A collaborative knowledge management system for concurrent design and manufacturing

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ABSTRACT: Knowledge systems for scientific and engineering endeavors must be able to insure the accuracy, completeness, and validity of their contents. When designed as such, these systems become the vehicle that fosters communication between designers and manufacturers, and drive the success of the engineered product. Shared information about product histories, materials, design intention, manufacturing techniques, and lessons learned provides an avenue for this communication and a foundation for concurrent design and manufacturing.

In implementing a knowledge management system for glass-metal seals, we found that the structure of expert communities, the patterns of communication across disciplines, and the informal sketches and stories that experts use in casual discussion are essential for a successful product. Although these contextual factors seldom find their way into structured scientific forums, they often reveal the broader strategies behind the development and application of knowledge. More importantly, preserving these "extra-technical" features gives a system's users an implicit experience of the subtle interpretations, viewpoints and strategies that define engineering expertise. This expert point of view, or expert voice, is difficult to elicit but provides valuable insight into the thought processes and problem solving strategies of the expert. Keywords: glass-metal seals, knowledge design, engineering research and development, concurrent design and manufacturing, design for manufacturability.

1 INTRODUCTION

Designing and engineering large-scale, high-consequence weapons systems is the primary mission of Sandia National Laboratories. Production of a safe and viable system requires continual interaction between scientists and engineers across specialized areas of expertise throughout a complicated cycle of design, manufacturing, and testing. In this setting, successful knowledge management must not only solve the problems of formalizing specialized, dynamic knowledge, but also convey the subtle skills, strategies, judgments, and heuristics that enable its effective use in large-scale collaborations. These strategies are deeply embedded in the experiences, history, and social relationships of human experts. It is this essential but largely tacit dimension of human expertise that makes formal knowledge management so difficult.

The Glass-Metal Seals project (GMS) is an effort to preserve knowledge of a diverse, loosely coupled set of technical specialties. Electrical and fiber-optic passages through metal component such as connectors, battery headers, and pyrotechnic actuators must remain hermetically sealed and function as effective electrical insulators across a wide range of temperatures and stresses. They must last 25+ year life spans while stored in environments ranging from the arctic to the oceans to the desert. Cracks or voids can decrease the strength of the seal, which many allow contaminants into the internal system or even failure in use.

The key to successfully producing such components revolves around a close union between the designers, manufacturers, and testers. For this to occur, each group must be cognizant of the others' concerns. For example, a designer who is aware that fixturing is one of the most complicated steps in production will consider the fixturability of the design before submitting it for production, knowing that doing so reduces the likelihood of failure in production. In this scenario, a designer simplifies the entire production cycle of a component by applying some basic knowledge learned from another domain.

Over several decades, Sandia National Laboratories has accumulated vast knowledge of glass-metal sealing technology. Allowing individuals in the production process to understand this knowledge before innovating within their own task reduces misunderstandings at production and test time, and allows for a smoother production cycle.

1.1 *Challenges*

To structure this knowledge, which spans technical fields including glass-ceramic chemistry, computer modeling of material behavior, metallurgy, manufacturing, component design and engineering, and troubleshooting, we chose a web-based environment. In designing this environment, we faced a number of challenges, including:

– The diversity of our target knowledge. Although all members of the design team are computer scientists with broad technical educations, we had no initial understanding of glass-metal seals. Nonetheless, we had to interpret what our subject matter experts told us, organize it in a way other experts and novices would find useful, and avoid errors and misunderstandings in the site's use.
– Multiple points of view among our experts. For example, glass-ceramic chemists have a different vocabulary and audience for their tools, methods, and results than production engineers. Their criteria for determining relevance and utility of information are as varied as their goals and backgrounds. How could we coordinate this into a single site?
– Broad system requirements. GMS needs to help novice engineers as well as experts. It needs to support ongoing engineering collaboration while preserving technical knowledge and encouraging new research over time. It needs to preserve both theoretical knowledge and actual experiences (i.e. troubleshooting, lessons learned) across a range of practical problems. Furthermore, it needs to foster communication between Sandia and its external suppliers: Sandia manufactures neither the glass nor the components, and the vendors who do must benefit from the system as well.
– The importance of experience and heuristics. Our experts are much more than walking repositories of technical information. Their value is in their ability to solve hard, novel problems by thinking creatively in complex technical domains. Our system must convey not only the necessary technical information, but also a sense of the tacit experiences, skills, strategies, and collaborative methods that enable engineers to use that information effectively in large-scale projects.

