept design review hosted by General Dynamics, K + P Agile, Inc. generated a series of potential methods for converting the AEGIS Tower to a cast aluminum product. Denison Industries examined the options, rendered as three-dimensional solids, that were posted to BSCW by K + P Agile, Inc. Upon review of foundry rigging possibilities with General Dynamics, Denison Industries agreed that the concept favored by General Dynamics was castable. Discussions were principally by telephone conference, supported by engineering analysis results and computer model representations shared in BSCW. This agreement allowed the concept design review to be scheduled for evaluation of the single most promising concept.

K + P Agile, Inc. demonstrated that the finite element modeling software it employs for prediction of mechanical behavior of solids generates solutions consistent with the method and software used by General Dynamics, by reproducing the strain behavior results of General Dynamics for the current AEGIS Tower weldment.

FDM-based commercial software was used by K + P Agile, Inc. to predict the filling and solidification of the tower casting. The temperature distribution history and solidification pattern were used by Denison Industries to modify the rigging and riser concepts. An LOM-scaled model was made by K + P Agile, Inc. for the design reviews.

Significant progress was made toward satisfaction of customer objectives (see “AEGIS Tower description and demonstration,” on p. 9):

- The current machined weight of the AEGIS Tower casting is estimated to be between 433 and 500 pounds, comfortably below the target of 525 pounds provided by General Dynamics. The range of weights represents the effects of some internal feature options.
- All exterior surfaces are curved and smoothly blended, which will reduce the radar cross-section compared with the current tower.
- The casting exterior envelope is equivalent to the current tower weldment in all essential dimensions, and all interfaces allow use of existing mounting hardware.

Clinkenbeard & Associates, Inc.

As the pattern maker for the Consortium, Clinkenbeard & Associates, Inc. devised mold and pattern concepts that allowed simple assembly and restraint of the mold and core pieces by the foundry. BSCW was used for communicating with the foundry strategies for implementing the feeding system and securing cores in the mold. Design updates posted by K + P Agile, Inc. were reviewed by Clinkenbeard & Associates, Inc. for their impact on the material and methods proposed for creating the tower mold patterns. Clinkenbeard & Associates, Inc. determined the quantities of pattern stock required, and initiated procurement.

Clinkenbeard & Associates, Inc. prepared for the concept design review and tooling design review by enumerating its responsibilities for the AEGIS Tower casting development, predicting resource and time requirements for its tasks, and creating physical models of the tower casting designs. Clinkenbeard & Associates, Inc. created layered object models (LOM) to aid in visualization of casting features during the concept design review and tooling review meetings.

Scaled layered object models (laminations of paper and adhesive) were produced by Clinkenbeard & Associates, Inc. from Pro/Engineer part files created by K + P Agile, Inc. Conversions of the Pro/Engineer solid models to the stereolithography (STL) format used by the layering machine were performed without difficulty. A one-tenth scale model of the initial tower concept exterior was created for the concept design review meeting, and a detailed one-quarter scale model of the refined design was used in the subsequent tooling review. The layered objects were valuable in conveying requirements for mold assembly, dimensional target fixture design, mounting, and internal access. The Pro/Engineer CAD 3D solid model was used to make tooling on a three-axis CNC machine tool.

GE Corporate Research and Development

GE Corporate Research and Development attended the concept design review and the tooling design review for the AEGIS Tower casting. At each of these meetings GE assessed the strengths and shortcomings of the collaborative software environment as described by the Consortium members. In addition, GE collected and organized casting technical specifications to aid in the design of the collaborative environment for casting acquisition under development by GE Corporate Research and Development.

General Dynamics

The General Dynamics Consortium members replaced their personal computers with machines equipped with 64 MB of dynamic memory, using the Windows NT operating system. This upgrade resolved all upload/download issues to date.

General Dynamics has made extensive use of the BSCW collaborative software for posting of information specific to the AEGIS Tower designs and general engineering documentation developed by them. The postings included the following:

- Computer-aided design models of the current tower weldment
- Finite-element model simulations of the mechanical behavior of the current tower
- Performance specifications for the proposed tower casting
- Graphical and text descriptions of internal company product development sequences
- Design and manufacturing development checklists
- Company-approved testing and validation methodologies for components and systems

The AEGIS Tower casting development was successfully supported through the formal concept design review and tooling design review. General Dynamics supplied and interpreted performance specifications as well as testing and validation requirements.

AC locomotive casting description and demonstration

MWM in Germany designed the locomotive casting and provided prototype tooling which was available at the start of the Consortium involvement. Though several castings had been made at the ductile iron foundry with this tooling, it was clear that castings with acceptable quality could not be made. These castings were on the GE Transportation Systems (GETS) critical path for launching a product and delays in manufacturing development threatened product launch. The Consortium approached GETS to offer agile development of production tooling to reduce the cycle-time risk and to demonstrate the impact of agile manufacturing on castings development. The Consortium task was to develop tooling suitable for reliable mass production of high-quality locomotive castings and to validate this tooling with two prototype castings. Approval was received from DARPA to demonstrate the agile manufacturing approach on the GETS casting under contract funding.

Description of Part and Customer Requirements

The GETS Integrated Front End (IFE) part is a large, complex, ductile iron sand casting. It is mounted on the locomotive engine crank case and is an integrated unit designed to provide cooling and lubrication of the attached turbocharger. A photo of the casting is shown in Figure 15. Both functional and structural demands are placed on the IFE casting. The surface finish must be smooth for required fluid flow through the passages while the material must contain the fluids under pressure without leakage. The casting, which encloses the heat exchangers, must be strong to support the turbocharger during use, yet light to satisfy engine performance requirements. Therefore, the design specifies a thin-walled casting with complex structures and the requirements demand tight dimensional tolerances and high material quality. The expected weight of the IFE in its final form is about 2300 lb and it measures $50'' \times 55'' \times 40''$.

Figure 15. Photo of integrated front end (IFE) casting.

Roles of consortium members

The established infrastructure and collaborating team of the consortium provided the foundation for the agile casting development cycle. For the GE demonstration casting, the key members were GE Corporate Research and Development, the analysis house K + P Agile, Inc., and the pattern maker Clinkenbeard & Associates, Inc. The ability to rapidly prototype the very large and complex thin-walled casting was key to the successful development demonstration.

GE Corporate Research and Development. GE's role was to lead, plan and schedule the demonstration development. GE also provided resources to monitor, evaluate, and stabilize the foundry practices and to modify, improve, or enhance the casting design or the casting process as needed. In addition, GE maintains the collaborative computer environment and was responsible for adapting the environment to address needs that evolved during the casting development demonstration.

K + P Agile, Inc. The design and analysis house of the consortium, K + P Agile, Inc. was responsible for converting the available 2D CATIA casting design into a 3D Pro/Engineering geometric model of the casting, for use by Clinkenbeard & Associates, Inc. in creating the production pattern. In addition, by performing casting process simulations, K + P Agile, Inc. was to identify critical parameters of the part and support the casting vendor in selecting optimum process parameters by analyzing effects of modifications to the rigging and other variable conditions.

Clinkenbeard & Associates, Inc. The pattern maker of the consortium was responsible for rapidly prototyping the casting based on a 3D model provided by the analysis house. This was done by creating physical models for design reviews before building the production pattern.

Roles of non-consortium members

It was necessary to partner with non-consortium institutions to acquire the casting. This provided the opportunity to demonstrate that the agile manufacturing environment developed under this program could easily be extended to an arbitrary casting process outside the consortium. GE Transportation Systems paid the non-consortium partners for their work, the Agile Program did not. However, the institutions were used as resources by the Consortium and served as test beds from which lessons learned were extracted for later incorporation as "best practices" in the collaborative software environment.

Teledyne Casting Services. TCS was the ductile iron foundry responsible for casting the IFE. TCS also provided guidance in the rigging, riser, and gating designs, advised on metal composition, and prepared the cast part for machining by removing the rigging. In addition, TCS made minor modifications to the prototype pattern when needed.

Bley Engineering. Bley Engineering was responsible for machining the casting for final assembly. In addition, Bley Engineering provided dimensional measurements of the part and facilitated preliminary nondestructive evaluation of the casting.

MQS. Radiographic examinations were provided by MQS to nondestructively evaluate casting quality as requested by TCS or Bley Engineering.

Arms Industries. Arms Industries is a pattern shop that supported the GETS casting effort with necessary modifications to the prototype pattern.

GE Transportation Systems. The casting customer, GE Transportation Systems, communicated the design, performance and acceptance criteria to the supplier team and maintained revision control of changes to the drawings.

MWM. As the part designer, MWM reviewed and evaluated proposed changes to the design. MWM also updated the CATIA drawings to reflect approved changes.

Chronology of the tooling development

Responsibility for development of the integrated front end casting was given to the Consortium in June of 1997. At that time, limited-use tooling for casting sample parts had been produced and delivered from a German pattern maker to Teledyne Casting Services in La Porte, Indiana. The pattern included no rigging or risers, although a number of gates had been included by the pattern maker. The foundry had executed a number of pours of the casting using disposable, hand-cut rigging forms composed of polystyrene foam and ceramic tubes.

Although none of these early castings exhibited the requisite casting integrity, GE Transportation Systems was able to learn by measurement and machining of the samples that the pattern possessed several flaws:

- A number of features were missing or misplaced
- Machining stock was inadequate to accommodate casting tolerances
- Core prints were not effective in positioning and restraining several cores

Because of these difficulties, and the expectation that the IFE design would continue to evolve, the Consortium determined that three-dimensional software models of the casting and production tooling would be required. This step, which might be considered unnecessary, given the existence of a two-dimensional engineering representation, was deemed important to ensure that the earlier experiences were not repeated, and to allow the new tooling design to be rapidly altered. In addition, the casting solid model could be used as the part geometry for process simulations, which were needed to guide improvements in casting integrity.

The event history of the Agile tooling development is displayed in Figure 16. After introduction of the Consortium, GE Transportation Systems, and the foundry, approximately one month elapsed, during which time the Consortium

- Obtained part files and drawings from Deutz MWM
- Initiated a casting design review
- Participated in a foundry process review
- Facilitated a failure modes and effects analysis (FMEA) of the current casting process
- Measured critical dimensions of an assembled mold

During the first week of August 1997, K + P Agile, Inc. began creation of solid models of the cores and molds, using IGES translations of the CATIA files secured from MWM through GE Transportation Systems. Due to scaling inconsistencies in the electronic representations created by MWM, the CATIA files were found to be unreliable, and could not be used to speed

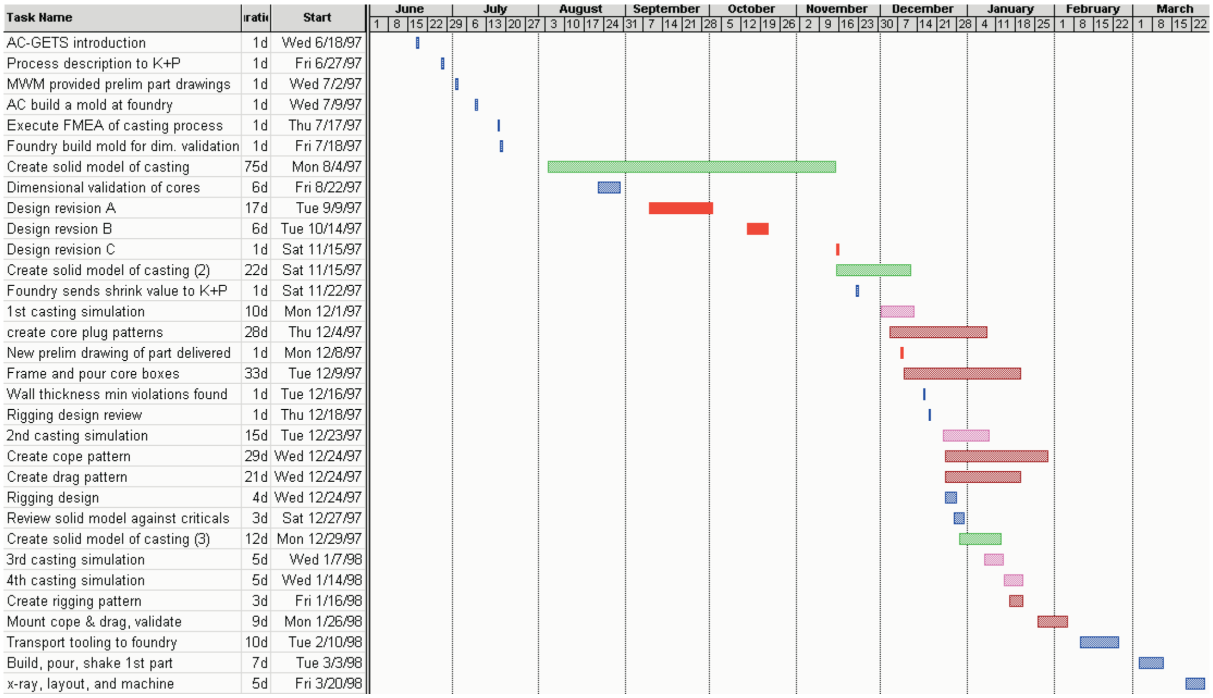


Figure 16. Event history of agile tooling development.

creation of the 3D model. K + P Agile, Inc. was forced to abandon the MWM computer-generated geometry and use physical drawings of the part to build the 3D model.

During an August break in the sample casting development at TCS, Clinkenbeard & Associates, Inc. took possession of the core tooling and created core impressions. These polymer "cores" were used to verify the prototype tooling geometries, aiding the computer model building activity at K + P Agile, Inc.

Three significant design revisions were incorporated into the solid model in the period spanning from August through November. These included the addition of four small cores, replacing an existing core with two smaller pieces to aid mold assembly, and altering the locations and dimensions of several bosses. In addition to the engineering changes requested by GE Transportation Systems and the foundry, K + P Agile, Inc. identified more than thirty drawing omissions or errors that could only be resolved by communication with the design owner at Deutz MWM. The combined design revisions resulted in an extension of the solid modeling effort into November. Among the limiting factors for completion of this phase of the work were the time delays required to obtain authorization of the decision-makers in the project for technical changes. Authority for technical decisions was shared, which added confusion and reduced consortium efficiency.

Upon completion of the draft solid model, a number of model deficiencies and further engineering revisions were identified. The subsequent modifications required an additional four weeks to complete. By this time, however, the design was stable enough that pattern stock could be prepared, and some CNC toolpaths created. In addition, the casting model was ported by K + P Agile, Inc. to casting process modeling software, and the first process simulation was executed in December.

During the months of December and January, Clinkenbeard & Associates, Inc. created the IFE tooling, which included ten core boxes and the cope and drag mold patterns. While the tooling was being machined, Clinkenbeard & Associates, Inc., K + P Agile, Inc., and TCS finalized the rigging design, cast the pattern plates, and delivered the plates to a contracted machine shop.

Although the impact on tooling schedule was modest, additional tooling costs were accrued by Clinkenbeard & Associates, Inc. to recover from a single documentation error that affected several cores as well as the cope and drag. The risk associated with proceeding with the design to this depth was judged to be worth the potential significant schedule reduction. The nominal wall thickness, to be applied to all unreferenced casting walls in the IFE design, was incorrectly stated on the drawings obtained from MWM, and was used by K + P Agile, Inc. to create the casting and tooling solid models. Additional processing of some core patterns was required to adjust the core surfaces to as-cast dimensions, as some core surfaces were inadvertently modeled with final machined dimensions.

Mounting the cope and drag patterns and validating their orientations and positions required a full week, due to the size of the equipment (each plate weighs 14,000 pounds). Shipment of the tooling to the foundry was effected in stages over a period of two weeks. The core boxes were needed by the foundry in advance of the cope and drag, and so were shipped earlier.

Core fabrication was begun the second week in February 1998, followed by cope and drag molds, with the first part poured, shaken (after in-mold cooling), validated (x-ray and dimensional layout), and machined by the second week of March.

Stabilizing foundry practices

The early Consortium emphases were on capturing the current TCS foundry process and identifying root causes for the producability problems. The casting defects ranged from serious dimensional inaccuracies and misruns to thin walls and sand corruption. Agile team members, present at the foundry during the casting process, uncovered numerous technical issues that then were resolved, captured as lessons learned, and converted into best practices. These best practices impacted both the production tooling development and the foundry practices and will be incorporated in the collaborative environment to aid in later DOD casting acquisitions.

A serious shortcoming of the available tooling was the inability to provide a stable and repeatable core setting process for mold assembly. The cores would also move or float during metal pour, resulting in significant changes in wall thicknesses in the cast part.

Because the rigging had to be built "by hand" each time a new casting was poured, the casting process itself was unstable. The mold assembly difficulties were so serious that the molds could only be assembled under the supervision of one specifically trained individual at the foundry. Figure 17 is a photo of the assembled cope mold. The styrofoam rigging can be seen surrounding the pattern.

Two of the major improvements made for the production tooling design were that: (1) the pattern was mounted on a rigid baseplate and (2) the rigging and gating system became part of the pattern itself. K + P Agile, Inc. simulated the effects of different rigging geometries to guide the final design. GE Transportation Systems paid Arms Industries to validate the concepts by adding a baseplate and incorporating the rigging with the prototype tooling. The quality of GETS' castings improved significantly as a result, and these improvements were incorporated in the production tooling pattern (Figure 18).

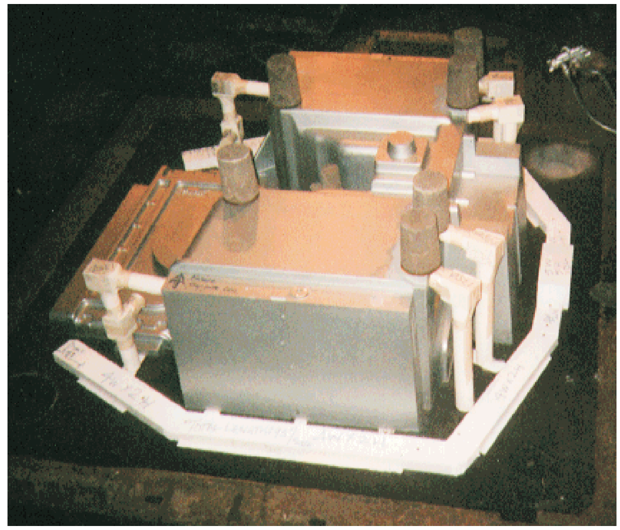


Figure 17. Cope-side rigging assembled in preparation for metal pour.

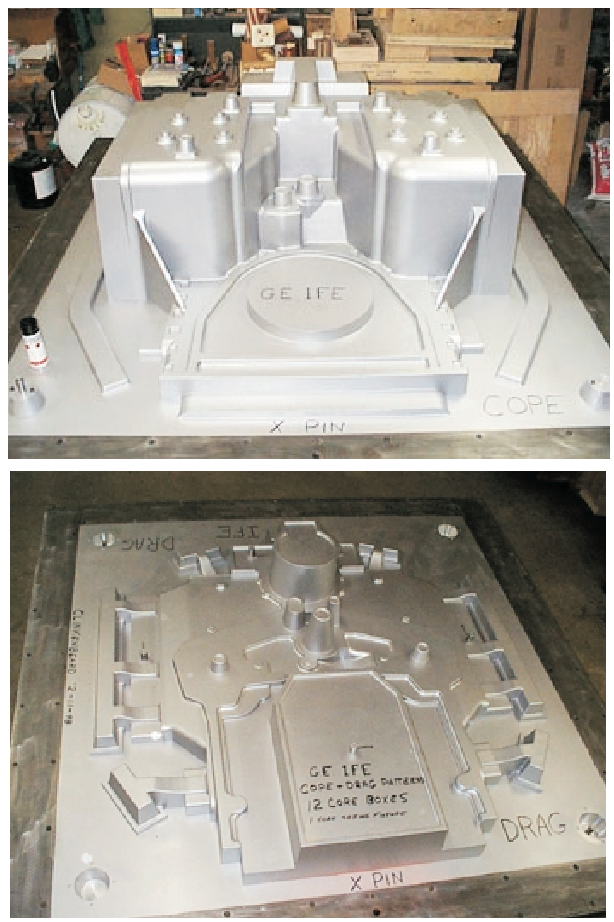


Figure 18. Cope and drag patterns.

In order to stabilize the core assembly, Clinkenbeard & Associates, Inc. made major modifications to the original core designs. Some cores were drastically changed to provide an interlocking assembly that would not float during metal pour. Clinkenbeard & Associates, Inc. built several physical models to demonstrate and evaluate these changes. LOM technology models were built to scale based on CAD models created by K + P Agile, Inc. These models were cut up into several sections and were invaluable in evaluating the part design and the CAD model accuracy. As a result of the new core assembly design, the core setting process at the foundry was simplified and required less operator training.

Casting design changes to accommodate robust machining

Early in the development cycle, Agile team members evaluated the machining process at Bley Engineering and identified several part features that jeopardized the quality of the final casting. Some of these features forced unreasonable tolerances on both the casting and machining processes. As an example, the small size of a single boss hampered the ability to accommodate slight warping of a casting by making small machining alignment changes, resulting in a scrapped casting. This resulted in a design change of the bosses to permit minor changes in alignment during the machining. Figure 19 shows the small, separately shaped bosses of original design and Figure 20 shows the new design. The latter bosses are flat as well as wider and deeper. Small, individual bosses have also been combined into a single large boss.

Other areas of the casting needed more stock to prevent breakthrough during the drilling process or less stock to reduce the machining time. The castings were also evaluated for shrink and porosity at the machine shop. This led to redesign of the venting and riser approach for the casting. The feedback from the machine shop was critical in developing castings that can be subjected to automated machining, necessary for large-scale production. Where possible, at GE Transportation Systems' expense, changes were implemented in their prototype tooling and resulted in a much improved yield of their prototype castings.

As design changes were identified and recommended by the Agile team, they were communicated to MWM through GE Transportation Systems engineering. After MWM had verified that the proposed changes would not contradict the casting design intent and approved them, GETS would revise their original drawings to reflect the changes. K + P Agile, Inc. would then incorporate the changes in their CAD models and analysis software and communicate the changes to Clinkenbeard & Associates, Inc. so they would be reflected in the production tooling. GE Corporate Research and Development would capture "lessons learned" from the changes when appropriate.

Figure 19. Original boss design—note small round center boss, a critical feature during machining.

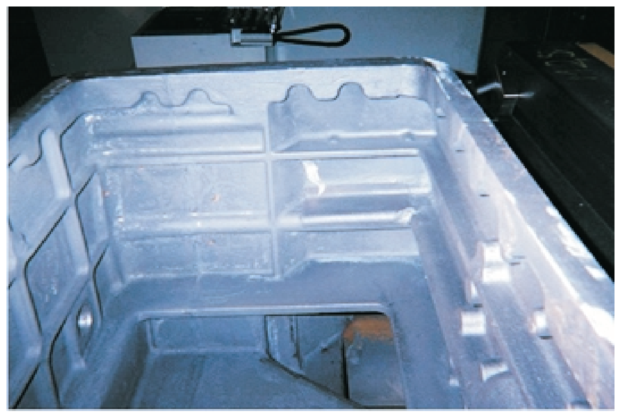


Figure 20. New boss design—rectangular shape permits small machining offsets.