1.2 *Structure*

Our initial vision of the system was of a single knowledge-based advisor or expert system for seal design. The knowledge system team has considerable experience in building such advisors in technical domains, and it was that experience that led our customer to us. However, as fieldwork and development progressed, the challenges of this project pushed us toward a much more complex, heterogeneous information design. In the face of such diverse knowledge and broad requirements, we realized this structure would not address all of our users' needs. For example, a single expert system could help a designer validate an idea, but what would a production agency learn from this?

In order to facilitate communication among the stages of production, we focused on broader issues surrounding seal design and implementation, of the problems people have faced in the past, and of the intuitive strategies our experts applied to their work. We wanted to communicate more than our expert's knowledge: we wanted to give our users an experience of the way they think. For these reasons, the GMS system has evolved into a complex web site that incorporates narrative histories of materials development and use, multiple knowledge-based problem solving advisors for material selection, troubleshooting, and seal design, databases for lessons-learned, lists of components using various glasses, and glossaries of technical terms, and links to experts and other knowledgeable contacts.

1.3 *Expert Voice*

This structure is more than a breakdown of the knowledge into scientific topics: it reflects our effort to preserve the different points of view (experiences, strategies, problem solving techniques) of our experts. These points of view are expressed in the expert's *voice*, or the individual's distinctive style for sharing expertise.

Early on in the knowledge engineering sessions, we detected a difference in the voice of the experts. What became important to the web site, and the focus of the knowledge capture, depended on the expert's area of expertise. This was reflected in subtleties of phrasing, attitude, their choice of examples, the way they spoke of their collaborations, and dozens of other shared details.

We found that differences in the way people talk about their work suggest much about their problem solving methods. For example, experts from different subject areas viewed a furnace schedule for one sealing system in multiple ways: the materials expert (Figure 8) discussed it in terms of its historical development, the processing engineer (Figure 7a) wanted strict adherence to the schedule during processing (see Figure 8a), and the failure analyst (Figure 7b) sought to troubleshoot the effects of a poorly executed schedule. As evident in this example, an expert's voice reflects the subtle character of his or her way of thinking about problems. We made it our goal, through the design process, to preserve this voice rather than distill it, and thus the concept of multiple mentors emerged.

The top-level organization of the GMS web site reflects these different points of view. Different sections address the materials science, design, manufacturing, and troubleshooting aspects of glass-metal seal technology, but this is more than a topical organization. Within each section, we have made an effort to preserve the points of view, notions of relevance, and even the representational styles of the individual experts. Each section reflects the priorities, representation style, strategies, relevance criteria, and history of the human expert that provided that knowledge. In this sense, the human expert is that mentor with a complicated body of knowledge to teach, and the system's user is the student.

1.4 *Participants*

The three main participants in this project are the software design team, the scientific and engineering community, and the guidance groups. The software designers synthesized the knowledge, developed knowledge representations, and designed and implemented the web environment, and are the authors of this paper. The scientific and engineering community, comprised of experts from within Sandia as well as production experts from outside vendors, provided the information and knowledge for the web environment. Some of these individuals are referred to by title throughout this discussion. Finally, the guidance groups provided funding as well as corporate-wide viewpoints on the project and how to improve it. Individuals in these groups want to streamline production while reducing failures. Two specific programs show where this project fits into corporate goals: the Process Development Program (PDP), which is responsible for "maintaining a viable technology base that is responsive to manufacturing technology requirements" (Sandia National Laboratories, 2003a), and Concurrent Design and Manufacturing (CDM), whose goal is to "concurrently design, procure/manufacture, and deliver technically complex, high reliability and low volume products" (Sandia National Laboratories, 2003b).

2 SYSTEM DEVELOPMENT

During the development process of the website, we often interleaved fieldwork and information design. Systematic fieldwork is effective in finding a deeper structure of human knowledge, while information design provides models and prototypes for communicating with our users.