CATIA to Pro/E model conversion

K + P Agile, Inc. began creation of the machined part solid model by interpreting IGES (Intermediate Graphics Exchange Standard) geometry files from the Deutz MWM part model made in CATIA. The drawings were preliminary, and suffered two revisions during the period that K + P Agile, Inc. was involved. Initially, attempts were made to use the IGES geometry files as input to Pro/Engineer. After some effort, however, complete translation was found to be impossible. The difficulty was traced to internally inconsistent use of cartesian axis scaling in the original representation by Deutz MWM, which could not be repaired with certainty. It became necessary for K + P Agile, Inc. to add dimensional inputs to the solid model using

manually determined measurements from scale drawings

- physical measurements of the core plugs made by Clinkenbeard & Associates, Inc. from the prototype tooling
- measurement of an IFE casting (in semi-machined condition).

- These physical measurements significantly increased the effort level required to create the casting model geometry.
- The solid model was created by generating a solid possessing the casting exterior surfaces, and performing boolean operations with the core solids. The final model is large (120 MB of file size) and has more than 1200 features; it was built using Pro/Engineer releases 18 and 19. Drawing inconsistencies and discrepancies were noted during creation of the solid model, and resolved in a sequence of discussions with GE Transportation Systems and Deutz MWM. A list of geometric modeling issues resolved by the Consortium are given in Appendix B. The sequence of interactions among K + P Agile, Inc., Deutz MWM, Clinkenbeard & Associates, Inc., and GETS were extensive and numerous, due in part to ambiguous and conflicting dimensions in the MWM drawings and several design changes requested by GETS. The most significant discussions are presented in Appendix A.

After the second iteration solid model was validated against MWM drawings, it was used to create cutter path for tooling. Subsequent changes (drawing related and design related) were incorporated into the solid model and tooling concurrently. A third iteration of solid model was furnished. There were more drawing and design-related changes, which were incorporated only into the tooling but not in the solid model. The solid model was updated after the tooling was made, and the first article was produced. Images of the solid models of the IFE casting, cores, and core-casting assembly are given in Figure 21.

Process simulation

Although the casting solid model continued to evolve after the completion of the first preliminary design, the computer model was stable enough that a geometry for process simulation could be used. Four casting and solidification simulations were executed to guide improvements of casting quality. The process simulations were focused on the parameters under control of the foundry and pattern maker, rather than part design. Because the process simulations were not used to guide part design, this experimentation was performed in parallel with the casting tooling design and part modifications.

The first simulation was an attempt to emulate foundry conditions using the prototype tooling at Teledyne Casting Services. Melt physical properties, pour rate, metal temperature, chemical composition, rigging, risers, and vents were defined from measurements of foundry conditions and the existent feeding system. The prototype rigging possessed a controversial feature: six elevated “step” gates were included to increase filling of the casting horizontal walls near the end of the pour, and to assure that the metal at the top of the casting was not cold compared to the bottom (which would lead to excessive free convection and unpredictable solidification progress).

Casting experiences of the Consortium suggested several changes that would be beneficial, even before the first simulation was executed. K + P Agile, Inc. expected that the following actions would be supported:

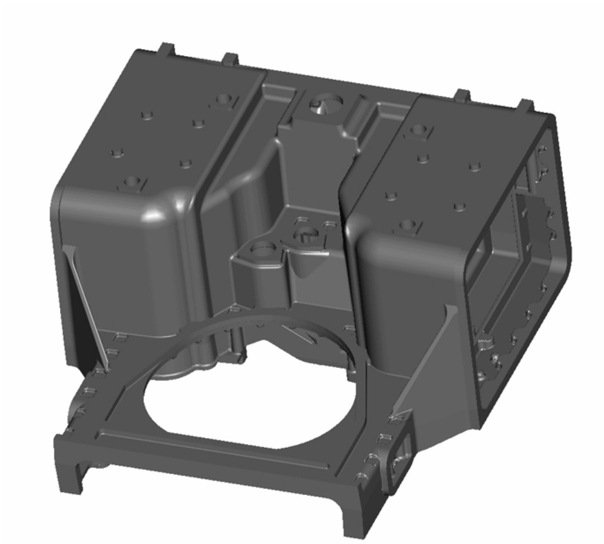
- Bottom gates could be increased in size, resulting in fast and stable filling
- Step gates should begin to deliver metal when 1/3 of the casting has filled (early fill leads to splash, late causes air entrapment)
- Different sprue:runner:gating ratio (1:2:2; 1:3:3; 4:8:3; etc.) would reduce slag
- Rigging should be changed where laminar flow was not attained
- Current venting and risers were not effective
- Metal delivery should be redistributed

First Simulation Results. Examination of the thermal and solidification histories provided justification that several aspects of the prototype rigging could be improved. Comparison of the results of castings made with prototype tooling showed that defects found in several of the castings correspond to undesirable melt temperature distributions and solidification progress. The simulation demonstrated that:

- Metal is not delivered through the step gates until 90% of the total weight is poured
- The step gates remain hot after filling is complete
- Step gate entrances are molten after the casting has solidified (metal will be pushed through them by graphitic expansion)
- The coldest place after filling is the top side of the casting
- The risers solidify too quickly
- Shrink occurs at both lower and upper sections

Some simulation graphics are presented in Figure 22. Possible problems identified from the first simulation:

- Improper riser shape and temperature—Riser is too cold
- Sprue taper should be considered—sprue is not full, all metal come into ingates immediately, causing high gas back pressure from step gates
- Gating ratio needs adjustment—moderate pressure drop from runner to ingates should be established. Runner area total should be bigger than sprue for smooth flow and slag reduction



View of the IFE casting solid model. Note openings of fluid passages formed by cores through the casting.

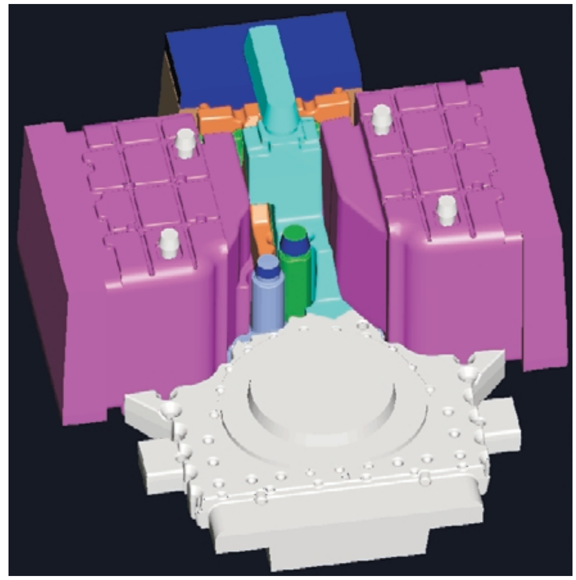
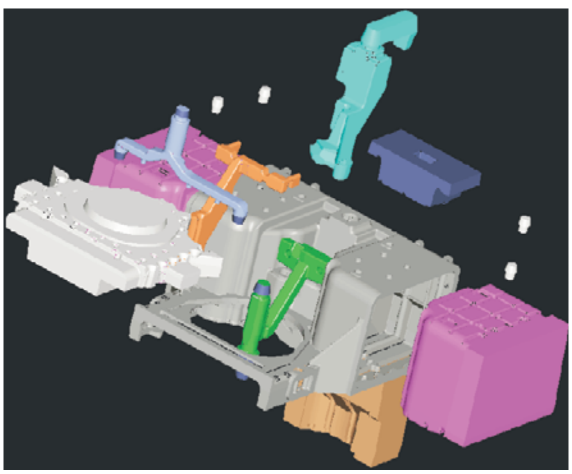
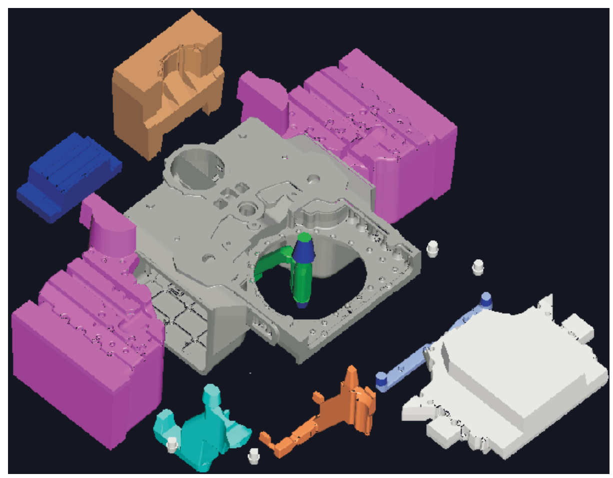


Image of the IFE cores in assembled positions without the casting solid model. Note the small distances between cores.



The IFE cores in an exploded view with the IFE casting solid model. The cores are shown removed from their encased positions to show geometric detail.



The IFE casting and cores in an exploded view, reverse side of the IFE casting solid model. Note the large number of bosses and cored holes.

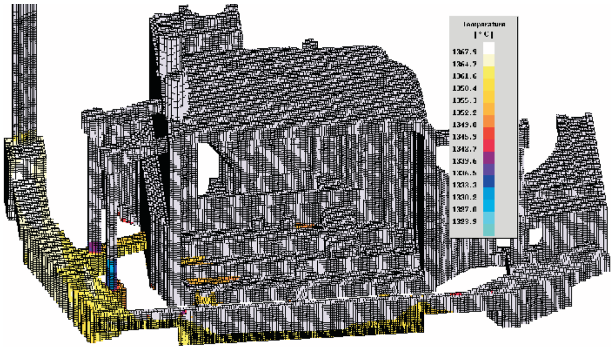
Figure 21. Solid models of the IFE casting, cores, and core-casting assembly.

- Improper riser neck shape—neck may not provide good feeding channel to casting
- Improper position of chills—chill under risers promotes poor solidification front control
- Not enough venting—large back pressure occurs from gas generated during the metal pouring
- Improper metallurgical control—carbon and carbon equivalent were not enough in several regions

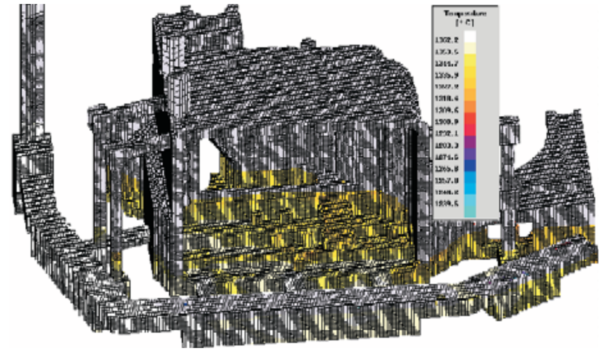
Recommendations from the first simulation. •Section risers from the prototype castings and cut them to see if piping occurs

- Use simulation results to adjust the pattern of solidification
- A subsequent simulation should be performed with no step gates in the feeding system
- Riser should be hotter to deliver molten metal to casting

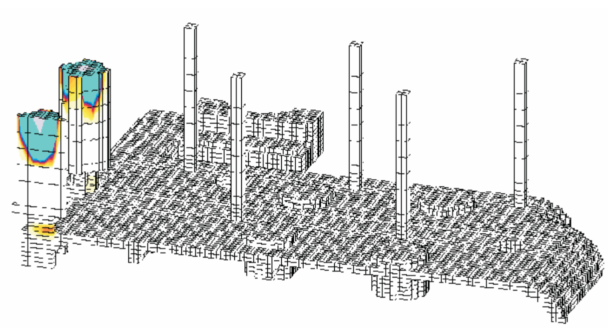
Second simulation.
Knowledge gained from examination of prototype castings, actual foundry conditions, and the first process simulation guided the selection of process parameters



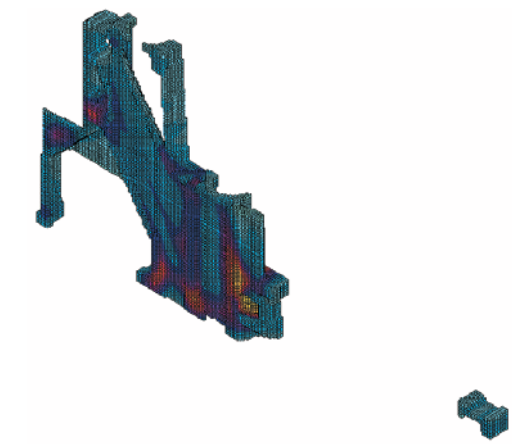
Temperature distribution with 20% of the mold filled in the first simulation.



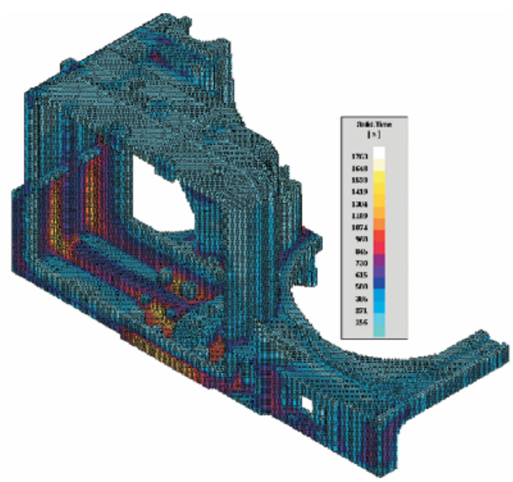
Temperature distribution with 50% of the mold filled in the first simulation.



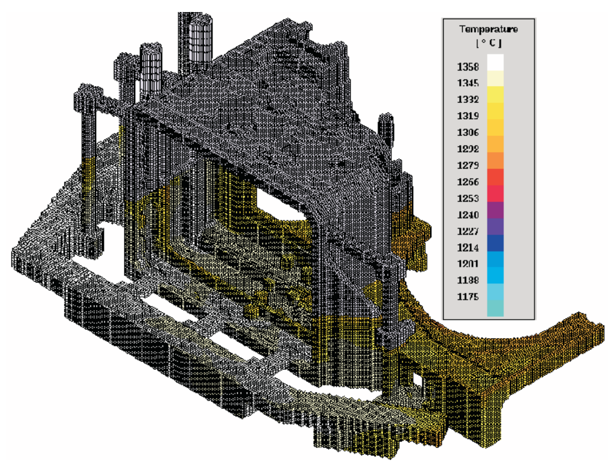
Temperature distribution with 80% of the mold filled in the first simulation.



Riser feeding pattern in the first simulation. Note contraction at riser necks.



Casting solidification time in the first simulation, showing shrinkage at the bottom.



Casting solidification in the first simulation, showing water and oil passage shrinkage.

Figure 22. Casting process simulation graphics.

for the second casting process simulation of the integrated front end casting. The changes from the first simulation were

- Sprue:runner:gate cross-section ratio changed to 4:8:3, and step gates were removed to produce moderate pressure at the gates. Without step gates, filling will be slower.
- Runner bar in drag side for fast and smoother fill, ingates on cope
- Vents added to the top of the casting
- Composition changed to C-3.6, Mn-0.3, S-0.01, Si-2.60, Mg-0.06, P-0.04, Cu-0.2

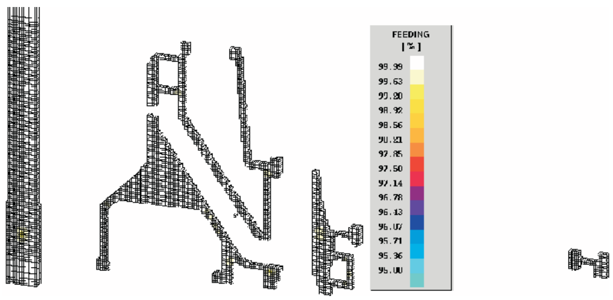
Second simulation results. Casting quality showed significant improvement in the second simulation. In particular, risers feed the casting effectively.

- Solidification is rapid and the pattern shows fewer isolated hot sections. The area of the oil and water passages cool more slowly and may have minor porosity

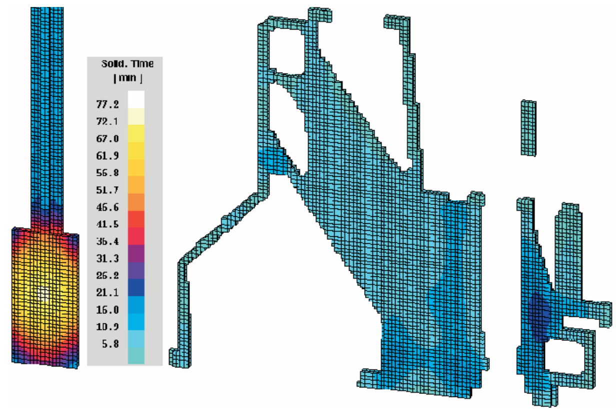
Still, some conditions were noted that would likely compromise casting quality:

- An area of the casting bottom cools slowly. This is the result of a thick wall and hot metal at the lower level.
- The filling time is very slow. Gating system pressure should be increased.

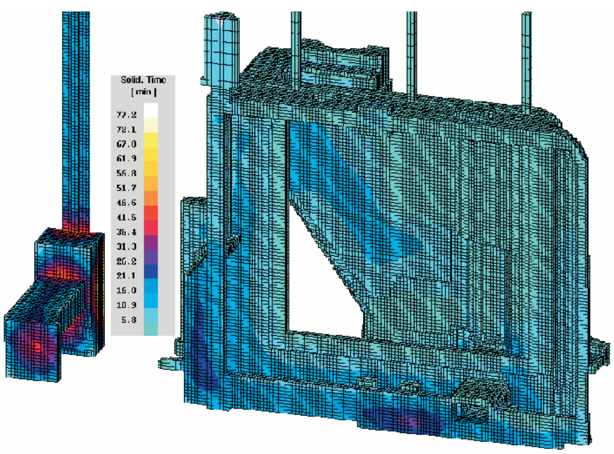
Sectioned views of the second simulation are presented in Figure 23.



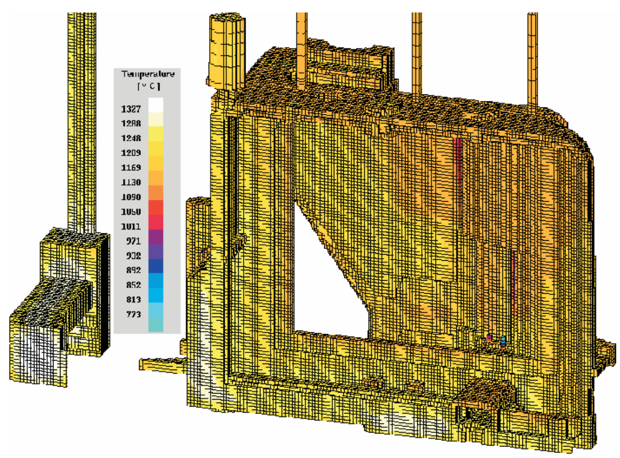
Heavy sections near the water and oil passages still show some propensity to shrink in the second simulation.



Solidification time for the second simulation in a section intersecting the water and oil passages.



A hot spot on the bottom during the second simulation. Shrink at this location is possible.



Solidification pattern of the second simulation after 5% of the casting has solidified, showing isolated hot section in one side wall.

Figure 23. Sectioned views of the second simulation.

Conclusions from the second process simulation.

- The upper risers are piping
- Cooling rate has increased, which is good. The area of oil passage and water passage cools slowly and may have minor porosity. The riser near this area should be checked for adequate piping at the foundry.
- The filling time is longer than desirable. A larger gating pressure differential is needed.

Recommendations from the Second Simulation.

- The step gates should be removed.
- More chills should be used on the bottom to eliminate shrinkage.

Third simulation. The third simulation was designed to answer questions raised during the second simulation and continued feedback from experiments in casting IFE prototypes at the foundry. The changes included:

- Exothermic sleeves were added about the middle risers
- Addition of 5 chills under the oil and air passages on drag side. Total chills now on drag side are 13.
- Replacing the silica core sand with chromite in cores 2, 7, 8 (thin passages). Chromite sand has greater thermal mass and conductivity, which should reduce the solidification time near these cores.
- Reducing the pour temperature to 2570 ˚F (1410 ˚C).
- graphite level was assumed to be 8%, rather than 12%

The addition of chills and a lower pour temperature are expected to reduce the hot spots on the oil, air and water passages. Chromite sand cores should enhance the chills to reduce the shrinkage.

Third simulation results. This simulation continued the improvements seen in the second simulation:

- The oil passage exhibited light shrinkage
- The middle risers piped due to thermal sleeves heating
- Top riser piped which successfully feed the boss.

Some problem areas remained, despite efforts to correct the deficiencies:

- The front wall has a shrinkage tendency
- The bottom still has a tendency to shrink

Images from the simulation software are shown in Figure 24.

Recommendation (third simulation).

- More chills are needed at heavy sections and bottom of the casting
- Reduce pouring temperature
- Due to design changes that have increased casting weight, pouring time should be allowed to lengthen
- Consider increasing riser size and adding exothermic sleeves at more locations

Fourth simulation. Additional refinements to the rigging system were made for the fourth process simulation, as well as changes to casting dimensions that increased the minimum wall thickness. The changes from the third simulation were:

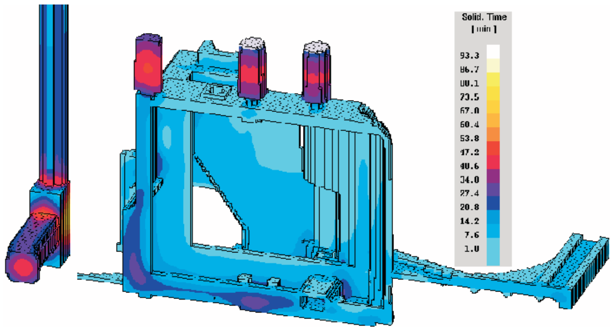
- Greater minimum wall thickness
- Nine chills on the bottom and all top risers with thermal sleeves

Fourth simulation results. This simulation shows better results than last one, yet some problems remain. Specific recommendations resulting from the simulation are:

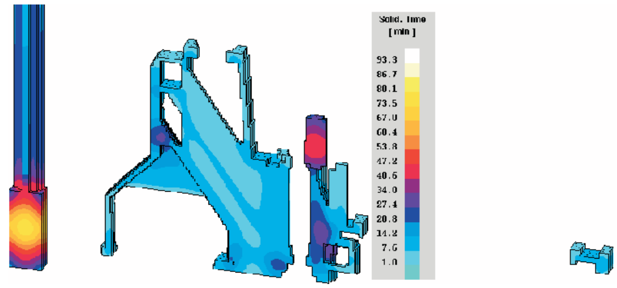
- Feeding needs to be improved where the wall thickness tends to create metal hot spots
- Pour temperature and time must be controlled tightly at the foundry for comparison with simulation to be valid
- Chemistry and microstructure should be watched. Low carbon (3.15% observed with one prototype casting) exacerbates shrinkage. If magnesium is too high, shrinkage will occur. If too low, carbon nodule formation is bad. Inoculation level and time decide nodularity and nodule counts. Control of magnesium fading is critical. Otherwise, even when Si is high, low nodule counts and chunk graphite still occur. Under these circumstances, elongation will be poor due to low nodularity.
- The nobake resin system will make the sand mold strongest about 2–3 hours after mixture. The mold should be coated after that time to allow moisture to escape and prevent mold cracking. Sand coating temperature and moisture need to be controlled. Acid demand value (ADV) should be kept low to fully stabilize resin and make the mold strong. The ratio of the two resin components and ratio to total sand weight must also be controlled.
- Views from the fourth simulation are shown in Figure 25.