2.1 *Fieldwork*

Thinking of this process as a cycle better reflects our use of multiple models of varying formality to communicate our emerging understanding of sealing technology with our experts. The techniques we use to resolve this methodology include:

- always conducting knowledge acquisition at the place where the expert works;
- freely interleaving observations, interviews, and research into printed material as our experts' and our own curiosity dictates;
- interpreting our experts' knowledge in light of our own emerging understanding of that knowledge's context;
- reconstructing history from multiple interviews and documents, requiring agreement among redundant sources to insure the accuracy of information.

2.2 *Information Design*

Our specific approaches to capture knowledge include interviews, joint evaluation (with experts) of historical documents, knowledge engineering sessions targeted at developing and evaluating low-fidelity, special purpose information models, and verification of both prototype software and other knowledge models.

The knowledge engineering sessions, both individual interviews and targeted collaborative environments, provides the core of the knowledge on the website. These successful techniques resulted from some earlier failed work with focus groups of experts. Initially, we found in-depth topic exploration with focus groups of experts lacked structure and sufficient detail, and tended to obscure individual expert voices and experiences in favor of discussions over details. Consequently, we began using individual meetings with experts for in-depth topic exploration, and we relied on the more structured focus groups, which we named targeted collaborative environments, for initial topic exploration, prototype evaluation, and knowledge verification, or any time the experts needed to brainstorm or check their memory.

Throughout the process, we find many of the practices of Distributed Cognition (D-cog) (Hutchins, 1996) to be useful. The main assumption of D-cog is that the best way to understand the structure of group activity is to focus on the information representations and tools that people use to communicate and coordinate their activities. Once these representations are determined, D-cog reviews the operations through which people transform them as well as the communication they enable. These representations and tools gave us great insight as to how information could be shared between the processes of design and manufacturing. For example, even though all glass-metal seals Sandia produces are documented by Pro-Engineer models and drawings, we found more casual communications, such as PowerPoint presentations and memos, were more informative. These documents, used by engineers in the context of meetings and design reviews, address the reasons behind their design decisions in ways more formal models cannot.

2.3 *Early Development*

A web-based environment in which a user can browse the breadth or depth of glass-metal sealing was a natural choice for the GMS tool. Other options accepted at Sandia, such as a comprehensive technical report or a single knowledge-based expert system, were not structurally flexible enough to capture the extensive diversity in knowledge and in information sources. The resulting system includes advisors, documents, narrative histories, technical specifications including vendor links, and databases for material set usage, lessons learned, and technical terms.

With a structure in mind, we began the knowledge capture process with S-glass (a contraction of Stainless Steel Sealing glass), which is an extremely high strength glass-ceramic developed at Sandia (Kleban, 2002). We chose it for three reasons: it is one of our more frequently used technologies, its strict processing schedule demands intense collaboration between designers who use it and engineers who process it, and most of the experts with it will be retiring soon.

Our first action was to synthesize the stories of the material's development and fuse it into a single history. This history is a central part of the web site, providing a valuable introduction to the material that is suitable for both new engineers and scientists from other domains. Based on our experiences in writing this history, we next designed the overall organization of the site to allow multiple mentoring voices to emerge. We express this organization in a navigation panel to guide the user as well as to preserve the structure of the mentoring relationships. Each associated group of experts has its own item on the panel, as discussed in Section 3.2. Figure 1 shows an example material set home page for S-glass with the navigation panel.

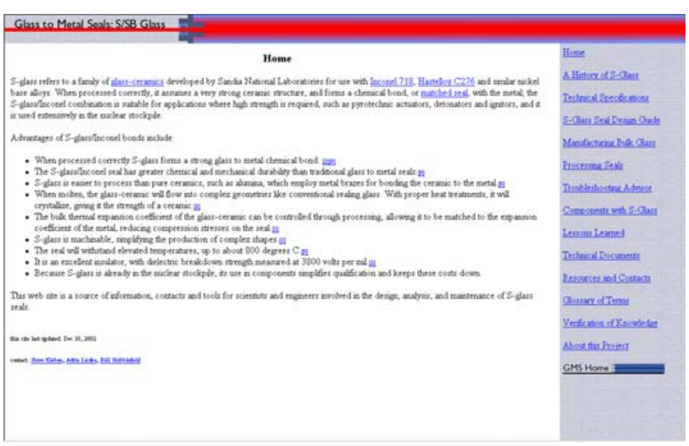

Figure 1. Navigation panel. This image shows the content of the navigation panel, which is consistent for all material sets.