Prototype and tooling (physical models, pattern building)

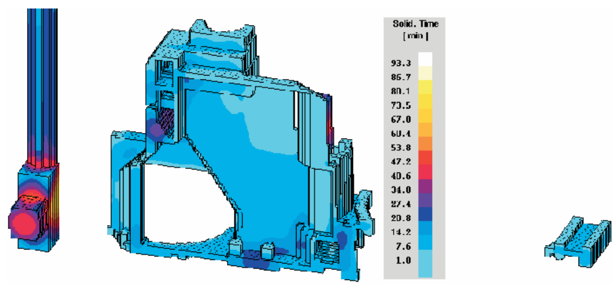
The first step in the development of the pattern equipment was to create a physical mold and core model, from the old pattern equipment that Teledyne Casting Services was already using, to produce IFE castings (this equipment was of an inferior design that was fraught with problems). The IFE casting is a complexly cored large casting. That fact presented a technical challenge for Clinkenbeard & Associates, Inc., because the cre-



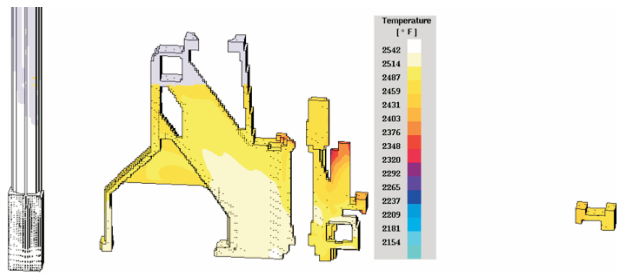
Solidification time from third simulation showing wall and bottom isolated hot sections.



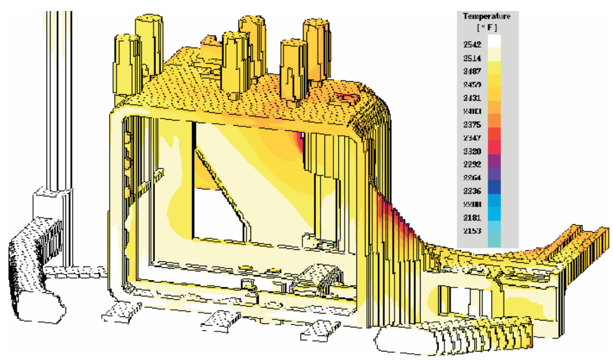
Solidification time from third simulation showing section of water passage. Passage wall may have shrinkage; riser feeding channel cools too quickly to effectively feed the casting.



Solidification time from third simulation showing upper left side likely shrinkage.



Third simulation with mold filled to 80%, showing bottom of casting is hot.



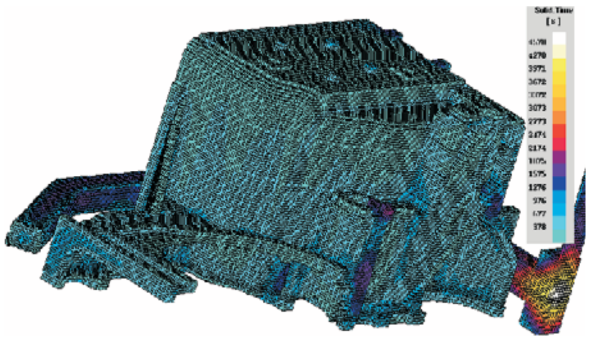
Third simulation with mold filled to 100%, showing bottom of casting is hot at the bottom ingate area and left vertical wall.

Figure 24. Images from third simulation.

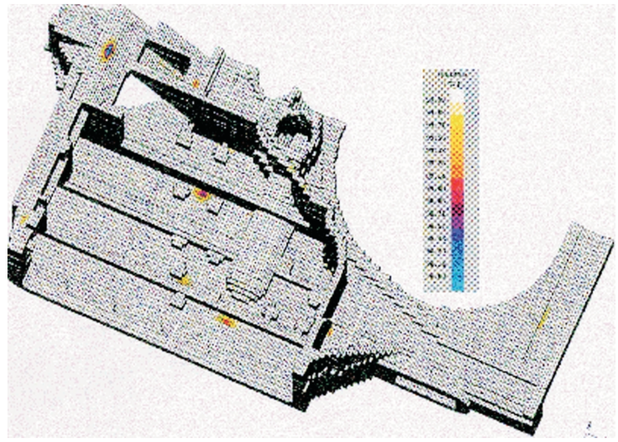
ation of an accurate set of molds and cores for a casting this large would normally be very expensive and would require a very long lead-time. In response to this problem, Clinkenbeard & Associates, Inc. developed a method that utilized a fast-setting urethane plastic. This plastic satisfied the needs as far as speed was concerned, but it was expensive, and it had a high rate of shrinkage when poured in massive quantities. After many iterations, a low-cost and very stable method was developed that used corn as filler for the urethane reproduction plastic (Figure 26). The new method was used successfully to make the molds and cores. These molds and cores provided the Agile team with a mockup to use for brainstorming the new, improved, pattern design. This mockup was then transported to K + P Agile, Inc. to be used as a visual aide when committing the team's design into a CAD model. During the CAD model creation at K + P Agile, Inc., Clinkenbeard & Associates, Inc. and the other team members visited K + P Agile, Inc., to further collaborate on the best practice for the pattern design.

At the request of the foundry and with concurrence of other team members, Clinkenbeard & Associates, Inc. procured large quantities of mahogany pattern lumber that it needed to build the patterns and corebox frames. The other materials required for the tooling included urethane for the corebox cavities, jellutong for large coreplugs, Ren plank for small coreplugs, plywood for corebox bottoms, steel for corebox and pattern facing, aluminum for cope and drag locators, paint, and general pattern supplies.

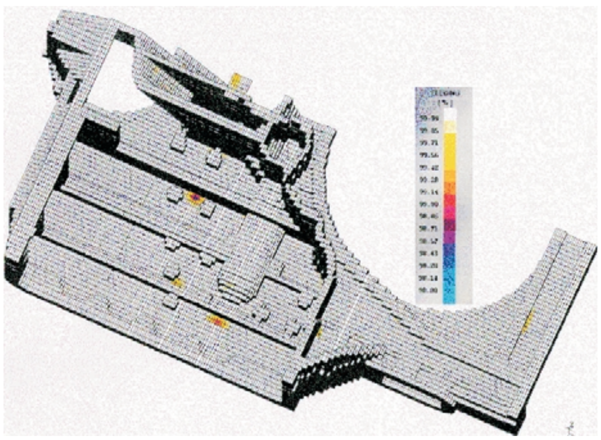
After receiving CAD data from K + P Agile, Inc., through various methods, Clinkenbeard & Associates, Inc. faxed a configuration control document (Table 2) to



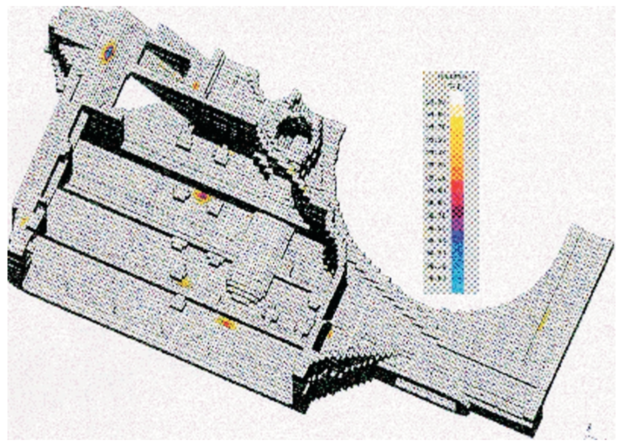
Fourth simulation solidification time at the interior of the casting. The vertical wall of the water passage may still shrink.



Fourth simulation feeding percentage at the base of the casting. Hot spots less pronounced than in previous simulations.



Fourth simulation feeding percentage at the base of the casting. Note that solidification time increases toward a central location where risers can be effective.



Fourth simulation solidification time at the base of the casting. Note that solidification time increases toward a central location.

Figure 25. Views from the fourth simulation.

Figure 26. Method using corn as filler for urethane reproduction plastic.

K + P Agile, Inc. for verification that the information received was proper. Clinkenbeard & Associates, Inc. did not use any data until an authorized individual faxed the configuration control document back, with a signature. After this verification, Clinkenbeard & Associates, Inc. pulled the CAD information into its Solid Concepts software, and applied a shrinkage factor to the data. The data were then saved under a new filename, with an "SH" prefix to indicate that the shrinkage factor was in place (failure to apply a shrinkage factor to the data will always result in a pattern that is unusable).

Initially, a scale model of the CAD data was constructed using SLA technology. The SLA model could be made very small, and thereby quickly provided a view of the design. This first model uncovered a problem that was undetectable on the CAD system. This problem was associated with the core setting sequence and with an issue of backdraft on the cope pattern. The problem was easily overcome with a change to the CAD data by K + P Agile, Inc. and a revised file was sent to Clinkenbeard & Associates, Inc. Later on in the pattern manufacturing cycle, a scale model was created of the actual IFE casting, using the LOM process. This technology is useful for larger, more massive physical models. LOM models can also be easily sectioned to show wall thickness and cored passage shapes, which would be not be possible when using SLA technology.

Table 2 Agile file transfer

file name	file size	file date—date file was last saved before FTP transfer to Clinkenbeard & Associates, Inc.	file date—date file was received at Clinkenbeard & Associates, Inc.	shrink factor applied to this file (write 0 if none)	sign off—please sign off to indicate this file is suitable for manufacturing
core-1-8.stl	3,231,484	12/6/97	12/8/97		
core-2.stl	2,802,984	12/6/97	12/8/97		
core-3.stl	29,689,784	12/6/97	12/8/97		
core-4.stl	30,688,084	12/6/97	12/8/97		
core-5.stl	25,202,384	12/6/97	12/8/97		
core-6.stl	1,317,484	12/6/97	12/8/97		
core-7.stl	3,525,884	12/6/97	12/8/97		
core-9.stl	3,634,984	12/6/97	12/8/97		
core-10.stl	783,184	12/6/97	12/8/97		
core-11-1.stl	11,684	12/9/97	12/10/97		

Clinkenbeard & Associates, Inc., through the Agile program, has developed a method of numerical control (NC) toolpath generation that is extremely fast and efficient. This method allows the addition of draft to patterns, without modifying the CAD model. During the creation of the NC toolpaths at Clinkenbeard & Associates, Inc., it became apparent that machine stock had not been added to the casting in some areas. The drawing that identified which surfaces were to be subsequently machined was not sufficiently clear in this regard, and caused the casting designer to misinterpret where machine stock was or wasn't required. The Agile team determined that Clinkenbeard & Associates, Inc. should take the responsibility of checking the CAD model to determine proper machine stock allowances. Since the drawing was unreliable, the next safest course was to contact the IFE casting machining vendor, Bley Engineering, and work with them to determine the machined surfaces. It was also a team decision that even though the CAD model would have to be modified to reflect the proper machine stock, this would have to be a concurrent activity, and Clinkenbeard & Associates, Inc. would employ other methods of providing this machine stock. The missing machine stock identified by Bley Engineering was incorporated and the NC toolpath generation was completed.

Wood was laminated together into pieces large enough to cut the core plugs and then set up on each of three computer-based numerical control (CNC) milling machines (Figure 27). Clinkenbeard & Associates, Inc. installed a high-speed control on one of the three machines, through the Agile program, and found that for very large shapes with ever changing surfaces it was up to ten times faster than the older technology. This machine was able to exceed the output of the two other machines combined. After machining, the plugs were sanded and sealed by hand, and readied for coreboxes to be made from them. The machining of the cope and drag patterns followed much the same procedure.

During the machining of the patterns it was discovered that a localized thin-wall condition existed in the design. Further investigation of the LOM scale model unearthed more thin-wall areas. An examination of the wall thickness callout on the drawing revealed a reference to an ambiguous tolerance specification that required costly corrective measures. The nominal wall thickness called out on the engineering drawing had been changed, by the end user of the casting, to a minimum wall thickness. The Consortium reacted by having Clinkenbeard & Associates, Inc. seek out and hire an independent engineer to check the CAD model for minimum wall thickness. Any walls that would not end up cast above the minimum were reworked by Clinkenbeard & Associates, Inc., and recorded. K + P Agile, Inc. was then able to keep the CAD model configuration up to date with the tooling. The gating system was also machined by CNC from the CAD data.

Figure 27. Wood laminated into pieces large enough to cut core plugs and then set up on each of three CNC milling machines.

After the patterns were completed they were sanded and painted and, along with the gating system, mounted on cope and drag plates (Figure 18). The cope and drag plate raw castings were supplied by Teledyne Casting Services. Clinkenbeard & Associates, Inc. designed the machining parameters for these plates and subcontracted the machining to a local machine shop that specializes in large heavy casting machining.

A mold of the mounted drag pattern was manufactured to enable the core plugs to be set into it and all of the core fits were validated. A variety of ills appeared at this juncture. The core clearance that was designed into the pattern in some areas was insufficient for good foundry practice. The solid modeler at K + P Agile, Inc. had not correctly interpreted the foundry's requirements. (It is useful to note that in each case where a problem was discovered, it could be traced to lack of validation by the organization imposing the rejection. For example: If the casting CAD model was validated by the machine shop that ultimately must machine the casting, they would be in the best position to accept or reject the data. Similarly, if the foundry checked the pattern CAD model for proper clearance and gating design, they would be in the best position to accept or reject the data. The benefit would not only be in reduced rework, but the validation could be accomplished in parallel with the manufacture of the tooling. Hence, a reduction in cost and lead-time.) Clinkenbeard & Associates, Inc. reworked the core fits to suit the foundry.

Another issue that was raised at this time was the existence of thick walls that were inherent in the design, but undesirable from a casting viewpoint (Figure 28). The Agile team made the decision to incorporate a design change, albeit late in the game, to avoid subsequent metallurgical problems. Clinkenbeard & Associates, Inc. reworked the heavy wall sections by adding material to the core plugs where needed and recording the additions for inclusion in the CAD casting model. One more validation procedure was implemented to verify that the cope mold would fit properly over the assembly. A skeleton framework was manufactured from the

Figure 28. Thick walls undesirable from a casting viewpoint.

cope pattern and set over the core assembly (Figure 29). With the validation complete and the final changes incorporated, the coreboxes were poured and construction was complete (Figure 30).

Clinkenbeard & Associates, Inc. shipped the pattern equipment by truck to Teledyne Casting Services and was present during the assembly of the first mold. The first mold was successfully assembled.

After the first casting was poured and validated, Clinkenbeard & Associates, Inc. visited the casting machine shop to assist and observe the machining of the first article. A record was made of the items that may require corrective action.

First Article Casting

A first article was cast to validate the new tooling and demonstrate the success of the agile manufacturing development process. The results were excellent. A new team at the foundry successfully assembled the cores quickly and without difficulty, demonstrating that the new tooling was acceptable for production use. The metal was poured at the recommended temperature and

Figure 29. Skeleton framework manufactured off of the cope pattern and set over the core assembly.

Figure 30. Poured core boxes and complete construction.

pour time and resulted in a dimensionally accurate casting. An x-ray evaluation verified that the material quality was within specifications. Feedback from the machine shop indicated that the casting machined very well. Careful examination of the casting geometry by the Agile team revealed that a few features were missing (missing bosses, a flange, thin wall due to draft, insufficient stock in some areas). These will result in some minor corrections to the CAD model and the pattern before the second prototype casting is poured. There is every indication that the new pattern will allow production-type mold assembly in the foundry followed by automated machining of the castings (Figure 31).

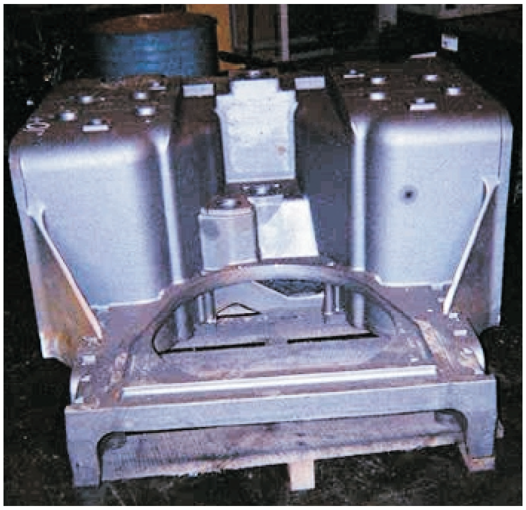


Figure 31. First article casting.

AC locomotive casting technical accomplishments

Comparison of Agile development against industry benchmarks

Responsibility for development of the integrated front end casting was transferred to the Consortium by GE Transportation Systems during attempts by GE's supplier foundry to cast functional parts with prototype tooling. At the time of the transfer, eight casting attempts had been made, resulting in parts with various and severe defects. In addition to poor casting integrity, the parts suffered from a large number of flaws due to omitted and misplaced features of the pattern, wall thickness deviations caused by core shifts, and failure to meet design intent due to unnecessarily restrictive feature dimensions made during part design.

The design provided to the Consortium by Deutz MWM through GE Transportation Systems was considered preliminary by MWM, notwithstanding that sample castings were being produced for use in functional tests on diesel engines. Many deviations from the documented design had been executed with the prototype tooling, and more were expected to be requested by GETS as the sample castings were finished and used in the locomotive test program. Because the actual IFE was far from a static design, it was obvious that full solid models of the production tooling would be necessary if the Consortium were to produce accurate tooling rapidly enough to meet the needs of GETS.

Agile Consortium performance against benchmark

Due to the transient nature of the IFE design, the activities in which the Consortium was involved during creation of production tooling had much in common with concurrent engineering developments. The initial solid model creation by K + P Agile, Inc. was modified frequently to address inconsistencies and omissions in the preliminary machine drawings of the IFE, and on three occasions due to engineering design changes requested by GE Transportation Systems. The elapsed time for creation of the first solid model for review was fourteen weeks. Published evidence of casting development times typically does not include time spent in creating the part design and generating documentation necessary to define the component and tooling geometric requirements. To maintain consistency with the most recent comprehensive casting acquisition cycle study "Benchmarking and lead time reduction,"* the time required for creation of the preliminary solid model of the IFE by the Consortium is not included in subsequent comparisons.

The Agile integrated front end development time is tabulated with two extant measures of casting acquisition cycles in Table 3. Note that the acquisition cycle from the U.S. Air Force includes reordering of castings from tooling that is already in the possession of the supplier foundry, which is significantly less challenging, in terms of delivery schedule.

Table 3 Comparison of Agile development of IFE castings with available benchmarks

Lead times*	Weeks
AMC new part prediction	31
USAF reorder period	25
Agile IFE development	18

* *AMC new part prediction and agile IFE development refer to new parts; USAF reorder period refers to a mixture of new and reordered parts.*

The AMC benchmark study determined the dependence of tooling development and part delivery times on some part and process characteristics through surveys of foundries producing steel, iron, aluminum, magnesium, and copper components by investment, die, and sand mold casting. The study analyzed survey responses to questions of a general business nature, as well as topics specifically tailored to each of the three casting processes. The study determined significant correlations between lead times and casting weight, wall thickness, and order size. The model presented for sand mold castings of all metal types was:

* *Benchmarking and Lead Time Reduction*, AMC Lead Time and Cost Reduction Program Management Report, October 25, 1996

New order lead time
$= 6.09 + 1.46\ OS + 0.008\ weight - 1.29\ wall$

where *OS* is order of magnitude of the number of components ordered, *weight* is the casting weight in pounds, and *wall* is a representative wall thickness in inches. The AMC new order lead time model prediction for the IFE would be approximately 30 weeks. Beginning the accounting from the release of the first solid model of the tooling, the Consortium required only 18 weeks to process the part through machining (which is not explicitly included in the benchmark study).

It is germane to note that the AMC benchmarking study did not actually determine the acquisition cycles for individual castings; rather, the survey relied upon the assumption that tooling and order delivery cycles for individual parts can be inferred from "typical" descriptions of each foundry's processes and products. Such deduction of specific performance from general anecdotes suffers from two deficiencies. The first clouds an otherwise useful view of casting development practice, the second precludes any potential for a precise picture:

- Because the survey responses do not include details of individual castings, the authors are unable to deduce the influences of casting complexity, such as the tolerances and number of critical dimensions, casting envelope, number of cavities or cores, metal grade, casting defect classification, inspection requirements, and post-casting processing.
- Because the respondents were not asked to follow a specific computational procedure in determining the "typical" casting characteristics, no conclusions can be drawn regarding the uniformity of the responses. If each foundry were to have provided statistical measures of the lead times required for specific numbers of sequentially produced casting designs, some defined level of probabilistic certainty could have been ascertained regarding the lead times obtained.

Due to the manner in which the AMC respondents were queried, it is not unlikely that the "typical" casting lead times were determined in a subjective fashion, and may not include appropriate representation from development efforts that experienced delays, as these might be considered atypical by the foundries. It is interesting to note that the Manufacturing Technology Directorate of the US Air Force has been collecting, for a number of years, lead time data for manufactured goods procured by the Air Force.* The lead times compiled by the Air Force for *repeat* order castings are nearly as long as the predictions presented by the AMC benchmark study for *new* casting jobs.

Process FMEA of locomotive casting development
Upon conclusion of the Agile tooling development for the locomotive casting, GE Corporate Research and Development collected examples of unexpected events and delays experienced in all aspects of defining and creating a production mold and modifying the prototype tooling for the integrated front end casting. A failure modes and effects analysis (FMEA) methodology was employed to extract opportunities for collaboration improvement in future acquisitions. The phases of the analysis are depicted generically in Figure 32. Specific application of the methodology applied to the IFE casting and production tooling activities are described below:

Measure. Failure modes of the casting development process were identified by reviewing demonstration castings and collecting examples of breakdowns that occurred in the development process. Each example was then reviewed to assess the effect or impact it had on the development process, generally characterized in terms of cost, time, and quality. The examples were grouped into like categories, which were used to derive the set of generic failure modes observed during the demonstration castings development processes. The example groups are as follows:

Development Team Missing Key Players.

Examples:

- Part design purchased from third party. Design process did not involve any input from supply base.
- Process Engineer not present during initial casting trials.
- No established liaison between customer and foundry.

Critical customer requirements not identified.