2.4 *Progress*

Our group started conversations within the glass-metal seals community at Sandia National Laboratories in the spring of 2002. In the early summer, we shifted our efforts from designing tools to writing a comprehensive, narrative history of a single glass-metal seal material set, S-glass. In the process of doing this, of blending the individual voices into a coherent story, we began to understand the deeper structure of the knowledge.

By the late summer of 2002, the critical process of verification began. We released a version of the site to the glass-metal sealing community in late autumn of 2002, and are currently in the process of moving the system from our internal network to an external server so our industrial partners can access it. We are also adding three additional material sets to the site.

3 THE GMS SYSTEM

A key requirement of the GMS system is to integrate diverse expert knowledge such as glass-ceramics, component design, production engineering, and stockpile support in a single knowledge environment that is useful both as an information gathering and as a communication tool. Some examples of this synthesis include explaining the science behind a processing schedule, integrating rules-of-thumb from several sources into a seal design advisor, spanning all material set knowledge to provide guidelines for material set selection, and combining development stories into a single history. This collection of information and synthesis of knowledge causes an individual to think beyond a specific requirement to the role and realization of that requirement in the entire process.

The following sections introduce instantiations of general knowledge-sharing tools for the GMS system. Examples range from simple static web pages to databases of lessons learned and technical documents to targeted knowledge-based systems.

3.1 *Navigation of Breadth or Depth*

The top-level page (Figure 2) is organized around the selection of a material set. Sandia relies upon four different glass-metal combinations, and the page has links to separate sites for each of these. In addition, the page has a link to a materials selection advisor. New users may either go straight to a material set, or use the advisor to select the set best suited to their needs. Experienced designers can justify their choice of sealing system or begin research into a new one from this page. Section 3.3 discusses the material selection advisor as an expert system in more detail.

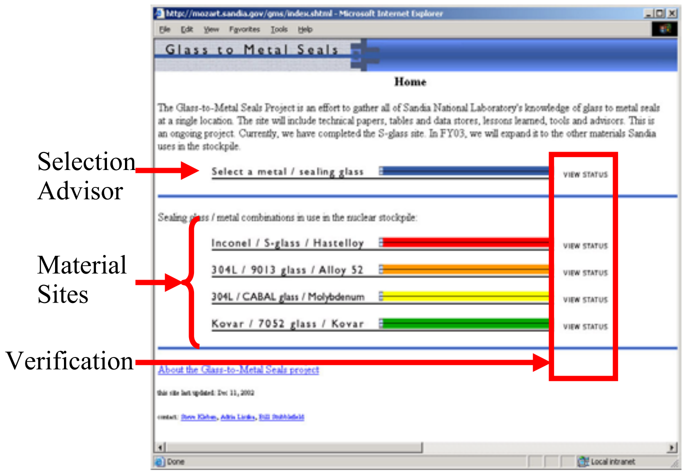

Figure 2. Top-level page. This is the home page for the GMS system. From this site, users can seek advice on which sealing system to use, go directly to a sealing system home page, or view the verification status of a particular sealing system.

3.2 *Navigation Panel*

Each of the sites for the four different sealing systems has an identical top-level structure that is captured in the navigation panel (Figures 1, 3). Some of the main categories include:

– Technical specifications. A straightforward compilation of material properties.
– Seal design guide. Narrative descriptions and question-answer tools containing knowledge of component designers and of engineering analysts.
– Processing seals. Advisors and discussions focused around manufacturing concerns, such furnace schedules, fixturing, and equipment.
– Troubleshooting advisor. Knowledge-based system reflecting heuristic knowledge of problems (i.e. cracks, bubbles) derived from all the experts.
– Lessons learned. A searchable database of lessons derived from all stages of design, processing, and troubleshooting.
– Glossary. A comprehensive database of terms for the material scientist, component designer, production engineer, and maintenance expert.

The navigation panel conveys the central metaphor we used in designing the system: knowledge management through multiple mentoring relationships. This helped us not only to divide the system up functionally, but also to think about the different types of guidance each section could provide.

A successful mentor not only answers the student's questions, but also steers the student towards a broader perspective. For these qualities of a good mentor to be apparent, we studied the individual topics and perspectives that combine points of view. Originally we envisioned one category on the panel per mentor, but in reality no expert is isolated in this way. There are also mentor-mentor relationships, and individual voice is essential in these as well. To preserve the human aspect, we imitated the social structure in which knowledge is both developed (the mentor-mentor relationship) and handed down (the mentor-student relationship) (Figure 3).