Examples:

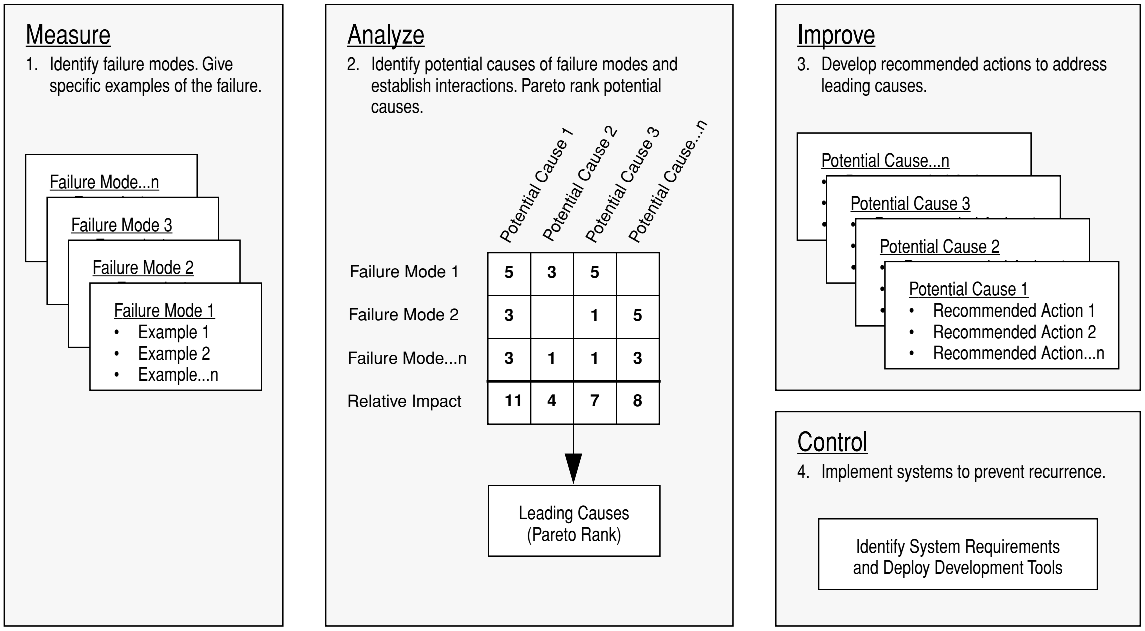
- Clearance requirements not specified for mounting enclosure.
- Internal passages not specified with a no-leak requirement.
- Method of filling production core boxes not specified.

Supplier does not understand part requirements.

Examples:

- Supplier does not know intercooler envelope clearance requirements.

* *Memorandum for USAF Aeronautical Materials Lead Time Report Users*, USAF Manufacturing Technology Directorate, 1997



	Potential Cause 1	Potential Cause 2	Potential Cause 3	Potential Cause...n
Failure Mode 1	5	3	5	
Failure Mode 2	3		1	5
Failure Mode...n	3	1	1	3
Relative Impact	11	4	7	8

Figure 32. Casting Development Process Analysis.

- Foundry operators not aware of all relevant part requirements.

Prototype tooling design flaws.

Examples:

- Mounting boss location on pattern does not match dimensions called out on print.
- Prototype core boxes were not split, making it difficult to form cores.
- Prototype patterns lacked sufficient draft and reinforcement.

Simulation does not match real-world results.

Examples:

- Shrink predictions in intercooler cavity top wall did not match real-world results because of miscommunication of actual riser configuration from foundry.

Undocumented process changes.

Examples:

- Sprue substitution from 2 × 3.5” to 6 × 1.5”.
- Numerous variations in process methods and equipment.
- New flask size substituted for cope mold.

Castings do not meet part requirements.

Examples:

- Casting leaks during engine testing.
- Bolt hole bosses cannot be drilled without breaking through casting.
- Cored mounting hole locations out of position because of floating cores.

Selected foundry not experienced with similar parts.

Examples:

- Complex thin-wall 2000-lb casting sourced to foundry that specializes in heavy castings 50,000+ lb.
- Second supply source not identified.

Unnecessary or improper part requirements or specifications.

Examples:

- Purchasing specification not previewed by foundry technologists.
- Specified 12% elongation was not required.
- Design intent not castable.

Example:

- Wall thickness on casting less than 10 mm, requiring numerous design and pattern changes to correct.

Drawing or modeling errors and inconsistencies.

Examples:

- 2D CAD drawing has numerous errors in nominal wall thickness.
- Preliminary part design was not static, final design not released.

Long cycle time for simulation results.

Example:

- Process simulation software model has 6 million elements and takes four days to run.

Excessive prototype trials to develop process parameters.

Examples:

- Several parts made with similar defects before modifying process.
- Numerous iterations required to find acceptable runner configuration.
- Extra trials required because chills and risers were placed in response to casting defects.

Required facilities not in place to support production.

Examples:
- Cylinder core transport pallets not available. Cores damaged while moved by hand.
- Production limited by number of available flasks.

The failure examples and failure modes do not represent all possible development process failures. However, it is believed they capture the significant majority of common development process failures. More castings would have to be reviewed to develop a fuller understanding of the universe of failure modes. In addition, more castings would be required to develop statistically significant data that could be used to derive quantifiable ranking for occurrence and impact. Because measuring breakdowns (defects) in the casting development process is a subjective activity, a gage reliability and repeatability study was not practical.

Analyze. Potential causes were identified by dissecting each development process failure mode. Because failure modes are generic, multiple potential causes are identified (root causes cannot be identified). To identify the leading causes in the casting development process, correlations were made between potential causes and failure modes using a Cause & Effect matrix, shown in Table 4.

Table 4 Development process failure mode analysis

	Potential Causes															
Process Failure Modes	Development process not defined	Vendor selection	Ineffective collaboration	Program risks not identified	No formal approval process	Late design changes	Manufacturability concerns unaddressed	Ineffective use of simulation tools	Poor availability of documentation	Unable to validate design changes on process	Poor configuration control	Inconsistent data formats	No integrated schedule	Out of control manufacturing process	No manufacturing data feedback mechanism	Insufficient qualification / validation plan
Development team missing key players	5															
Selected foundry not experienced with similar parts		5	1	3												
Critical customer requirements not identified	5		5													
Unnecessary or improper part requirements or specifications	3		3		3		5									
Supplier does not understand part requirements	3		5		3				5							
Design intent not castable	3		5	3	5	1	5	3								
Uncommunicated design changes	3		5		3	1					5					
Drawing or modeling errors and inconsistencies			1		1	3			3		3	5				5
Tooling errors and inconsistencies			1		1	1	3		3		5	5				5
Long cycle time for simulation results			3		1			5	3		3	1			3	
Simulation does not match real world results							1	3							3	

A relative ranking was assigned for each possible relationship, and a relative impact was determined for each cause by summing the relative rankings. The leading potential causes of defects in the casting development and procurement were identified, and were found to include:

- Development process not defined – roles and responsibilities of the supplier chain members

were not always communicated effectively, slowing progress.
- Ineffective collaboration – critical part requirements and process constraints were not always obtained quickly by those making decisions affecting the part design or process conditions.
- Manufacturability concerns not addressed – features of the casting design were unnecessarily constraining for machining, and design choices made during creation of the prototype tooling resulted in slow mold assembly and unacceptable variation in casting dimensions.

Improve. Recommended actions were developed for each leading cause:

Development process not defined.

Recommendations:
- Formalize development process steps and stages. Employ manufacturing quality and design tools (QFD, FMEA, Thermometer Charts, etc.)
- Technical specification review should be part of sign-off process. Definition of critical customer requirements and critical to quality characteristics (CTQ's) should be included in the initial review stage.
- Leverage new technology/product introduction approach (tollgates) for each stage of the development process.
- Identify required team members and roles.
- Feasibility reviews should be included at each development stage. Consideration should include castability, manufacturability, machinability, inspectability, etc.

Vendor selection.

Recommendations:
- Develop supplier selection certification checklist.
- Institute vendor selection risk assessment.

No formal approval process.

Recommendations:
- Approval process should include consistency of technical specification as well as the values for the specifications.
- CTQ's must be agreed to up front in the development process.
- During initial development phases, proper considerations must be made and agreed upon by stakeholders to address feasibility issues, including castability, machinability, inspectability, etc.
- Develop mechanism to formalize approval process for changes to the casting technical specification. Notification to affected parties should be automatic.
- Review milestones should be established for significant tasks such as drawings, modeling, simulation, tooling, etc.

Manufacturability concerns unaddressed.

Recommendations:
- Develop design-for-manufacture guidelines and establish a means of communicating producibility information between the knowledge base (foundry engineers, machinists, etc.) and the customer (product designers).
- Include manufacturing feasibility and producability reviews as appropriate in the development process. All manufacturing operations and considerations should be included (casting, machining, inspection, etc.).

Poor Availability of Documentation.

Recommendations:
- Provide access to on-line information for all contributors.
- Capture information in computer file formats when possible, using digital cameras and scanners when necessary.

Poor Configuration Control.

Recommendations:
- Implement means to automatically track and identify information that is no longer current. Notification to affected parties should be automatic.
- Technical specifications should be maintained through a single reference point (document). There should be no ambiguity regarding the value of a specification and where the specification is called out.
- Configuration control should be monitored using the GYR tacking method to indicate the general "health" of the casting development. GYR should assist in assessing the convergence at a given step in the development process.

No Integrated Schedule.

Recommendations:
- Create development process timeline that includes major project elements. Generic casting development templates should be available for use as a starting point. Timelines should be customizable as required to meet the need of a given casting application.
- Make schedule part of development process review stages.

No manufacturing data feedback mechanism.

Recommendations:

- Customer (end customer or next in sequence process) should identify critical feedback parameters (CTQ's).
- Provide a means for the supply chain to communicate and distribute key process information requirements.

Ineffective collaboration.

Recommendations:

- Develop workgroups (i.e., mailing lists) to ensure information is communicated to necessary individuals.
- Include appropriate sign-off review steps in development process to ensure each group understands latest design information and technical specifications.
- Establish a DFX database to link knowledge base information to part designers. Feasibility sign-off reviews should be included in the development process.
- Develop an appropriate change notice mechanism to facilitate information exchange.

Program risks not identified.

Recommendations:

- Include structured risk assessment reviews and follow up review into the development process.
- Identify expert resources to review progress of high-risk activities.

Late design changes.

Recommendations:

- Institute product reviews and risk analysis in the development process.
- Include feasibility reviews to help reduce design-for-manufacture related design changes (tolerancing, etc.)
- Develop means to quickly communicate design changes and assess impact.

Ineffective use of simulation tools.

Recommendations:

- Identify alternative simulation tools to reduce simulation cycle time. Where appropriate, attempt to leverage reduced order modeling to minimize build and run time.
- Integrate simulation efforts in development process timeline so they can be used to drive the manufacturing development process.
- Develop guidelines to assist in the selection and use of simulation tools.

Inconsistent data formats.

Recommendations:

- Maintain library of file translation programs.
- Generate public format files in addition to proprietary formats, where possible.

Out-of-control manufacturing process.

Recommendations:

- Leverage process quality tools, including DOE, SPC, etc.
- Provide facility for supplier to provide feedback on CTQ's.
- Require process control evidence in product specification.

Insufficient qualification/validation plan.

Recommendations:

- Include validation and qualification planning requirements into the development process. Design-verification test plans, and preliminary prototype and in-process production inspection plans should be developed.
- Develop a knowledge base of inspectability guidelines.
- Include inspectability reviews as appropriate in the development process. All manufacturing operations and considerations should be included (casting, machining, inspection, etc.).

Each recommendation was reviewed to determine its effectiveness in mitigating the causes and resulting failure modes, including the specific examples observed during the demonstration castings. When possible, recommendations were formed as methodologies or mechanisms. The large majority of recommendations are within the scope of the Agile Development of Castings program, and are being addressed by the Consortium.

Control. Implementation of the recommended actions forms the control strategy. Features of the web-based collaboration tools are being developed to improve execution of future casting acquisitions by improving communication and specification infrastructure. Failures of the development process are being addressed by augmenting the collaborative infrastructure with documentation of methodological tools, such as quality function deployment (QFD), FMEA, new product introduction guidance, and robust design techniques.

Execution of the FMEA improved the use of information gained during the locomotive casting acquisition by allowing quantitative comparisons of the severity of the difficulties encountered in developing production tooling and modifying the casting process and prototype tooling. Many of the lessons learned by the Consortium during this acquisition are guiding current activities.

Muzzlebrake

In April 1997, Benét Laboratories and the Watervliet Arsenal established the Integrated Casting Design Team (ICDT) with the purpose of improving casting component quality while also reducing acquisition costs and delivery times. An eight member multidisciplinary team was formed consisting of individuals with mechanical, metallurgical, manufacturing, quality assurance, and acquisition backgrounds. For the first year of its existence, the team partnered with the Defense Logistics Agency (DLA) and one of their primary contractors, the American Metalcasting Consortium (AMC). The ICDT investigated, developed, and implemented its casting design process, which is a modified version of the AMC process known as CAST-IT. Because of this unique partnership, the team was able to participate in several casting designs and acquisition seminars, benchmark the best casting design and acquisition practices through site visits, and investigate and utilize tools to improve the metalcasting design and acquisition process.

The ICDT demonstrated successful utilization of its process on several components. These include: a centrifugal casting for the Paladin M284 Cannon prereservoir, an investment casting for the XM777 Lightweight Howitzer towing bracket, an investment and sand castings for the XM297 Crusader tube manifolds, and two sand castings for the marine drive Thrust Assembly for an auxiliary propulsion unit, used on FFG, SSN and SSBN class Navy vessels. The success of the ICDT and partners was recently acknowledged by being selected to receive Vice President Gore's Hammer Award. This Award recognizes the team for using reinvention principles to create a government that works better, costs less, and delivers results that the American people care about.

The Benét Laboratories' Integrated Casting Design Team was chosen as a design focus for demonstration of the Agile Castings collaborative tools with the Consortium because of the group's experience with modern design and manufacturing integration methods. The contributing staff at the Lab (and the associated Watervliet Arsenal) were charged with

- assessing the usability of the collaborative tools developed by the Consortium, and providing advice concerning augmentation and modification of the software.
- assisting the Consortium in testing the code performance under various conditions.
- providing opportunities to exercise the *AC Notebook* in casting design and procurement activities involving cast components for the U.S. Army.

The Integrated Casting Design Team (ICDT) at Benét Laboratories has managed a conceptual design with the Consortium members of an integrated towing bracket/muzzlebrake for a future direct support weapon system. This system requires a muzzlebrake and a removable towing eye. The first prototype was quickly fabricated by modifying and welding some existing components together. The muzzlebrake casting is a single baffle brake with an integral mounting detail located on the bottom that interfaces with the second casting, an offset towing eye. After machining, the two components are assembled utilizing two ball lock pins. The towing eye is removed from the muzzlebrake prior to firing the system.

In the event that additional prototypes are required, Benét requested manufacturability and cost assessments from the Consortium for a dedicated assembly. The ICDT structured a project on the *AC Notebook* that included the muzzlebrake and towing eye castings. Pro/Engineer CAD files of the early fabricated design, the two casting designs, and the finish machined muzzlebrake were uploaded from the Laboratory to the *AC Notebook* server at GE Corporate Research and Development. Other pertinent requirements, specification documents, and several images were also included. The Consortium members were introduced to the project during a joint teleconference and notebook collaboration session.

Table 5 shows the initial structure of a casting development project created by Benét Lab. Document names shown in boldface type were populated with files by Benét prior to the start of collaboration.

As can be seen in Table 5, the design project structure is ordered and detailed (the use of numbered workflow entities allows the default table listing to present the items in a logical order). The project leader created all of the structure, down to the document level, uploaded the background information (requirements, preliminary analysis of performance, and finished part solid models), and created the empty documents for the responses of the Consortium. During the first phase (concept), the Consortium was asked to respond to the request by Benét concerning the feasibility of the two-casting assembly. In their responses during the first phase, the Consortium members posted to documents 1.4.1–1.4.4 questions and comments concerning the material specification, geometry, validation and inspection techniques, and were answered by the project manager. This method of communication presented a number of advantages:

- The *AC Notebook* allowed communication using images, solid models, and text files
- Version control for drawings, text files, and images were maintained automatically by the Notebook, while allowing access to superseded documents
- Each of the participants received the same response simultaneously.

Table 5 Muzzlebrake project

PHASES:		
1. Concept	2. Process Design	3. Prototypes
TASKS:		
1.1 Requirements	2.1 Identify Process	3.1 Prototype Tooling
1.2 Fabricated Design	2.2 Cost Estimates	3.2 Prototype Casting
1.3 Casting Concepts	2.3 Process Modeling	3.3 Machine Prototypes
1.4 Consortium Review	2.4 Process Review	3.4 Prototype Testing
DOCUMENTS:		
1.1.1 Performance Rqmts	2.1.1 Tooling Plan	3.1.1 Rigging Data
1.1.2 Towing Eye Rqmts	2.1.2 Foundry Plan	3.1.2 Foundry Data
1.1.3 Muzzlebrake Rqmts		
1.2.1 Fab Image Files	2.2.1 Fab Cost Estimate	3.2.1 Inspection Data
1.2.2 Pro E Fab Files	2.2.2 Eye Casting Estimate	
1.2.3 Stress Analysis	2.2.3 Mbrake Casting Estimate	
1.3.1 Casting Image Files	2.3.1 Preliminary Rigging	3.3.1 FM Results
1.3.2 Eye Casting Pro E	2.3.2 Solidification Analysis	3.3.2 Machining Comments
1.3.3 Mbrake Casting Pro E	2.3.3 Other Analysis (Stress)	
1.4.1 Comments on Eye Config	2.4.1 Comments on Rigging	3.4.1 Functional Test Results
1.4.2 Comments on Eye Rqmts	2.4.2 Comments on SA	3.4.2 Field Test Results
1.4.3 Comments on Mbrake Config	2.4.3 Other Comments	
1.4.4 Comments on Mbrake Rqmts		

- While missing or ambiguous information was being supplied or clarified, the Consortium members performed process simulation experiments to validate casting rigging designs, and verify castability. An example of a filling simulation of the muzzlebrake is shown in Figure 33. This type of communication is particularly valuable during casting process design. Many of the decisions made by foundry process engineering are difficult to describe without tools for visualizing the impact of choices. For example, Dennison Industries controlled the solidification of the muzzlebrake through placement of heat sinks ("chills") near the casting. Exact placement of chills can be of critical importance to product designers, as the indications left by the practice may deleteriously affect surface finish. With synchronous collaboration, such geometrically complex issues can be resolved quickly and with little effort.

2.2.3. Technology enablers

Being involved in the Agile Castings program has enabled all the members of the Consortium to improve their individual capabilities and business practices.

K + P Agile, Inc.

K + P Agile, Inc. has completely evolved the way it does business in the last three years by effectively using the Internet and related technologies to enable it to be more competitive and more responsive to its customers. These include defense, commercial casting users and OEMs relevant to the metal casting manufacturing industry.

Three years ago, the decision was made to invest in a dedicated high-speed Internet connection to enable the company to better serve its customers. Previously K + P Agile, Inc. had E-mail on a dialup basis. connecting to the Internet every half hour. While this was fine for normal text messages, it was becoming increasingly clear that the connection speed was insufficient for exchanging a variety of file types via E-mail. Having E-mail in itself, however, also allowed faster and more accurate communications with customers and vendors. Very often phone conversations can be misunderstood or remem-

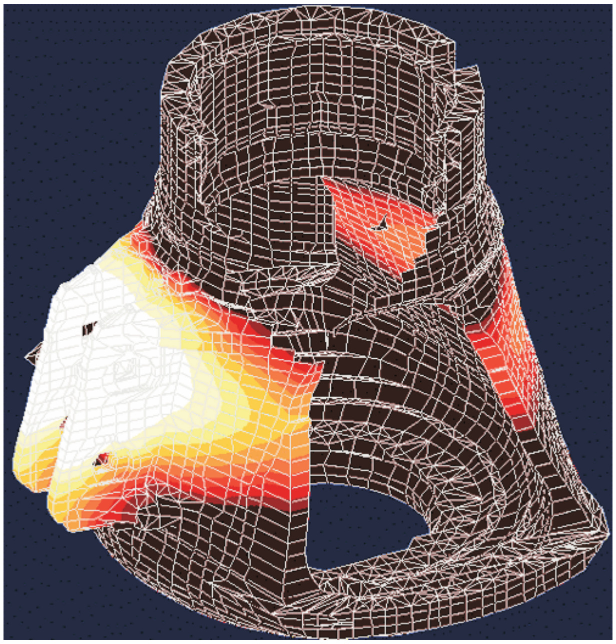


Figure 33. Temperature profile during a simulation of cooling the muzzlebrake, using a finite element method. The highest temperature is represented as white.

bered incorrectly, especially when dealing with a lot of numbers and measurements such as loads and constraints.

K + P Agile, Inc. installed a 768K fractional T-1 line in 1996. This brought a variety of changes to the company. It enabled direct Internet connectivity for browsing, sending and receiving of E-mail, and the ability to host its own web presence internally. More importantly however, it allowed establishment of an FTP server for file transfers. While E-mail may be suitable for files that are 1–3 megabytes, most E-mail servers reject messages larger than this. K + P Agile, Inc. needs to share numerous files of different types such as quotes, CAD drawings, casting process simulation results, finite element analysis results, etc. with its customers. While this might take time on a fast Internet connection, it still can be done in a few hours versus waiting a day or more for a package containing the same information.

The benefits of this initially were limited to the connections of our customers. Three years ago, many did not have Internet access, or they had very slow connections that limited the effectiveness of this type of business. Today 90% or more of customers and vendors have Internet access and many more have high-speed connections. This further reduces the time involved from the beginning to the end of the job.

Last year K + P Agile, Inc. opted to increase our 768K fractional T-1, to a full 1.54MB T-1 connection. The overall effect on business yields marginal improvement, however it does open up new possibilities. Sending 500+ MB of data to a company that also has a T-1 connection is far more feasible now than it was before, and in fact K + P Agile, Inc. has done this on many occasions. K + P Agile, Inc. is currently experimenting with Internet conferencing via audio, video and white boarding, to help further modernize its business practices. This provides the ability to show these results via the Internet while in real-time communication with the customer, which is a vital asset to our business. This would further reduce the turnaround time of delivery, as well as aid in accuracy, by reducing communication errors and common misunderstandings. Reducing these types of misunderstandings avoids lost productivity due to errors, rework and delays. The reduction of this type of productivity loss is crucial to providing high-quality services under the pressure of short turnaround times.

With the current communication infrastructure K + P Agile, Inc. is able to achieve a goal of 48 hrs turnaround time for a majority of the quotes related to design, analysis and rapid prototyping. This includes intense communication with our vendors for tooling, casting and machining. Furthermore, most of the engineering final reports are sent to customers electronically.

Clinkenbeard & Associates, Inc.

3D solid modeling—Before involvement with the Agile Casting program, Clinkenbeard & Associates, Inc. did not do 3D solid modeling. All modeling was done using 2D CAD and 3D surfacing. 3D surfaced models had to be converted to IGS data, then converted again into STL data in order to use rapid prototyping technology. This program allowed the implementation of the Pro/Engineer 3D solid modeling package, which outputs STL data directly from a solid model. Native Pro/Engineer files from our customers could now be received, providing the ultimate data communication tool.