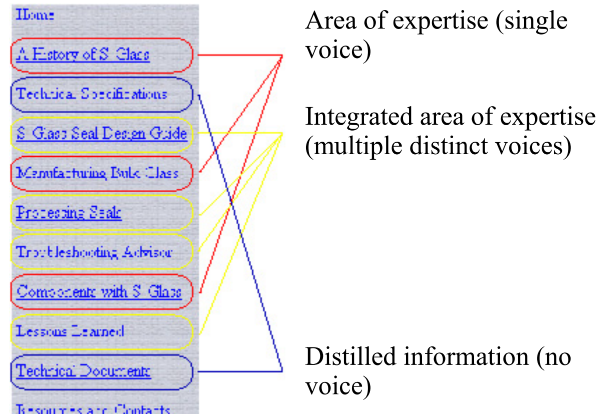

Figure 3. Navigation panel. This illustration breaks up the navigation panel into knowledge acquired from one expert or mentor, synthesized from several mentors in a mentor-mentor relationship, or distilled from no mentors. Remaining items such as the glossary are complementary details.

Sharing this knowledge among processes in a concurrent design and manufacturing enterprise is a key step towards streamlining production and reducing failures. An example mentor-student relationship is depicted in Section 1.1: the student is the designer who wishes to understand fixturing so as to incorporate the production engineer's concerns in the design. The mentor is the product engineer involved in designing and assembling the fixtures, and is represented virtually in the GMS system (Figure 4).

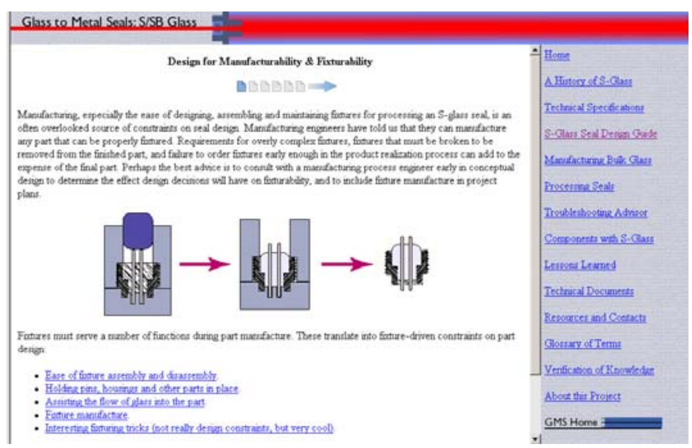

Figure 4. Design for fixturability. After learning about fixturing from a virtual production mentor, a designer might be able to simplify a component in order to take processing complexity into account.

Mentor-mentor relationships, on the other hand, are the main contributors to the verification of knowledge, as two experts discussing a controversial topic will often come to some sort of consensus. Even if they do not, the reasons why the two experts think differently on the subject matter indicates an area where further exploration and research is warranted. An example of this is the discussion of S-glass furnace schedules between a materials expert and a production engineer. The materials expert argues that a shorter theoretical schedule, which removes the growth hold (Stage D, Figure 7a), produces the same quality seals as the longer qualified schedule, but the production engineer insists that he cannot risk using the shorter schedule until it is qualified. This reluctance to try the abbreviated processing cycle, even though it would save money in the long run, was based on the fact that thousands of seals had been processed using the longer schedule, and the production engineer has high confidence in the ability of his engineers to implement it. Although he accepted the theoretical possibility of changing the cycle, he preferred to use the proven manufacturing method rather than possibly waste money trying a new, unproven schedule. This ongoing debate is detailed in several places on the website, interleaved between advisors and narrative discussions.

3.3 *Knowledge-Based Expert Systems*

Most of our advisors follow the classic knowledge-based systems pattern of asking questions and ranking potential solutions, which follows an expert's pattern of asking a novice designer questions about a proposed seal, and then giving advice. The materials selection advisor, introduced in Section 3.1, is one example of this type of advisor. To further emulate this interaction style, we allow users to click on any question and get not only how to answer it, but also why it is important (Figure 5). In fact, a user can learn much about the subject matter by reading the question explanations.