Computerized pattern design—Clinkenbeard & Associates, Inc. has developed a computerized pattern design methodology that allows for fast and accurate pattern designs that utilize STL based modeling tools. The implementation of software from Imageware, Solidview, and Materialise have enabled the addition of machine stock, shrinkage factors, wall thickness, core prints, and separate pattern, and core. Prior to this methodology, many of these tasks were done by hand at a cost that was sometimes 10 times higher than today.

High-speed pattern machining—Prior to this program, the feed rates that were achievable while machining patterns averaged 15 to 20 inches per minute. The constraints that existed were from three areas:

- CNC control throughput.
- End mill design.
- NC toolpath generation techniques.

To overcome the first constraint, the CNC machine tools were replaced or new controls retrofitted to enable faster throughput. To overcome the second constraint, special pattern end mills were designed that could withstand higher rates of feed and speed. To overcome the third constraint, CAM software was utilized to produce more intelligent toolpaths with minimum wasted motions. As a result, the feed rates now achievable when machining patterns averages 500–900 inches per minute.

Rapid prototyping of physical models—After the program began, it was clear that to enable fast casting acquisition, many physical models of the casting design would be needed throughout the design process. Clinkenbeard & Associates, Inc. utilized it's existing Rapid Prototyping capability of Laminated Object Manufacturing (LOM), as well as two new technologies that were emerging:

- Fused deposition modeling (FDM).
- CNC rapid prototyping technique.

Whenever the physical model was of a thin-walled casting, the FDM method had an advantage over the traditional LOM that was being used. The LOM is not suitable for this type of application. The high speed pattern machining methodology developed was also found to be capable of producing CNC rapid prototypes. In many instances, this method was far less expensive that either LOM or FDM. CNC has the additional benefits of improved accuracy and a huge selection of potential materials from which the models can be produced.

Computerized pattern verification—Clinkenbeard & Associates, Inc. used a combination of blueprints and IGS wireframe data to verify the patterns it made before this program. After developing computerized pattern designs, it became evident that a faster method of verification needed to be implemented. A product from Imageware was installed that enabled direct comparison of the machined pattern with the 3D data being used for manufacturing.

Internal computer networking—Prior to this program, a Microsoft Windows for Workgroups network was used, connecting a handful of its' computers together. In order to provide total connectivity throughout the company, a Windows NT network was installed. It is the backbone of Clinkenbeard & Associates, Inc. operation, from quoting though manufacturing, all the way down to shipping and invoicing.

Internet communication and marketing—For seamless communication for all Consortium members, an ISDN line was installed. Clinkenbeard & Associates, Inc. also developed a website to enable the marketing of the Agile Casting technique. This website generates new business on a daily basis. Clinkenbeard & Associates, Inc. customer base has also expanded as a result of the Agile Castings program.

Atchison Casting Corporation

At Atchison Casting Corporation, the primary method of document control was a manual paper-laden sequence. This resulted in a protracted cycle time for design review, cost estimate generation, and subsequent customer price quotes. Atchison Casting Corporation has now implemented a change to the Windchill control system which has resulted in the creation and implementation of an internal web-centric database. This will result in a more expeditious sequence and will fully utilize the infrastructure and technology enablers of our Consortium participation for both internal and external communication.

Denison Industries

As a result of the Agile program, Denison Industries was able to expand its internal communications network by linking its two foundries and the main administration group via a unique "Wireless Campus WAN" communications network. Using the "IEEE 802.11 Wireless Standard," the WAN network runs at near LAN speeds, utilizing microwave towers at each of the three factory locations.

This new communications network allows for the transmission of cost information on a demand basis from anywhere in the system, allows access to the latest engineering levels on current components, and standard online router information and standard practices manuals.

Due to Denison Industries' remote location, internet connectivity was upgraded to near T-1 wireless capability, so that large modeling files can be submitted to and from customers, and sub-contractors such as Clinkenbeard & Associates, Inc. and K + P Agile, Inc.

Both Pro/Engineer and Simtec systems are being utilized in casting design, and process development, and both interface with key customers and suppliers. The future of e-Commerce systems at Denison Industries will be based on the enhancement tools that were developed during this program.

Cost control improvements, through the use of these more-rapid systems, have been enhanced. Additionally, preventative maintenance systems were upgraded, customer service response times improved, and the first article development cycles significantly reduced as a result of Denison's Agile involvement. Most importantly, Denison has learned more about the art of the possible during these casting exercises and will be a more competitive force in the foundry industry as a result of these experiences.

3. Achievements of the Project

3.1. CHANGING THE GAME—EXAMPLES OF SUCCESS

3.1.1. Allison Transmissions Advanced Amphibious Assault Vehicle (AAAV) casting

A new transmission housing casting was design and developed by Allison Transmissions for General Dynamics Land System for the AAAV Program. This casting is a transfer case, which is part of the drive system for the AAAV. Allison Transmissions is responsible for the drive train portion of the vehicle. All of this is being done for the US Marines.

Allison Transmissions had the design close to completion prior to the Consortium's involvement. This casting is a very complex part. Since many other components were started much earlier in the program, it became one of the main constraints to finishing the prototype units on time. A request for a proposal was submitted by Allison Transmissions to the Consortium. When the project started, the housing casting was on the critical path of the AAAV transmission development program. Since Denison Industries is a current casting supplier to Allison Transmissions, the costs for casting process modeling, tooling, and prototype rough castings were submitted through Denison on a strictly commercial transaction basis (i.e., no government funds were used). The Consortium was brought in for tooling and casting prototype manufacturing. A purchase order was issued to Denison Industries, who in turn issued an order to Clinkenbeard & Associates, Inc. for prototype tooling, and to K + P Agile, Inc. for rigging analysis and casting process modelling as their first tier suppliers for a fixed price, not to exceed cost. Since the Consortium members had a prior history of working together, they were a natural choice for a successful conclusion.

The part is a large, complex aluminum casting measuring 29" × 42" × 20" that requires 34 cores to produce, in addition to the cope and the drag. Many of the cores are long oil passages that are very small in diameter. Castings in this category typically take significant development time to produce a casting that meets the required specifications. Due to the tight schedule, it was necessary to produce a useable part on the first pour. Since both Clinkenbeard & Associates, Inc. and Denison Industries have many years of experience in complex, thin-wall castings, chances of a successful first pour are very high compared to companies without this expertise.

The combination of large and small part features required that the process simulation be large, in order to adequately represent fine detail. One of the most significant features of this project were the unforeseen complexities due to lack of provisions for holding the cores in position over long distances. Very high aspect ratio cores were required to form small passages in the casting. A number of the pattern elements necessary to form these cores are shown in Figure 34. Thin cores are difficult to mold

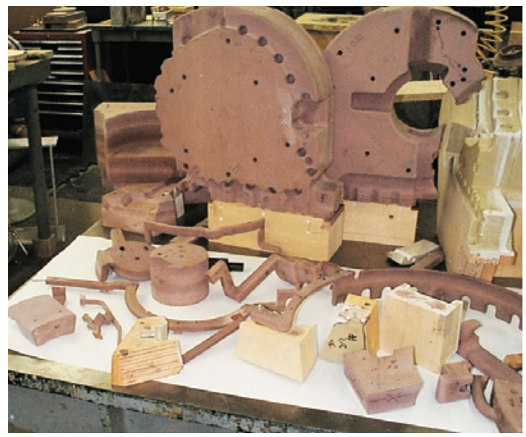


Figure 34. Master core plugs used to create the molds and core boxes for the Allison Transmission AAAV casting. Ultimately, each of these parts was reproduced by Denison from sand, to complete the transmission sand mold. Note several long thin elements.

from sand, challenging to handle, and prone to deformation during casting. In addition, the passages created in the casting must be cleared of sand, which can result in high cleaning costs. Junctions of smaller features created by several cores in close proximity were designed into the casting (Figure 35). In these instances, relative positions of fine features were difficult to maintain, leading to additional costs in pattern design, and increased risk that critical feature positions would be out of tolerance. The nature of this design makes the core shape and setting sequence one of the key factors to successfully producing this part. Furthermore, during the manufacturing, changes had to be incorporated due to engineering changes.

At the beginning of this program, the Consortium met to discuss methods of tooling construction, pouring orientation, and solidification modeling. A scaled-down rapid prototype model was produced for this meeting, as shown in Figure 36, to facilitate quick input from team members. Each time changes

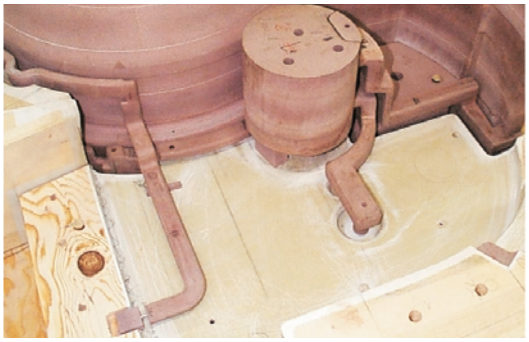


Figure 35. Assembled section of the Allison Transmission AAAV casting pattern. Note the small spaces among pieces in the right half of the image.

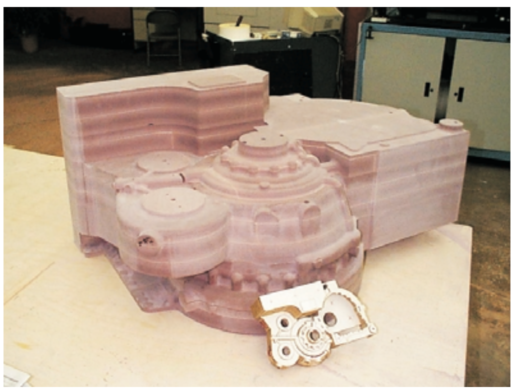


Figure 36. Scaled-down rapid prototyping model and master pattern.

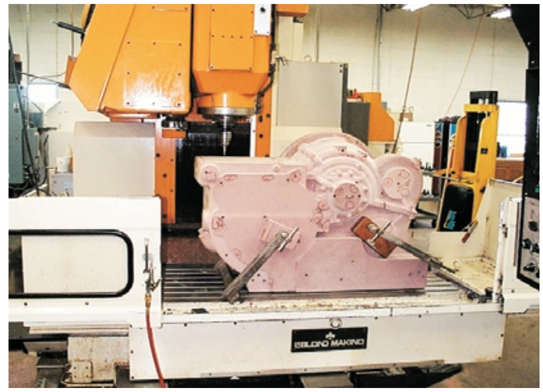


Figure 37. Master pattern being machined.

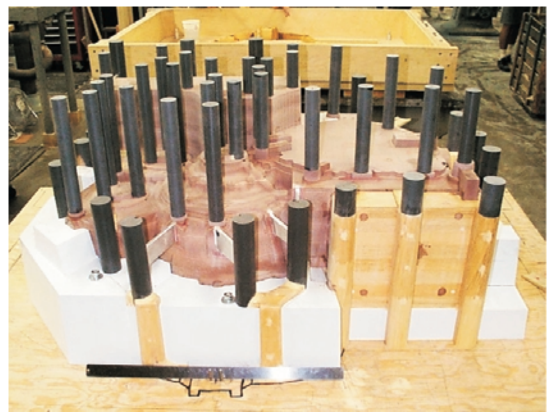


Figure 38. Cope pattern with gating.

were made to the design, another scaled-down rapid prototype model was produced to quickly communicate the new information to team members.

During construction, many technical issues needed to be resolved. Most were addressed after construction of the interior core master plugs. They were produced and set up in correct orientation for viewing. A meeting was held with Allison Transmissions engineering, Denison Industries, Clinkenbeard & Associates, Inc. and K + P Agile, Inc. to discuss problem areas. Design changes were made that would make this part more easily manufactured. With the actual core setup in place, Denison Industries was able to design the gating system during the same visit. Once the gating design was complete, K + P Agile, Inc. was able to model it in Pro/Engineer (CAD software) and run it through the solidification program to look for gating design improvements.

For such a complex part, casting process modeling is key to validating rigging and process parameters, such as pour rate and temperature. The model also helps insure the pour will be right the first time. K + P Agile, Inc. carried out two iterations of the moldfilling and solidification simulations. Issues related to design for manufacturability were revealed during tooling development and rigging design.

The tooling was designed and built by Clinkenbeard & Associates, Inc., as shown in Figure 37 and Figure 38, and a prototype casting was successfully poured by Denison Industries. During pattern construction, design changes made by Allison Transmissions engineering needed to be incorporated into the tooling. Since the whole process was done utilizing 3D solid models, the changes were viewable by team members from their own locations. These engineering changes resulted in over 750 additional hours to the project. Table 6 shows the chronology of the events for the development process.

Table 6 Chronology of Allison events

Date	Activity
5/7/98	K+P and Questek had preliminary meeting at Allison to give overview of AMDC Program
6/1/98	Downloaded file from K+P FTP site for review
6/10/98	K+P received CAD file from Allison, converted to stl format and distributed to Denison and Clinkenbeard using BSCW
6/11/98	RFP issued to the Consortium (Denison)
6/18/98	Quoted tooling
6/28/98	K+P, Denison, and Clinkenbeard estimated cost for casting process modeling, tooling and casting responsibility
6/29/98	Denison submitted cost proposal on behalf of the AMDC
7/1/98	Allison evaluated proposal and issued PO based on proposed timeline. Final design file sent to Clinkenbeard using FTP.
7/2/98	Clinkenbeard received sign-off sheet via fax from Allison (this was to verify Clinkenbeard was working to the correct CAD data—done by verifying file size)
7/2/98	Clinkenbeard received shrink factor via fax from Denison.
7/3/98	Manufacturing started at Clinkenbeard
7/6/98	Allison Engineering okayed using 1.5 degrees draft via phone to Clinkenbeard
7/12/98	Sent digital photos via E-mail to Allison for review of tooling progress
7/14/98	Clinkenbeard was encountering mismatches of core and casting in the CAD file. This was discussed via phone and followed up by Allison sending a view of the affected area via FTP to confirm everyone was talking about the same area. Allison sent a new corrected file.
7/15/98	Discussed via phone how to plug required core prints—weld or mechanical? Allison was used to welded print holes; was going to send a new file for boss changes to the exterior to accommodate weld version.
7/16/98	Received new boss configurations via FTP. K+P, Clinkenbeard, and Denison reviewed rigging and went over core design and parting plane.
7/17/98	Received drawings via mail from Allison.
7/20/98	Faxed to Denison looking for cope and drag sand mold size.
7/20/98	Clinkenbeard faxed core support question to Denison and Allison. One of the real problem areas.
7/20/98	Allison via phone to Clinkenbeard okayed putting a hole below the coffee can area. Denison to weld later.
7/21/98	K+P received IGES file for analysis through FTP—not usable.
7/28/98	K+P received STL file for analysis from Allison through FTP
7/29/98	K+P said via phone they would bring rigging drawings.
7/30/98	K+P finished solid model of the rigging and sent to Denison for approval by STL file format using BSCW. Clinkenbeard received gating drawings. Allison, Denison and K+P visit Clinkenbeard for review.
8/5/98	K+P carried out first iteration of Casting Process Modeling and communicated results by phone.
8/11/98	Clinkenbeard received via fax information to complete the gating in areas with questions.
8/11/98	Clinkenbeard received via fax from Allison views of problem areas they had discovered.
8/11/98	Clinkenbeard had discussion with Denison via phone concerning shipping.
8/12/98	Clinkenbeard received fax from Allison concerning previous problem areas.
8/13/98	Clinkenbeard notified Allison via phone they would start shipping equipment that they felt would not be affected by upcoming changes. Also looking for new models of problem areas.
8/13/98	Received new models via FTP from Allison.
8/14/98	K+P carried out second iteration of the Casting Process Modeling. Results were communicated by a report and teleconference with Denison.
8/18/98	Denison called Clinkenbeard to discuss #10 core, which was very difficult; they were concerned about being able to produce it.

Table 6 Chronology of Allison events (Continued)

Date	Activity
8/25/98	Denison called Clinkenbeard to say they received another shipment of equipment.
8/27/98	Denison called Clinkenbeard to discuss blowing cores. They had been rigging up to this point.
8/31/98	Denison called Clinkenbeard—should have cores blown by Friday.
9/4/98	Denison called Clinkenbeard to discuss molding issues of specific areas.
9/9/98	Allison called Clinkenbeard to discuss overrun on cost due to changes and complexity
9/11/98	Denison called Clinkenbeard to discuss problem aligning #5 core. Result of a locator bar possibly fitting 2 ways when it should have been made to fit only one direction, which would have prevented Denison from being able to do it wrong.
9/15/98	Allison called Clinkenbeard and said they expected to get okay to cover the overrun on cost.
9/16/98	Denison called Clinkenbeard and reported the core setup looked great so far—this is after making a new core with the locator bar on correctly.
9/25/98	Denison reported via phone the first casting passed zyglo—success.

Timing for this project was critical. If a normal acquisition cycle had been used, the quote process would have taken 4 weeks, tooling 16 weeks, and first article casting 10 weeks—for a total of 30 weeks. The Consortium's collaborative experience, along with improvements currently in place at various team members' locations, enabled a request for quote response in a couple of days, tooling production in 5 weeks, and the first useable casting 3 weeks later. Clinkenbeard & Associates, Inc. was able to ship the first 27 core boxes in 5.5 weeks, and the remaining 7 core boxes in just under 7 weeks. This includes the incorporation of changes required by Allison engineering. The original quoted delivery was 6 weeks, based on requiring 17 cores to produce this casting—the actual equipment consisted of 34 cores, including multiple engineering changes.

Another major accomplishment was the excellent communication flow between the Consortium and Allison. Because the Consortium had no previous experience with Allison, it was a significant achievement to experience no delays due to poor communication. Below is a table of the detailed communication between the Consortium and Allison during the project.

If the Consortium had been involved during design and product development, the end result would have been a more castable/manufacturable design in terms of tooling fabrication and maintenance, core setting, casting cleaning, and welding. In addition, the risk of mold filling failure or serious casting defects could have been reduced. A number of specific results were realized from the AAAV casting development:

- The CAD model translation from Unigraphics to Pro/Engineer via the Intermediate Graphics Exchange Standard (IGES) resulted in solid models that required some repair prior to use. The use of STEP protocol was found to be useful.
- Specific features of the transmission housing part design caused unnecessary challenges for the pattern maker and foundry. Earlier interaction between the supplier companies and the casting customer could have sharply reduced these difficulties, without function changes to the part design.
- The chain of communication established among the primary, secondary, and tertiary tier suppliers did not result in rapid communication of larger concepts (such as the part design intent) from the customer to all members of the supplier team. If Allison Transmissions had been given use of the *AC Notebook* to disseminate and receive critical information, communication difficulties would have been circumvented.

This successful program was a good test for the Consortium. The AAAV development is now entering phase 2, which will require much of the work to be produced again to an improved configuration. Discussions with Allison concerning this upcoming work have already taken place. There were other, less complex castings on the same program that took much longer and did not turn out successfully. The Consortium is in a good position to do more work based on past performance. Allison has expressed interest in using the *AC Notebook* environment, and in executing future casting acquisitions in closer collaboration with the Consortium.

3.1.2. Sundstrand housing casting example

Clinkenbeard & Associates, Inc. supplied Sundstrand three different bar-stock impellers and three cast and machined inlet valve housings, as shown in Figure 39. The castings, part of a main fuel pump for a military aircraft, is part of a development program not in production at this time. The part was designed prior to Consortium involvement. Clinkenbeard regularly supplies Sundstrand with bar-stock components, and also

Figure 39. Aircraft pattern and core plug.

supplies their foundries with tooling for them. Sundstrand's only restriction was that the casting activity had to be subcontracted to a Sundstrand-approved foundry.

For this project, Clinkenbeard was given a purchase order to produce tooling and supply machined castings. Clinkenbeard would produce the tooling and subcontracted two foundries for the casting activity. One of the foundries was Denison Industries, a member of the Consortium, although it was not an approved foundry. Because Denison's participation in the casting allowed a demonstration of agile methods, their efforts were considered part of the Agile Castings Program. All of Clinkenbeard's efforts were paid for by Sundstrand.

This casting had to meet grade C requirements and producing it required 2 exterior and 1 interior cores. Since the Consortium members are located in different parts of the country and both Clinkenbeard and Denison are experienced in aerospace work it was decided all decisions would be made utilizing 3D models and conference calls. This worked very well, facilitating discussion and agreement on parting lines, core requirements, foundry rigging and gating design.

Clinkenbeard started producing shapes immediately for the tooling while foundry-pouring decisions were being made as shown in Figure 40. The tooling was completed in just 7 days and sent via FedEx to Denison for next-morning delivery. Clinkenbeard and Denison stayed in close communication, as shown in Table 7, about the tooling progress so that the order could be planned in Denison's production schedule. Denison was able to produce the 3 cores plus the cope and drag molds as shown in Figure 41, and pour the casting on the same day tooling was received.

The casting as shown in Figure 42 went through nondestructive testing and heat treat the next day. Total time in the foundry was 3 days. Denison shipped radiographic, liquid penetrant and chemical physical certifications, and x-ray film along with the casting. Separate cast test bars were poured with the castings and heat treated together. Radiographic inspection showed the castings to meet or exceed Grade B, which meets most aerospace requirements. The castings were inspected with liquid penetrant and met Grade B.

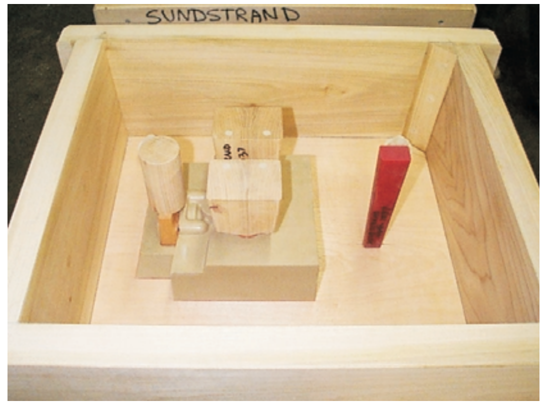


Figure 40. The mold box for the Sunstrand housing.

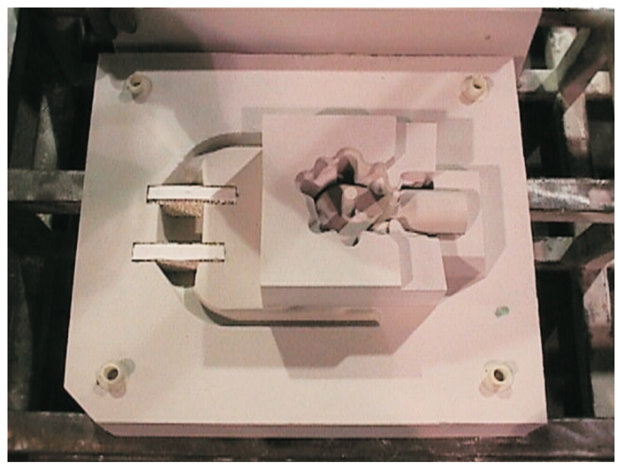


Figure 41. The drag mold of the Sunstrand housing.

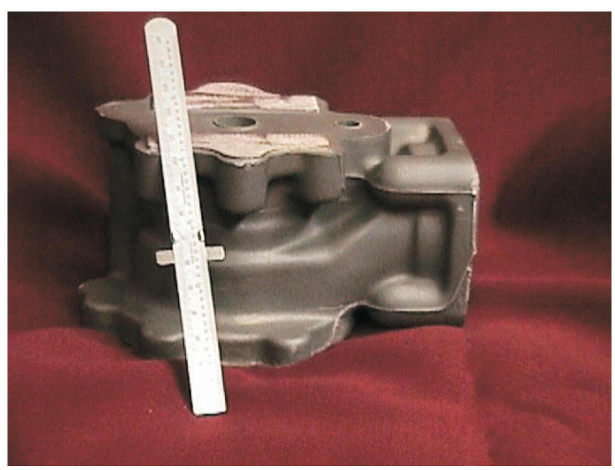


Figure 42. The finished part.

Table 7 Chronology of Sundstrand events

Date	Activity
5/8/98	Sundstrand Aerospace placed an STL model of a DOD casting it needed to procure on the Clinkenbeard FTP site and signed off on the revision level of the model.
5/9/98	Clinkenbeard added the appropriate shrinkage factor to the STL model and began building the exterior master pattern on the Stratasys FDM 8000. The total build time using P400 ABS plastic filament was 53.7 hours. Clinkenbeard also began manufacturing the interior core plug. The core plug was machined out of Ren-plank 450 and took 8 hours to produce.
5/11/98	Denison received model from Clinkenbeard FTP site.
5/12/98	All master work was completed and reviewed and prototype foundry tooling construction began. The tooling required consisted of Cope box, Drag box, one interior core box, two side core boxes, all reproduced using foundry grade urethane.
5/16/98	Denison agreed on pattern and gating concept.
5/19/98	The equipment was finished and shipped in three shipments to speed rigging at Denison. On this date, the interior core box was shipped.
5/20/98	The Cope box and Drag boxes were shipped.
5/20/98	The core box for internal coring was received at Denison.
5/21/98	The two side core boxes were shipped. The pattern was received and two models were made using the cold box air set process (pepset).
5/22/98	In the morning, the two side core boxes were received and made with the air set process.
5/26/98	A package containing radiographic, liquid penetrant and chemical physical certifications, along with x-ray film and the castings, was overnighted to Clinkenbeard and Associates on May 26, 1998.

The results of test bars were as follows:

- Tensile: 49007
- Yield: 35700
- Elongation: 6.1%

While the casting requirements were grade C this casting passed grade B requirements in all tests. This project yielded two castings that met all design intents in under three weeks. Industry average lead time for this type of activity is usually on the order of twelve weeks.

If a typical cycle were used it would consist of a quote process of 4 weeks, tooling 4 weeks and casting production of 4 weeks. With the Consortium's experience and enhancements in place, the first useable casting was completed 19 days after receipt of 3D models from the customer. While the program did not dictate a critical delivery on this part it does inform the industry that great strides have been made in the acquisition of castings if the right tools and sources are utilized. More work is expected to come from this exercise since Sundstrand has been a long-term customer.

This is another case where being involved in the Agile Casting Program has enhanced all the members' capabilities. In this particular case everyone was very comfortable with not having a physical meeting to discuss design and production issues prior to proceeding with this project. The speed advantages of agile methods were clear in this example. The same tooling, however quickly and well produced, would not have resulted in the same rapid results if the foundry had not employed agile methods demonstrated in close communication and electronic file sharing with the patternmaker.

3.1.3. VME subrack

General Dynamics Defense System (GDDS, formerly Lockheed Martin, Pittsfield, MA) a former Consortium member in 1997–98, presented to the Consortium an existing VME subrack manufactured by fabrication and weldment. The VME subrack is an electronic enclosure for the command and communication related circuitry used by the U.S. Navy. GDDS determined that by using a one-piece casting, significant cost saving and reduced cycle time could be realized. The primary objective was to replace the existing fabricated/weldment subrack with a cast part without affecting any other equipment in the assembly or the function of the assembly. Design, manufacturing and quality related requirements were laid out at the onset of the program.

K + P Agile, Inc. was the tier-one supplier to GDDS and executed the industrial contract, project management and client communications for this project. Clinkenbeard was a subcontractor to produce the tooling, and Denison Industries was a sub-contractor to produce two prototype rough castings and a current machine shop vendor was subcontracted to carry out the finish machining and painting. Figure 43 shows the existing weldment and Figure 44 shows the initial conceptual cast model.

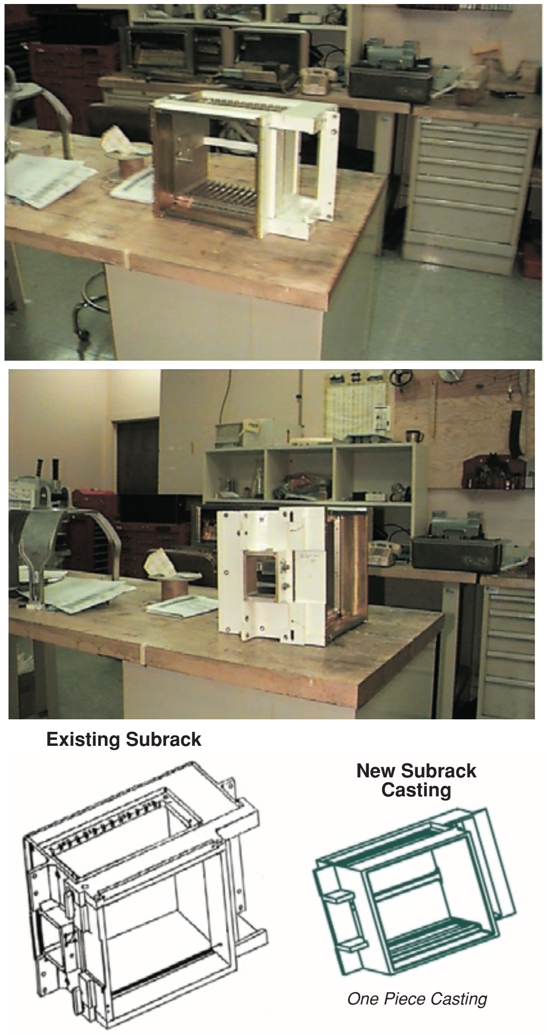


Figure 43. Existing weldment – finished component.

The timeline demanded by GDDS's customer (U.S. Navy) for the entire acquisition, the casting requirements as listed below, and the shape complexity place this conversion into the category that demands an integrated approach consisting of intelligent modeling, design, analysis, process simulation and rapid prototyping technologies. The initial risk assessment done at the beginning of the program highlighted the need for the agile manufacturing system.

The timeline did not allow any additional casting sampling and the first casting had to meet all the casting requirements. The conventional approach, which consists of traditional trial and error to validate the casting geometry and process parameters, would have taken at least 40 weeks of development time. Additionally, K + P Agile, Inc. offered a single point of contact for the entire conversion and prototype manufacturing, thereby eliminating the danger of reproducing redundant efforts such as separate solid modeling for design, analysis and tooling. Also, the contract was for the fixed cost and time

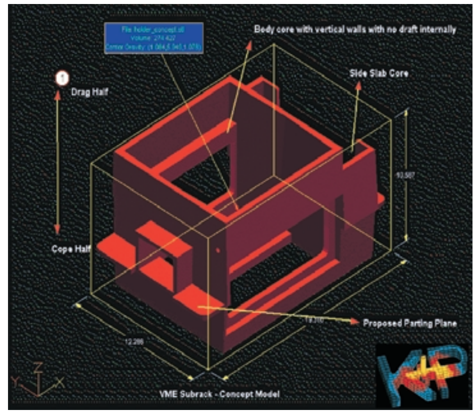


Figure 44. Conceptual cast model used for the collaboration between the team members .

line. The team members had the communication in place for the document sharing and white boarding using *AC Notebook* software which otherwise would have added additional time and cost associated with the travel for face-to-face meetings among the Consortium members—K + P Agile, Inc.; Clinkenbeard & Associates, Inc.; and Denison Industries.

K + P Agile, Inc. product engineers converted weldment to one-piece casting route, keeping in mind the manufacturability of the product. The initial conceptual design was communicated using the *AC Notebook* with the foundry and the tool shop. The software was used, along with teleconferences, for document sharing and communication of the conceptual one-piece casting design options and casting orientation with respect to the parting plane. *AC Notebook's* whiteboard was used to collaborate, in real time, the proposed tooling construction related information such as parting plane, core prints, and rigging. Also, the same enabler was used to discuss the casting process modeling analysis results such as filling sequence and predicted shrinkage locations.

Casting process modeling was used to validate the geometry for the castability, to optimize the casting process parameters, and to predict the internal soundness before any hard tooling was made. While creating the master model, which consists of machined part geometry, rough casting geometry, and tooling geometry, design issues were concurrently discussed and implemented with the team members. The interim design iterations were communicated using a full-scale model using layered object modeling (LOM) produced by K + P Agile, Inc. as shown in Figure 45. Overlaying the solid model of the existing weldment validated the final casting design model. Assembly form and fit validation was carried out using the full-scale LOM model manufactured by K + P Agile, Inc.

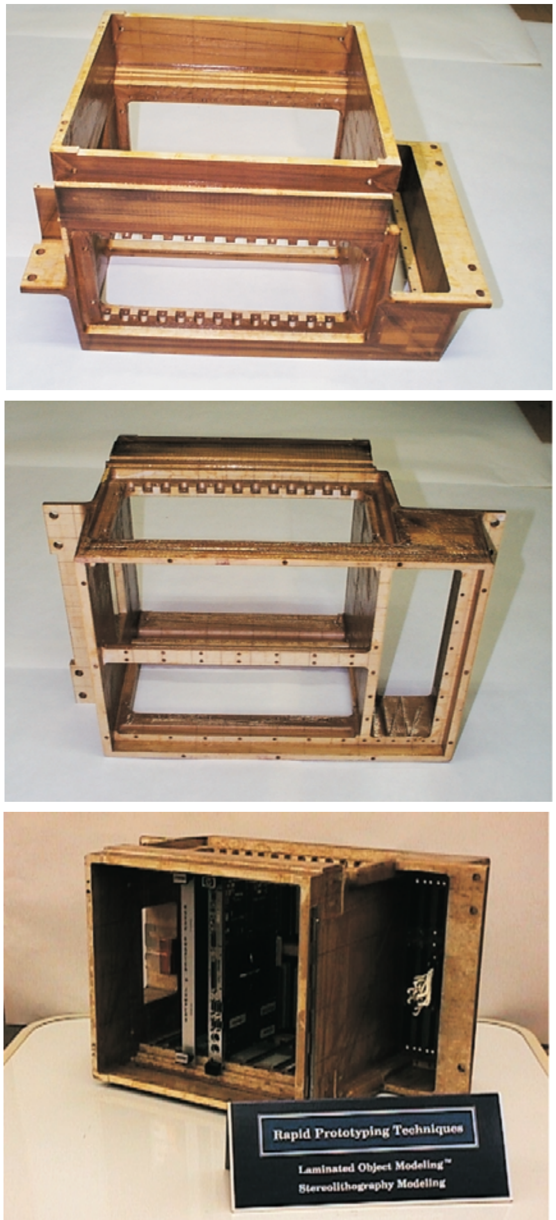


Figure 45. Full scale LOM model produced by K+P Agile, Inc.

The casting quality and acceptance criteria were developed after reviewing FEA results for a sound product development. Based on the material and manufacturing process, shock, vibration FEA and fracture mechanics tests were performed for the final design. K + P Agile, Inc. worked closely with Denison Industries and Clinkenbeard & Associates, Inc. to develop parting plane, risering and gating systems earlier in the product development, and created solid models of the same. The part geometry, rigging design, and casting process parameters were optimized by carrying out mold filling and solidification simulation. The goal was to

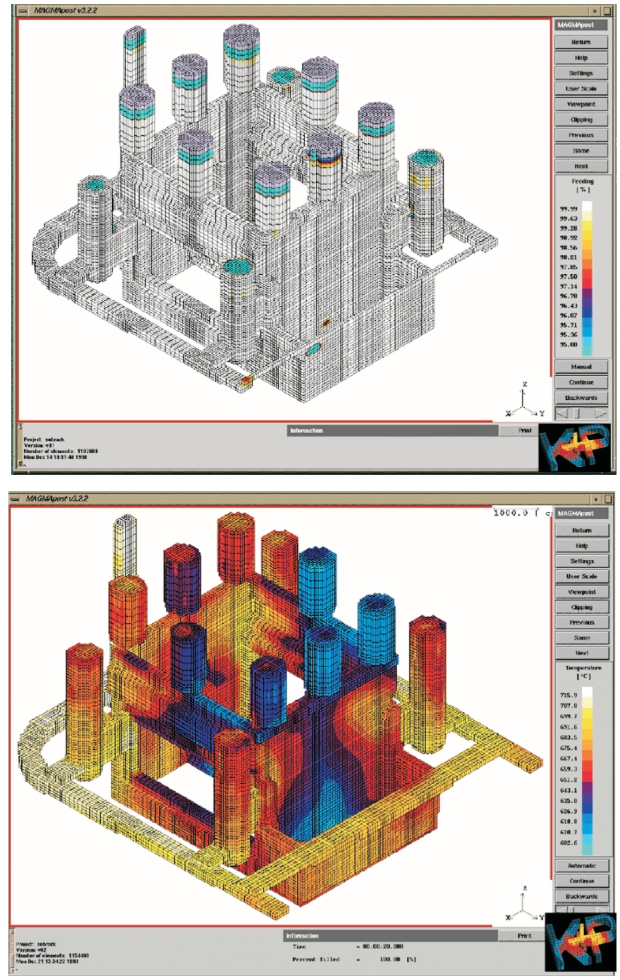


Figure 46. Predicted shrinkage porosity – 1st Iteration.

make casting right at the first time. Figure 46 shows the first of two iterations that were carried out.

The Consortium developed the geometry of the patterns and core boxes, which in turn were used to manufacture prototype tooling shown in Figure 47 using a combination of 3-Axis CNC milling and manual bench pattern making. K + P Agile, Inc. helped GDDS develop casting specifications such as surface finish, internal soundness, dimensional tolerances, etc. A K + P Agile, Inc. engineer followed up at Denison Industries the first article through the layout table. The first article inspection included 100% dimensional inspection, and applicable NDT. The Consortium provided GDDS with two prototype castings in finished condition, one is shown in Figure 48 and the as-machined surfaces are shown in Figure 49. K + P Agile, Inc. provided engineering drawings with all the notes for the machined component with the cast components.

The resulting part had the following specifications:

- Process: Chemically bonded sand process

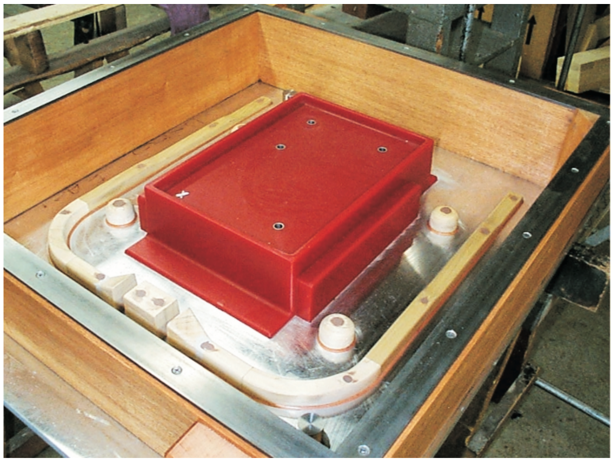


Figure 47. Urethane/Wood Pattern.

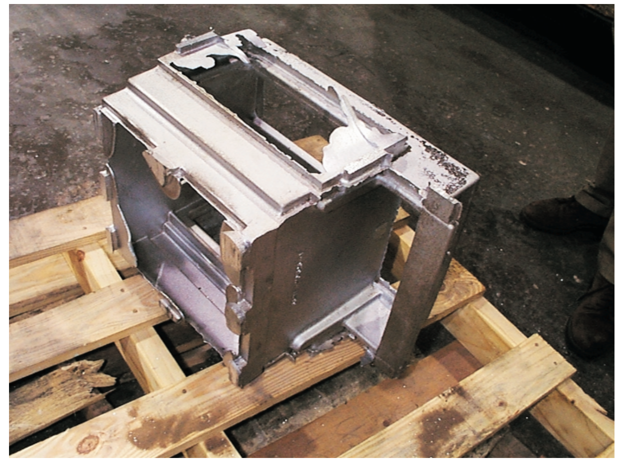


Figure 48. Rough casting – 1st prototype.

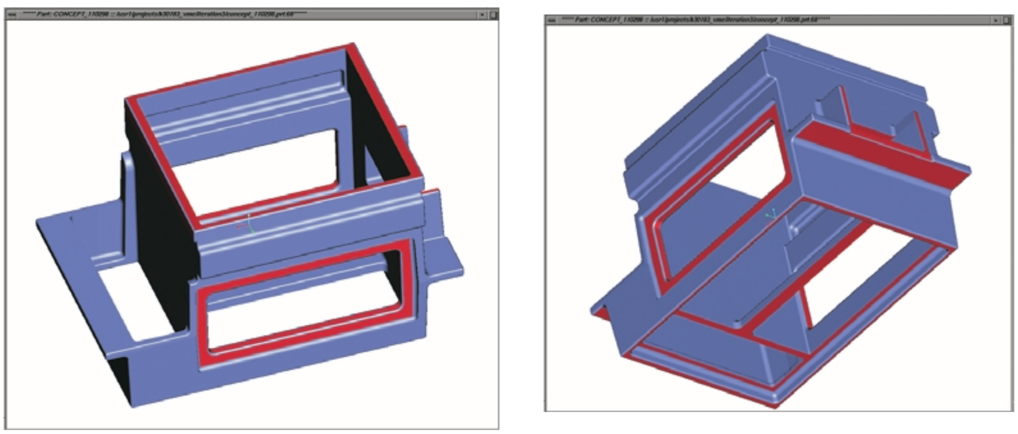


Figure 49. Finished design with matching surfaces marked.

- Alloy: AL Alloy Casting Alloy A356 T7, ASTM B26
- Heat treat: IAW MIL-STD-6088
- Dimensional:
  - — Cast Edge Radii – Sharp to 0.188
  - — Cast Fillet Radii – 0.250 min. as otherwise specified
  - — Cast Walls – 0.375 +0.090–0.030 (Note: Wall thickness may vary up to 0.400 inches max in local areas. Variation will not exceed 2% of local wall area.)
  - — Draft Angle – 2 degree draft except where noted.
- Cast tolerances unless otherwise specified:
  - — Angle ±1 degree
  - — Dimensions ±0.060 up to 6.00 inches ±0.090 over 6.00 inches up to 12.00 inches ±0.12 over 12.00 inches
- Surface finish: 560 IAW AA-CS-E18
- Processing allowances: gates, burrs, flashing, and parting line evidence up to 0.03 inches on nonmachined surfaces and 0.06 maximum on machined surfaces is allowed. Evidence of chills are allowed in internal surfaces only.
- Nondestructive testing: liquid penetrate inspect all castings IAW ASTM E1417; etching prior to LPI is not required.
- Weld repair: weld repair is allowed per IAW ASTM B26. Examination of weld repairs by radiography is required.
- Certification: certification is required for material chemistry, mechanical properties, radiography, and liquid penetrate inspection.
- Inspection: inspect casting IAW MIL-STD-2175, class 4, grade D, except where noted.

Currently the component is under production at Denison Industries. Since the design was developed collaboratively, the end result was a manufacturable design simulated for the worst casting process parameters, which gave the customer (GDDS) and the foundry added confidence in achieving the casting quality requirements in production. The modified one-piece casting design would be incorporated into the EGISS, DCSS and MIB designs in the future.

The casting from conceptual stage till the delivery of the first functional prototype including design, analysis, validation, production tooling and casting was carried out in 14 weeks. The preliminary, interim and final design reviews were held with the customer and the U.S. Navy. The form, fit and functionality including the critical alignment, shock and vibration of the existing weldment were maintained. This casting change did not affect other requirements. The new design and manufacturing process was validated before any hard tooling was made using computer process simulation technique and the design was validated by carrying out FEA to model shock and vibration tests. The first article was produced successfully, meeting all the casting requirements. The product unit cost was reduced by 40%, component weight was reduced from 24.9 lbs (fabricated assembly) to 23.2 lbs (one-piece casting) and the component acquisition cycle was reduced from 40 (as best estimated by GDDS) weeks to 14 weeks. The component is now under production at Denison Industries. Modified one-piece casting design will be incorporated into the EGISS, DCSS and MIB designs in the future.

Typically, the casting user, GDDS, would have developed a casting design without getting the feedback of the experienced design and foundry-manufacturing engineers. Also, the design would not have been validated for the worst casting scenarios. The tooling would have been built with the conventional manual pattern making. The foundry would have gone through a series of sampling plans to perfect the process parameters and to validate the geometry for the manufacturability. This would have resulted in the increased cost and extended timeline for the acquisition due to retooling and resampling. Also, this part involves very tight tolerances for the as-cast and finish-machined features. If the collaboration with the machine shop was not sought for, the additional difficulties in the first article qualification would have occurred. The estimated time for the entire acquisition from the fabricated drawings to the functional fully machined prototype would have taken at least 40 weeks.

3.1.4. Examples of document control

The experience at Atchison Casting Corporation is an example of how the participating companies have benefited from the collaboration as part of the Consortium.

Atchison Casting has participated in the Consortium very actively, resulting in significant improvement in business practices. Collaboration with the Consortium highlighted a need for change within the traditional business operating system and has driven Atchison to overhaul its document control system.

Atchison's primary method of document control was formerly a manual paper-laden sequence as shown in Figure 50. This resulted in a protracted cycle time for design review, generation of cost estimates and subsequent price quotations back to the customer. Atchison has now implemented a change in the control system that has resulted in the creation and implementation of an internal web-centric database. The first web-centric application is the request for quote process as shown in Figure 51. This will result in a more expeditious sequence and will fully utilize the infrastructure and technology enablers our Consortium participation has established. This will encompass both internal and external communication.

The benefits of this mechanism have been process simplification, timeliness, version control, and archiving, which are key to the agility of an organization and its ability to deal with tight schedules, lower cost and late engineering changes.

3.1.5. Examples of collaboration

The structure of the *AC Notebook* does not preclude use for other distributed group activities, without any significant modification. Two large projects involving GE Corporate Research and Development, Lockheed Martin, and other organizations have been using the notebook to share files and manage project information. Both of these projects place a premium on rapid and secure communication involving the handling of large and varied computer files to engineers and scientists at several sites. An example of a project view at the document level for one of the noncasting activities is shown in Figure 52.

For the future, the functionality of the software has great value within GE's organization. Already the tools developed for the *AC Notebook* have been used in various forms for sharing information through various development lifecycles. Typically these have involved collaboration between various business units.

Beyond the product development cycles that the GE businesses are involved with are other initiatives involving many organizations within the business. These objectives typically have very aggressive goals and involve teams that are part of various organizations, IT networks, and backgrounds that may be distributed throughout the U.S. and sometimes around the world. Due to the short nature of the GE business cycles the execution pace of these initiatives puts enormous pressure on getting results quickly.

The ability of subteams to take on the various tasks of the initiative and work independently yet within the larger context is crucial to timely deliverables. This requires the ability to construct structured mechanisms

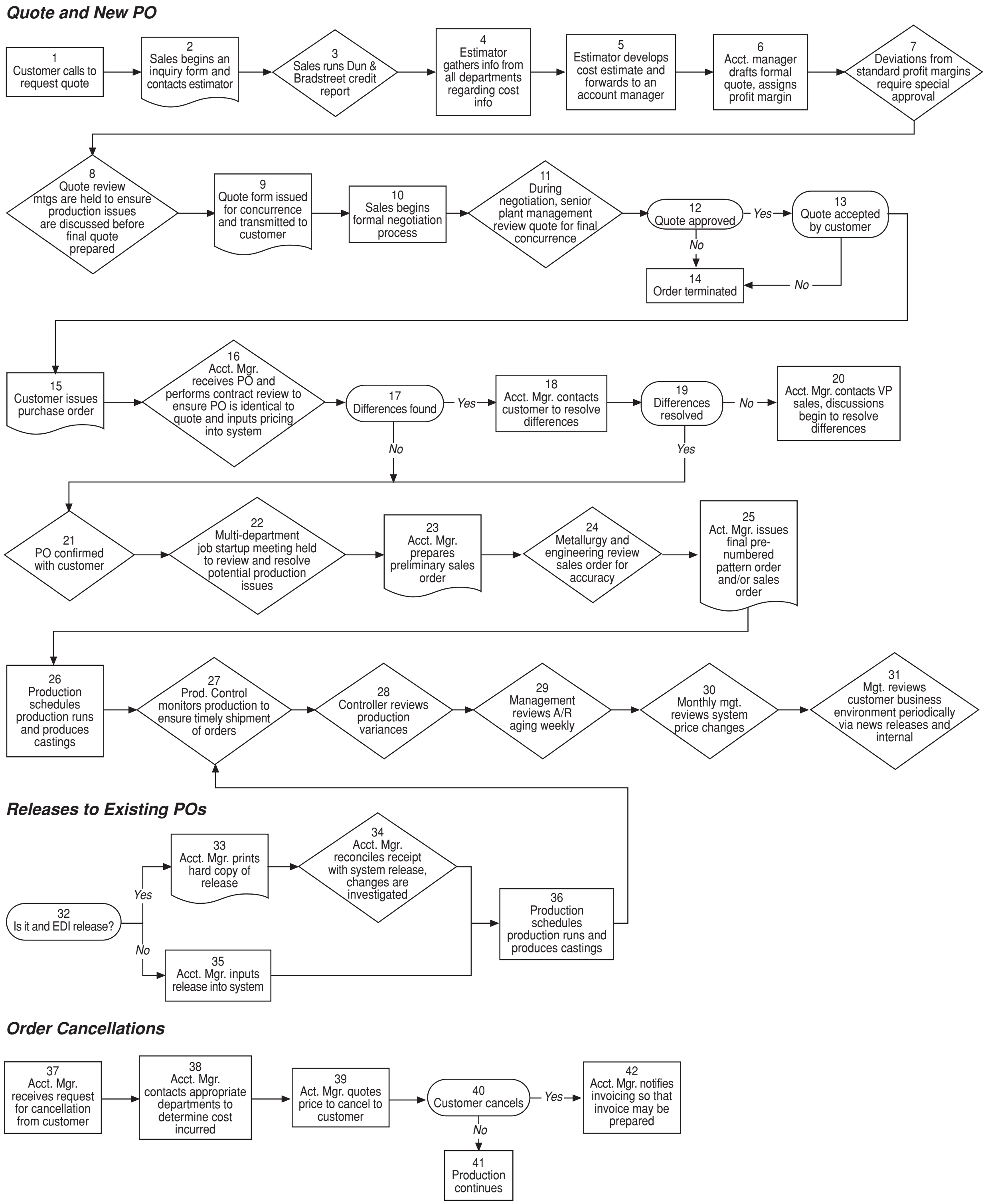


Figure 50. The former manual quote process.

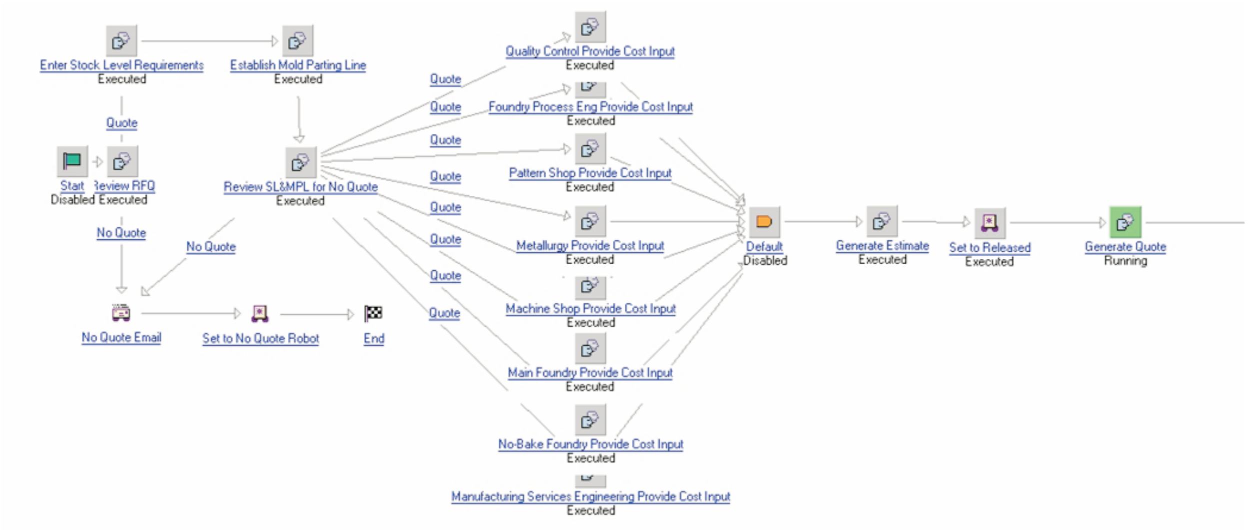


Figure 51. New, web-enabled quote process.

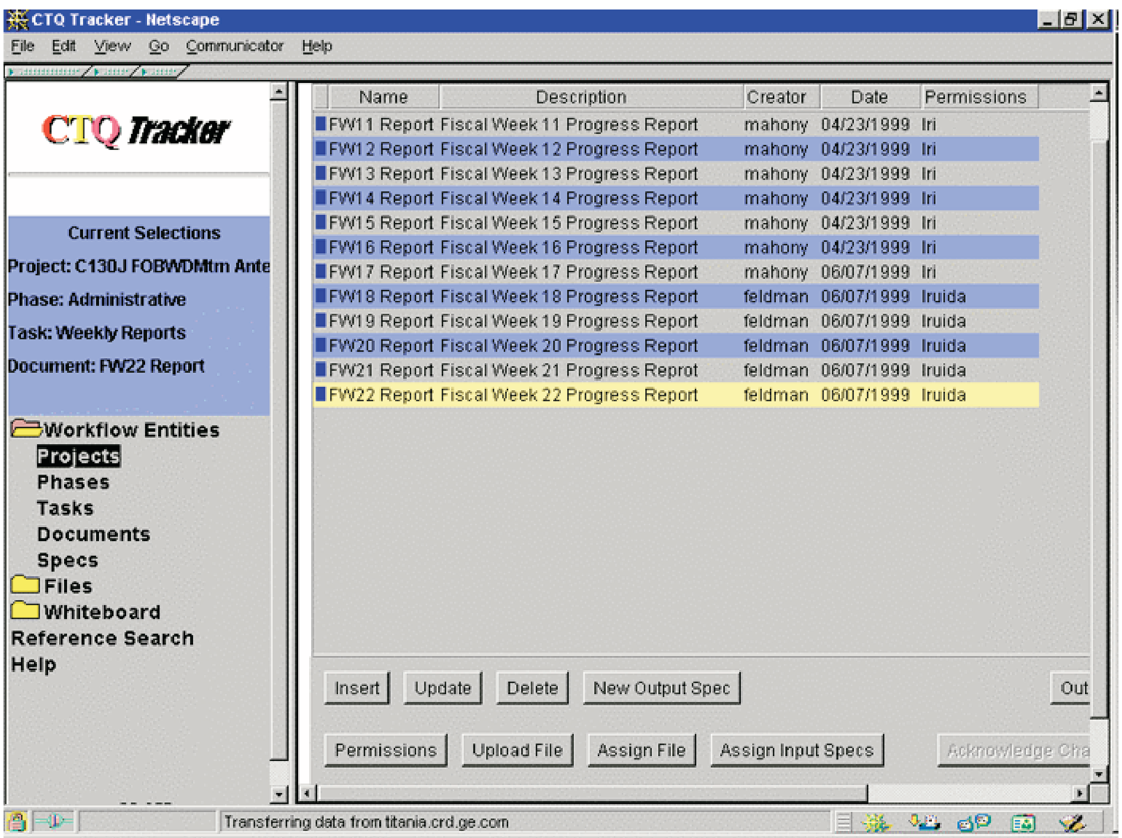


Figure 52. Project screen for a collaborative research project involving GE Corporate Research and Development and Lockheed Martin Corporation .

for sharing the information quickly by the champion of the initiative and ability to provide subteam leaders autonomy of execution. Visibility of the state of the whole initiative to the manager, however, is important to its success.

The *AC Notebook* provides the tools to enable this interaction, yielding dramatic reductions in time and effort. The tools for project management that can be used through Internet browsers facilitate connectivity from anywhere. The flexibility of the security features allows the manager to set up any level of access or restriction from the overall project down to the individual documents. The tasks can be assigned to subteam leaders and progress tracked at any level. The notebook also allows projects to be set up "on the fly," facilitating immediate action taking advantage of the existing infrastructure.

Within GE, the initial basis for use of the *AC Notebook* will be for projects between GE Corporate Research and Development and the GE businesses. The vision is that through using it, the businesses will realize its potential and request servers of their own for collaboration within their organizations and with their vendors.

3.2. TECHNICAL ACCOMPLISHMENTS

3.2.1. Functionality of the AC Notebook

The *AC Notebook* software tools have matured through the alpha test cycle, to become a robust suite of collaboration utilities. Functionality falls into three main categories: project management, synchronous collaboration, and reference searches. Data accessed by the tools are stored in a common database, and so are available to all of the tools.

Project management

Hierarchical project structure—One of the requirements of the Consortium was a means of representing a project hierarchy. When a new casting acquisition process begins, a project can be created within the system which is accessible to all members of the supply chain. This project is divided into phases which may occur in series or in parallel. The phases are divided into individual tasks which may be assigned to any user. Documents produced during the execution of a task can be stored under that task. Each of the versions of that document can be stored as an individual file under the document. The resulting structure is a hierarchy of project entities. Figure 53 shows how a project stored in the *AC Notebook* is organized. The top level is the Project; this would be the specific casting on which the Consortium is collaborating. Each project is divided into one or more phases. Two phases may follow one right after the other, or they may run in parallel. Each phase is bounded by a start and end date, but there is no explicit relationship between two phases. Beneath each phase is a set of tasks. Again, as is often the case in a casting acquisition, tasks may run in series or in parallel; their schedule and duration is determined only by their start and end dates. Within each task is stored one or more documents related to that task. A document is intended to store all of the versions of a File containing data pertinent to that task.

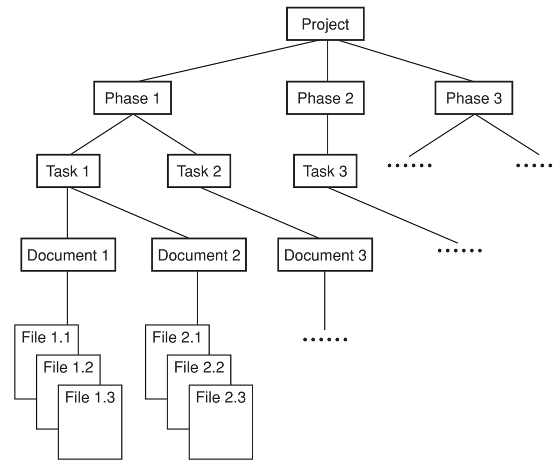


Figure 53. Project hierarchy within the *AC Notebook.*

Specification management

In addition to their place in the hierarchical project tree, the documents are also part of a graph structure that represents the flow of information throughout the project. This graph is used to "propagate" changes to downstream documents by giving them a red or yellow status. The documents within a project hierarchy are interconnected through their interaction with a set of "specs." Figure 54 shows how documents are connected through specs, which are critical pieces of information that are output from one document and input into another. Specs and their relationships to the documents are defined manually, by the user. Each spec represents a piece of information that is the output from one document and the input to one or more other documents.

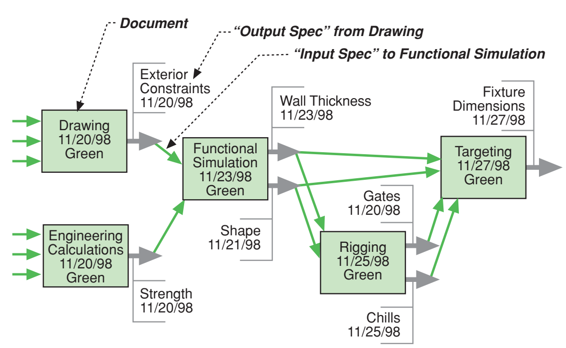


Figure 54. Relationships among documents and specs.

A document is assigned a red, yellow, or green status based on whether or not its input specs have changed since the last time the document itself was updated. When the user uploads a new version of a document (i.e. a new file), he/she has the opportunity to indicate that one or more of the pre-defined output specs from that document has changed. This causes all directly dependent documents (that have this spec as an input) to be assigned a red status. A red status indicates that at least one of the input specs to the document has been modified, and that the document has not been updated to account for the change. In addition, all documents that are further downstream (that get input specs from the directly dependent documents) are assigned a yellow status. A yellow status indicates that a document further upstream is red. It is then the responsibility of the owners of the affected documents to check the input specs to see what has changed, and then either make changes in his/her document to account for these changes, or indicate that the changes have no effect on his/her document.

In the example shown in Figure 54, assume that the user uploads a new version of the drawing document and that he indicates that the exterior constraints spec has changed. This action would cause the functional simulation document to turn red and the rigging and targeting documents to turn yellow. If the owner of the functional simulation document then uploaded a new set of simulation results to account for the new exterior constraints, changing the wall thickness, then both the rigging and targeting documents would turn red. In this way, the changes to the drawing document would propagate through the entire project. By creating the relationships between the documents and specs, and by consistently recording changes to documents and indicating modification to the related output specs, users can ensure that all members of the supply chain are made aware of changes throughout the casting process.

Like documents, each phase is assigned a status within the system. However, the status of a phase is based on whether or not it has been "signed off." The end of each phase can be made a "tollgate" by associating one or more signatories with it. While the end date of the phase is still at least one week away, the status of the phase is green. If less than one week remains before the end date and at least one of the required users has not signed off, the phase turns yellow. If the end date passes and not all required users have signed off, the phase has a red status.

File storage

As stated earlier, files can be stored as individual versions of a document under a particular project. Although this is the preferred means of storing files within the system, it is also possible to store a file in the system without associating it with a document or a project. This allows users to share a file rapidly, without having to create a project hierarchy around it. This is useful for files that do not necessarily fit into a single project, such as general casting best practices, Consortium meeting agendas, etc.

Tollgates

A "tollgate" can be placed at the end of any phase by requiring one or more signatures for the completion of the phase. The red/yellow/green status of the phase is dependent upon a combination of the end date of the phase and whether or not all required users have signed off. As long as the end date of the phase is still at least one week away, the status of the phase is green. If less than one week remains before the end date and at least one of the required users has not signed off, the phase turns yellow. If the end date passes and not all required users have signed off, the phase has a red status.

Permissions

It is possible to create a set of permissions on a project, phase, etc. Types of access that can be controlled are: "read," which allows reading of files; "list," which allows viewing meta-data for projects, phases, etc. in tabular form, "insert," which allows creation of new phases, tasks, etc., "delete," which allows the deletion of phases, tasks, etc., "write," which allows the updating of phases, tasks, etc., and "admin," which allows the setting of the permissions themselves. Permissions can be granted or denied to individual users or to entire groups of users. Access permissions can also be set at any level of the project hierarchy. It is possible, for instance, to make nearly an entire project accessible to all members of the supply chain, but restrict access to one task or one document to a single user. This allows even competitors in the casting industry to work together on one casting without the danger of sensitive data on another casting being compromised.

The project management component of the software tools developed by the Consortium is displayed in an intuitive, tabular user interface in standard web browser windows. Global access to project information is provided by a persistent frame in the left of the window, while responses to selections made in that frame and through screen rendered "buttons" are displayed in the larger right frame. Figure 55. shows a listing of projects; as with all tabular representation, the widths and order of the displayed columns can be altered by dragging the objects with the mouse cursor. The pop-up menu obtained by clicking with the right mouse button allows the user to act on the selected row item. From this viewed location, the user can alter or remove the highlighted item (with the necessary permissions) or descend

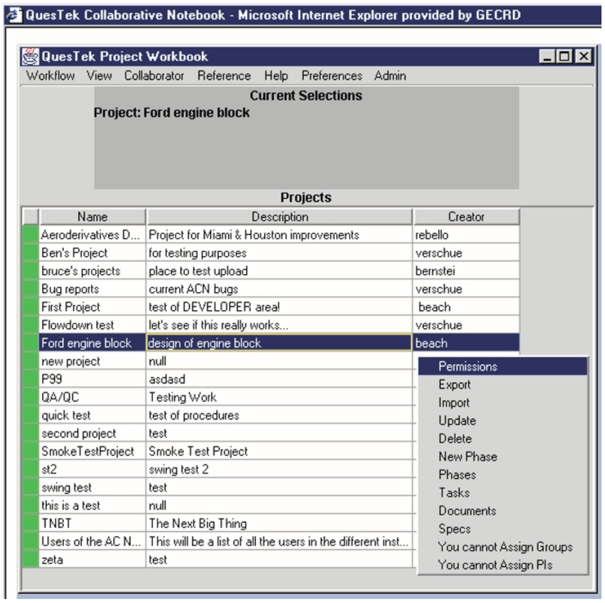


Figure 55. **Project screen view of the *AC Notebook*.**

the project hierarchy by choosing phases, tasks, or documents. At the edge of the right frame is a column that alerts system users as to the status of the workflow entities displayed in the table. The status of a project will change from green to yellow, and finally, red, as the deadline for project ending approaches and is surpassed without all necessary phase signatories admitting satisfactory completion.

An important management concept embodied in the software is the feature that allows association of specific information (specs) with the documents contained within project tasks. Users with the necessary permissions are able to name and/or assign specs as being controlled by (output specs) or used by (input specs) certain documents. When a document owner alters a document (by uploading a new Version) and marks an output spec as changed, any document that has been identified as using the spec (by association as input) has its status color changed to red. documents that depend on that which was altered, but are removed from the altered document by at least one intervening document, are changed in status to yellow, if the prior status was green. With this scheme, collaborators can see at a glance whether any critical information that they rely upon has been changed, alerting them to investigate the cause. This is readily accomplished within the notebook, as any input spec associated with a document will seen with red status, if the document creation date is less recent than the spec upon which it relies. Figure 56 shows the dialog box that is used to create a new spec and assign it as output from a document. Any number of specs may be applied as input to a document by selection from the previously created population, using the dialog box

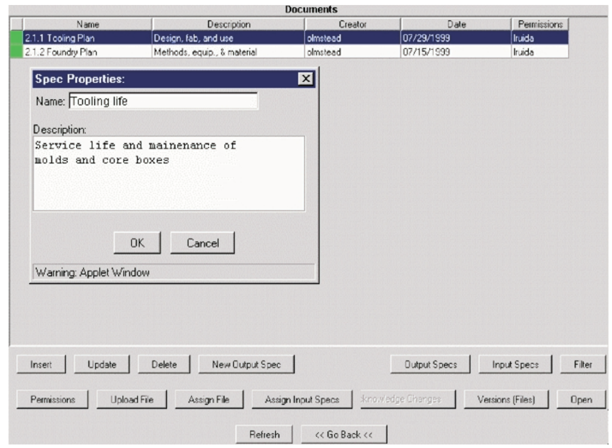


Figure 56. **Assigning a new spec as output from a document.**

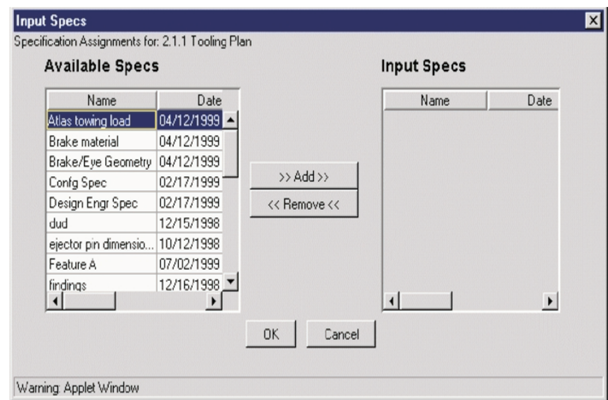


Figure 57. **Selection of specs to be applied as input to the document.**

(Figure 57), that is displayed when a qualified user selects the “Assign input specs” button.

Synchronous collaboration

The whiteboard developed for the *AC Notebook* is has a number of special features that distinguish it from other whiteboard applications. First, like the rest of the *AC Notebook*, it requires no software other than a browser to be installed on the client machine. Second, it does not require a persistent connection between each client and the server; rather, all communication happens through secure HTTP transactions. This allows even clients with firewalls to use the whiteboard. Finally, in addition to standard drawing tools like “pen,” “line,” “oval,” etc., the whiteboard allows users to load a GIF or JPEG image directly from the *AC Notebook* file archive into the background of the whiteboard. This image can then be marked up using the drawing tools while participants discuss the changes over the telephone. The *AC Notebook* whiteboard is a particularly useful tool for sharing image files among a large, distributed group. The sessions can be open to all users, or protected by password, and can be joined and exited by any member (other than the session creator) without disturbing the state of the image and overlaid text and marks. The background image can be automatically dimensioned to fit in the window, or the window can be altered to accommodate varying sized images. User input to the whiteboard, and the server updates, are passed as encrypted packets using hypertext transfer protocol (HTTP). This has allowed secure transactions with rapid image update cycles, even across restrictive firewalls. is an example of a whiteboard session window with added text and marks overlaid upon the background image. The left column of icons are the user operations supported by the whiteboard tool: selecting an overlay object on the screen (prior to dragging to another location), drawing rectangles, ellipses, freehand lines, segmented and straight lines, adding text, changing the background image, deleting text and drawing marks, and ending the collaborative session (Figure 58).

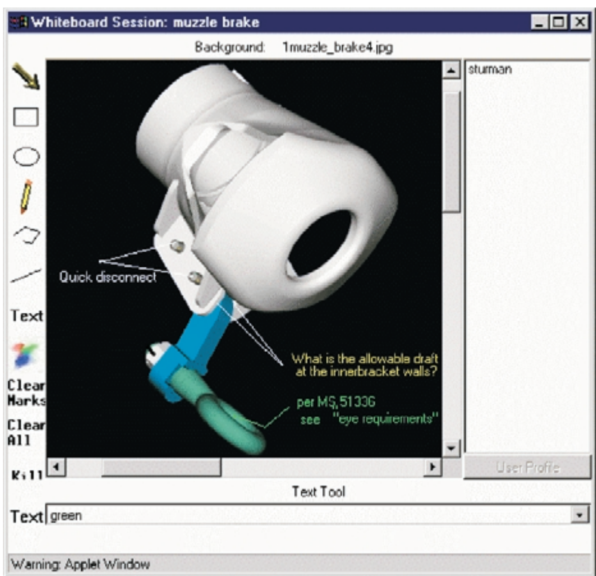


Figure 58. A collaboration session with text and marking overlays.

Reference searches

The *AC Notebook* includes a tool for archiving and retrieving information of general interest, that may be required for a number of projects, or that is not of proprietary concern. The Reference Search tool was created to allow collaborators the opportunity to retain documents of persistent value in a fashion that was easy to manage, store, and recall. When files are uploaded to the *AC Notebook*, a user with appropriate privilege is given the option to mark the file as "reference". To aid others in effectively locating desired information, reference files are tagged with a single main topic and one or more keywords. The words can be created by the users, or chosen from the existing lists displayed by the reference tool. shows the Reference Search window and a retrieved reference file stored as reference in the *AC Notebook*. Any file in the *AC Notebook* can be made a "reference" by associating with it a "main topic" and one or more "keywords." This feature is especially useful for the identification of a "best practice" from a casting acquisition. By using a consistent set of keywords and organizing files under appropriate main topics, it is possible to allow users to find files with similar subject matter that span multiple projects. It is important to note that the same permission structure still applies to a file after it has been made a reference. Any files that are not readable to a particular user will not appear in the reference list if that user searches for its main topic and keywords.

Software implementation

Figure 59 is a diagram of the client-server transactions that occur during the operation of the *AC Notebook*. Although this diagram does not include all components, it covers the ones that are relevant to this discussion.

One of the major advantages of this software over many other collaborative tools is that it is essentially "zero client"—no special software other than a modern web browser is required to be kept on the user's computer. All code resides on a central web server, in this case at GE Corporate Research and Development. An authorized user may access the application by loading the *AC Notebook* URL into his/her web browser. At that time, some of the Java code is loaded into the user's browser. This code, consisting of Java applets and their supporting classes, runs within the Java Virtual Machine and remains on the client for the remainder of the session. The primary function of the client-side Java is to provide some of the basic user interface capability, thus reducing the client-server traffic and improving the performance of the system.

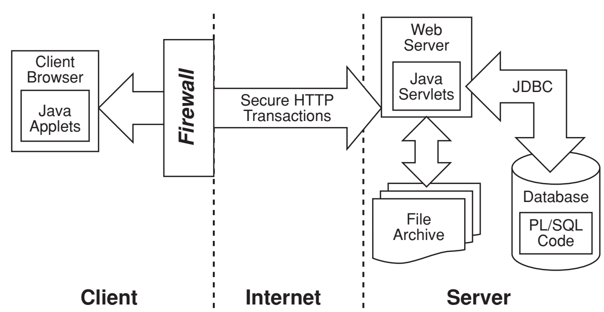


Figure 59. Client-server interactions.

The rest of the code that makes up the *AC Notebook* resides and runs on the server. The Java servlets provide access to shared resources on the server. These include the file archive, the database, and the whiteboard session data. In addition to the Java servlets, some of the server-side functionality is performed by PL/SQL routines stored in the Oracle database. These routines improve performance by grouping operations that would normally require numerous database queries and providing the result through a single transaction.

All data are passed between the client and the server through HTTP transactions. Although potentially somewhat slower than sockets because of the lack of a persistent connection, HTTP transactions have the advantage of working through client firewalls. The socket implementation used in the first Java prototype could not be used at two of the Consortium member sites because of their particular firewall configurations. The current version of the *AC Notebook*, in which Java applets on the client communicate using HTTP with Java servlets on the server, has been used successfully by all Consortium members.

Security of the data in the AC Notebook is provided using SSL (Secure Socket Layer) on the web server. SSL authentication is more secure than BASIC HTTP authentication for a number of reasons. SSL encrypts all HTTP transactions so that they would be indecipherable to anyone who did not have the session key. In addition, access to the *AC Notebook* is granted only to users holding a digital certificate, which is issued by the party hosting the application (GE Corporate Research and Development). Key identification information from this digital certificate is sent along with every HTTP transaction, and this information is used programmatically to enforce a permissions model for reading or modifying data within the *AC Notebook*.

3.2.2. Deployment of the AC Notebook

GE will distribute to the Consortium members copies of the software and all available documentation for the *AC Notebook*. QuesTek Innovations LLC successfully installed a previous version of the software and successfully added functionality to it. All the Consortium members intend to continue using the software in the future. Several of the Consortium members have expressed the plan to enhance the functionality and/or create a new system based on this prototype.

3.3. PARTING SURFACE GEOMETRY

The Consortium has produced an algorithm that creates STL or ASCII computer files of smoothly-varying parting surfaces for two-part core boxes. The method requires that the parting direction and parting line be predefined by the software user. If the parting line circumscribing the model of the core can be accommodated by a single parting surface, the program will generate two ASCII or STL files, containing smoothly-varying, matching surfaces extending from the parting line to a plane normal to the parting direction. These

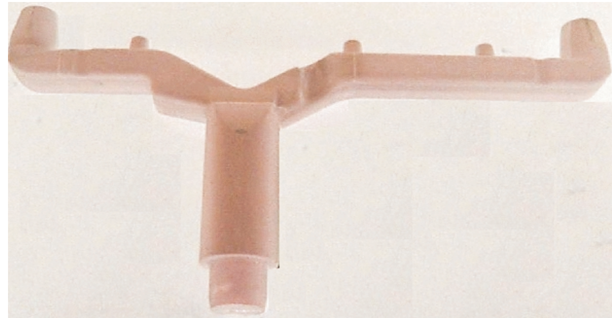


Figure 60. T core with segments of non-coincident axes. The parting line must intersect the core at the largest width about the entire object.

files can be supplied to machining system controllers to produce the core box surfaces.

Figure 60 is a photograph of the mating surfaces of an example box that was cut using surfaces generated with the computer method. STL representations of the two parting surfaces generated with the algorithm were converted to toolpaths with the control program translator PowerMILL (Delcam Corporation), and used to drive a CNC milling machine. The core cavity is, essentially, an L-shaped cylinder with an out-of-plane bend on one leg. The test box was machined with a one-quarter inch diameter hemispherical milling tool.

Parting surfaces for more complicated core shapes have been rendered with the computer-assisted method. Figure 60 shows a large fluid-handling passage core for a locomotive engine casting. The core is a T-shaped component in which the central axes of joined segments do not intersect. The computer method was successful in generating a tessellation pattern that could be used to define the parting surface adjacent to the core. The surface created by the algorithm is shown in Figure 61.In this image, the unfilled portion represents the core, red triangles occupy the region in which curved surfaces are allowed, and the green triangles span the flat parting sur-

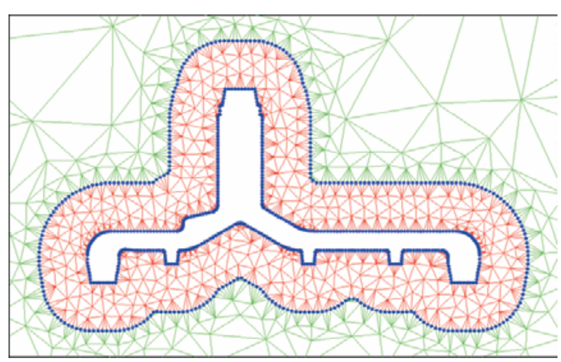


Figure 61. Tessellations of the planar parting surface (green), surface where curvature is allowed (red), and triangle nodes that intersect with the core parting line and the planar parting surface (blue).

face of the remainder of the domain. Blue points denote the surface nodes that lie on the parting line and perimeter of the constant-level surface.

The Consortium and University of California Professor Rida Farouki have demonstrated that a nearly automated method for creation of nonplanar parting surfaces suitable for sand corebox manufacture is practical. The software developed uses STL representations of a core and parting line to create smoothly-varying parting surfaces readable by 3D model viewers and machining toolpath translators.

The software is able to construct a parting surface from this parting line but the goal of computing a valid parting-line on the model surface has proven extremely troublesome in the context of STL models. The reason for this is that the STL files created by most CAD systems involve tessellations of very poor quality. There are unintended regions of undercut, ambiguous areas where the parting line is indeterminate, and the existing triangle edges are usually inconsistent with an acceptable, smooth parting line. Many applications may be forgiving of the idiosyncrasies of STL files, but unfortunately parting-line determination is not one of them.

A totally automatic parting-line determination is impossible unless the quality of STL files improves dramatically. Based on these observations, Professor Farouki concluded that some form of user-guided “fix up” would be essential. The software computes a parting line and the user reassigns triangles, splits them as necessary, and decides which undercut regions are “real” and which are merely artifacts of the tessellation, etc.

Wide adoption of this software application should result in greater freedom in casting core design, and more rapid and accurate creation and production of core boxes requiring nonplanar parting surfaces.

3.4. THE FUTURE OF COMMERCIALIZATION

The Consortium, which includes a diverse group of metal casters, design engineers, and software developers was created to provide an Internet-based platform for fast development of complex sand castings. In the condensed period that the group interacted, it became clear that “partnering” could enhance casting development and speed-to-market issues faced by the industry.

That partnership approach to casting development provided enough stimuli for several of the core team members to form a continuing alliance based on the Consortium’s success.

As the casting industry has matured in the United States, speed to market remains the key to financial success. The lessons learned during the last three years have provided insight for the group and a means to move “at speed” during the development process. The sharing of online information can help eliminate the “clutter” that exists today in the casting acquisition and development process. The modeling and engineering tools that can be shared with a partnership approach can make the “first article” casting a good one.

The *AC Notebook* software developed by the Consortium does provide the Internet-based portal for the future of the casting development and acquisition process. What remains to be seen is whether the partnerships that were formed during the development will stick together for future projects.

Clinkenbeard, Denison, and QuesTek have committed to an ongoing relationship that should provide continuing successes. This group will utilize the existing software and continue to invest in its development. They remain convinced that the development cycle for complex castings can be improved even further.

K + P Agile, Inc. plans to use *AC Notebook* selectively on projects with their existing customers and vendor alliances for the effective collaboration, for the secure data file storage and sharing, and for real-time communications using whiteboarding functionality. A selective group of customers and vendors will be trained and given secured access to the *AC Notebook*. It will be an enabling tool to K + P Agile, Inc. engineers and customers to bring agility to the concurrent product and process development projects related to casting and composite. Also, K + P Agile, Inc. has submitted a proposal that has been accepted and is under contract negotiation with the U.S. Navy (ONR) on agile manufacturing development of Resin Transfer Molded composite components. As a part of this effort, the *AC Notebook* will be further enhanced and customized to adapt to the composite manufacturing process related collaborations. This government-funded program will help maintain and develop the source code to meet the demands of the team members to carry out concurrent product and process development related communications in real time over the Internet. The *AC Notebook* will allow secure and controlled access document exchange and whiteboard collaboration. The *AC Notebook* software will be used for the overall project management of the contract, for the document/file repository and for the whiteboarding real-time communications.

GE Corporate Research and Development has a major initiative called E-Engineering, aimed at increasing the speed at which it can react to the marketplace in all areas of engineering. The vision here is to enable our business entities, our suppliers, and our customers to automate the work flow for product development, do distributed project execution and real time collaboration. The complete functionality *AC Notebook* provides is currently not available in any other product. The vision is to make it part of a suite of tools that will help our businesses reduce their business cycles. The initial use within GE will be for projects between GE Corporate Research and Development and the GE businesses. The vision is that the businesses will realize its potential and request servers of their own for collaboration within their organizations and with their vendors.

4. Conclusions & Recommendations

Over the past few years, software products and services intended to facilitate transactions among businesses have grown, along with general interest in electronic commerce. The greater focus of software companies has been in automating routine inter-business transactions (e.g., automatic purchasing of standard products), and improving intra-business group communications. Although increasing, significantly less effort has been expended to foster secure, flexible collaboration tools that are equally useful among and within organizations. Military castings are designed, manufactured, validated, and machined by distributed specialist companies, often in short-term alliances. Traditional linking of the information infrastructures of these companies (as has been accomplished by large retailers and commodity goods producers) would likely be restrictive and impractical for foundries and casting service providers. The technical interactions required during casting design and production are rarely routine or repetitive, and require the involvement of particular technical specialists. Many of the collaborative "groupware" products for innovative collaboration presume that participants are trusted colleagues that share the same business goal. A lack of robust security and adaptable permissions structures cause these products to be inappropriate for use by arms-length business transactions. In addition, many groupware tools do not assist collaborators in organizing and tracking the complex evolution of technical specifications, or cannot manage transactions involving many different file formats.

The Agile Manufacturing Development of Castings Consortium has created an integrated set of tools for rapid and robust communication with distributed groups. The codes have been tested and used by the Consortium pilot member companies to manage casting design and manufacturing cycle. The Consortium has demonstrated that significant reductions in casting development effort and communication time are possible using the methods and tools created under the pilot. The *AC Notebook* has the potential of having business transactions, such as purchase orders, billing, and invoicing integrated in, along with the technical communications.

Broad adoption of the *AC Notebook* by the casting supplier industry will require that the Consortium succeed on two fronts. Potential users should be apprised of the existence of the software and its utility, and concomitantly afforded easy access to the software, or its use. Challenges facing the Consortium are known; the typical casting industry company has modest expertise and resources to devote to information technology. Frictionless communication and collaboration are becoming a near necessity for the industry, however, as expectations for faster acquisition cycles intensify.

Appendix A
Key Events Related to Solid Model Building

Date	Event
8/13/97	Initial IFE Meeting
8/22/97	Meeting @ K + P Agile, Inc., Measured Old Cores
8/29/97	Meeting @ K + P Agile, Inc., Measured Old Cores, Talked strategy with Ron
8/30/97	Initial Rev 1 Completion of core 7, core 2, core 4, core 5, core 9
9/9/97	Meeting @K + P Agile, Inc., Re-designed prints, Discussed Draft
9/12/97	Conference call with GE, Discussed 25 Issues (Not including Pat Harris stuff)
9/15/97	Initial Rev 1 Completion of core 6
10/1/97	Received New Drawings from GE (Not all issues resolved)
10/7/97	Conference call with GE, Several Issues discussed
10/13/97	Modeled Core #1 & 8
10/15/97	Several calls & faxes to Tomas Honner
10/17/97	More discussion with Tomas Honner about dwg discrepancies
10/20/97	Meeting @ K + P Agile, Inc. with Jacob - Big List of issues
10/21/97	Re-work of Core 1-8 Based on New Design
10/21/97	Added Colaescer Bosses
10/23/97	Received Revision to 10/21 data
10/23/97	Received Intercooler core hole changes
10/24/97	Received Revision to 10/23 data
11/14/97	First Final Release
11/15/97	Meeting @ K + P Agile, Inc., GE, Clinkenbeard & Associates, Inc., added cores 10, & 11 Plus 11 additional changes (effected all cores)
12/8/97	Meeting @ Clinkenbeard & Associates, Inc. to go over the files
12/11/97	Second Final Release
12/30/97	Meeting @ Clinkenbeard & Associates, Inc., (Wall thickness issues)
1/5/98	Tele Meeting @ Clinkenbeard & Associates, Inc., GE
1/8/97	Meeting @ Clinkenbeard & Associates, Inc. to discuss fixes to wall thickness
1/12/98	Third Final Release
2/3/98	Meeting @ K + P Agile, Inc., Changes, How to decrease wt. Plus 12 issues
2/6/98	Re-work Core 9 to decrease wall thickness,
2/7/98	Discussed with Ron Changes to Core 4, 5 Based on 2/3 meeting
3/16/98	Took Pictures of Cores @ Clinkenbeard & Associates, Inc. Over 45 Changes Not on drawings.
3/20/98	Received OK to start re-work based on pictures from Jacob
3/30/98	Changes incorporation denied by GECRD

Appendix B
Drawing/Dimensional Discrepancies

Location	Item	Thin wall conditions / Description	Cause	Fix	By
A	1	fill in cuts on core 3 side of master casting	Modeling error	Modify external model	K + P Agile, Inc.
B	1	sheet 3 location 15Q dim 32 needs to be larger	Model built as per GE Transportation Systems (GETS) drawing	Modify model to achieve 15.9mm thick.	K + P Agile, Inc.,GETS
	2	center of conic - is off by 7mm	Modeling error	Modify model	K + P Agile, Inc.
C	1	fix + DFT condition	model built as per 13mm dim.on drawing	Modify model to achieve 15.9mm thick.	K + P Agile, Inc.,GETS
	2	fix wall thickness	model built as per 13mm dim.on drawing	Modify model to achieve 15.9mm thick.	K + P Agile, Inc.,GETS
D	1	fix core-7 to achieve 15.9 mm	angle and round undefined in drawing used dimensions by measuring actual core slugcore to build model	Modify core #7 to achieve 15.9mm	K + P Agile, Inc.
E	1	as per Thomas H & Pat to duplicate round on both sides	model built as per GETS	need to fix after items H & C	K + P Agile, Inc.,GETS
F	1	make wall 15.9 mm	Model built as per GETS drawing	Modify model to achieve 15.9mm thick.	K + P Agile, Inc.
G	1	look at undercuts on core 3 [holes] need OK by GE	Model built as per GETS drawing	Modify to square pads	K + P Agile, Inc.,GETS
H	1	check off, check wall thickness	Model built as per GETS drawing	Modify model to achieve 15.9mm thick.	K + P Agile, Inc.,GETS
I	1	Sec A-A surface extend, GE TS okayed for entire length	Model built as per GETS	Modify model from outside	K + P Agile, Inc.,GETS
J	1	drawing says 13mm, we want 15.9 inside	Model built as per GETS drawing	Modify model inside surface	K + P Agile, Inc.,GETS
K	1	make sure 15.9 by adding bigger radius	Model built as per GETS drawing	Modify model to achieve 15.9mm thick.	K + P Agile, Inc.,GETS
L	1	change outside radius to make 15.9	Model built as per GETS drawing	Modify model to achieve 15.9mm thick.	K + P Agile, Inc.,GETS
M	1	drawing called out 13mm add to inside to get 15	Model built as per GETS drawing	Modify model from inside (core 4 & 5)	K + P Agile, Inc.,GETS
N	1	same as M; core 4, 5	Model built as per GETS drawing	Modify model from inside (core 4 & 5)	K + P Agile, Inc.,GETS

Location	Item	Thin wall conditions / Description	Cause	Fix	By
O	1	same as N; core 1-8	Model built as per GETS drawing	Modify model from outside	K + P Agile, Inc.,GETS
P	1	check model SB through hole	modeling error	Modify model	K + P Agile, Inc.
Q	1	ribs stay as is	as per drawing	no fix (please refer to note 2)	K + P Agile, Inc.
R	1	remove from core, core 4, 5	Model built as per GETS drawing	Modify model from outside	K + P Agile, Inc.,GETS
S	1	remove material from core 1-8	Model built as per GETS drawing	Modify model from inside (core 1-8)	K + P Agile, Inc.,GETS
T	1	outside [on core - 6] to 15.9	Model built as per GETS drawing	Modify model from outside (core 6)	K + P Agile, Inc.,GETS
U	1	same as T dia. 400 changes, sheet -2 B-12	Model built as per GETS drawing	Modify model from outside (core 6)	K + P Agile, Inc.,GETS
V	1	make a fudge on core - cut	Model built as per GETS drawing	Modify model to achieve 15.9mm thick.	K + P Agile, Inc.,GETS
W	1	look at model, take off core #2	Model built as per GETS drawing	Modify model to achieve 15.9mm thick.	K + P Agile, Inc.,GETS
X	1	core 4, 5, 3 remove material to 15.9	Model built as per GETS drawing	Modify model from inside (core 3,4,5)	K + P Agile, Inc.,GETS
Y	1	core 3 - remove from core 3 to 15.9	Model built as per GETS drawing	Modify model from inside, ribs as it is	K + P Agile, Inc.,GETS
Z	1	to the outside 15.9 pattern	Model built as per GETS drawing	Modify model from outside	K + P Agile, Inc.,GETS
AA	1	to the inside 15.9 core 4, 5 [check]	Model built as per GETS drawing	Modify model from inside (core 4 & 5)	K + P Agile, Inc.,GETS
BB	1	sliver, Ron to fix	modeling nightmare!	fix manually	Clinkenbeard & Associates, Inc.
CC	1	Sheet 2 loc. F13. to get wall thickness of 15.9 mm	Model built as per GETS drawing	Modify from outside by changing R295 dim.	K + P Agile, Inc./ GETS

Note 1 As per Jacob's direction given to K + P Agile, Inc. and Clinkenbeard & Associates, Inc. on 12/18/97; the minimum wall is set to 13 mm and nominal to 15.9 mm wherever not specified
on the drawing. Also, all drawing dimensioned wall thicknesses less than 15.9 mm will be changed to 15.9 mm nominal. The model for the
tooling is made to nominal wall condition.

Note 2 Clinkenbeard & Associates, Inc. and K + P Agile, Inc. decided that all the ribs (especially in the inter cooler area) should stay the way they are spelled out on the drawings and note 1
will not apply to them. In other words, if the rib thickness is 12 mm, it will stay 12 mm in the model and the tooling is built to 12 mm.

Note 3 Wherever it says fix by K + P Agile, Inc./GE Transportation Systems (GETS), those are the changes which need to be communicated to GETS so that their drawings can be modified.

Location	Item	Thin wall conditions / Description	Cause	Fix	By
Note 4	For fixing the model / tooling following considerations were given listed with priorities: 1. Wherever possible, remove the material from the cored surface as it is easier to machine the core slugs than to add material to pattern. 2. Increase the wall thickness opposite to the dimensioned surface. In other words, try to stick to the drawing dimensioned surface and move the other surface to get the required thickness. 3. In some areas, we had concern about the assembly clearance. If that is the case, the castings can be usable by milling the area of interference. 4. Don't touch the machined features. The consequence is the available machine stock may not be 10mm. 5. If the pattern (external surface) is not milled yet, we have tried to add material on the outside. 6. Afet wall thickness modifications, if round and fillets are not possible to model, Clinkenbeard & Associates, Inc. will mill them as per agreed upon values. K + P Agile, Inc. will communicate those areas.				