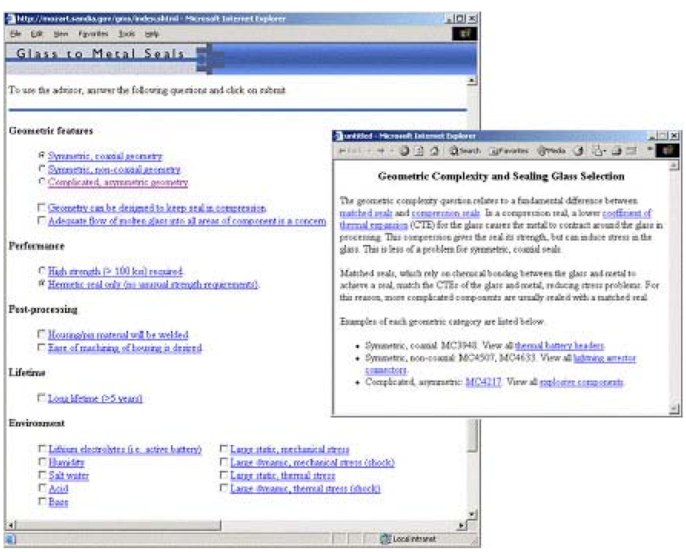

Figure 5. Question-answer style advisor. The Material Selection Advisor demonstrates the question-answer technique in a mentoring relationship. The pop-up window describes one question, geometric complexity, in detail.

Advisors can also implement more quantitative forms of knowledge. For example, a Design Advisor takes real-valued dimensions, and then computes the quality of a seal design (Figure 6).

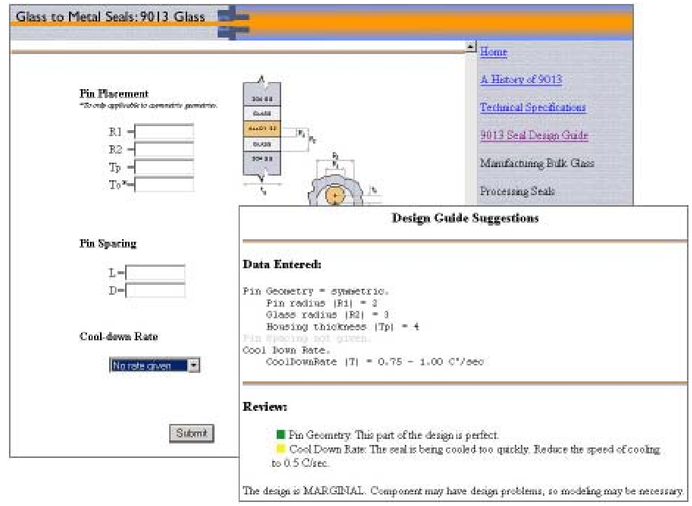

Figure 6. Design advisor. The design advisor imitates the question-answer pattern inherent in the mentor-student relationship, but uses real-valued data. The inset shows the layout of advice.

In contrast to the question-answer format, our discussion of the effects of furnace schedule changes on seal quality centers around a browsable graphic of the furnace schedule (Figure 7a). This was the way our processing experts taught us nuances of the sealing cycle, by focusing on rate, temperature, and time of the stages. In our tool, a user can click on any stage of the cycle to read the effects of modifying the parameters of that stage.

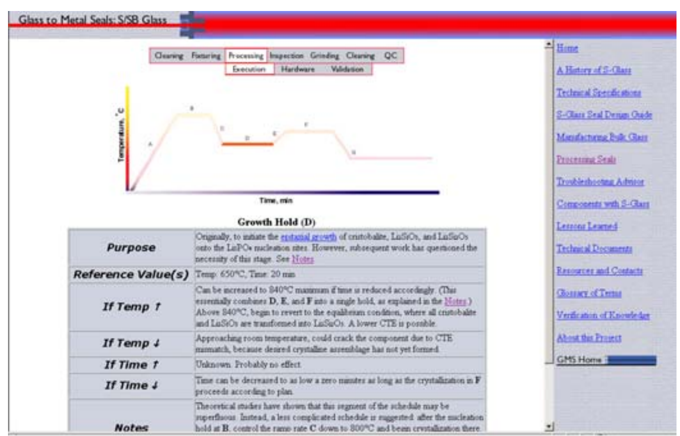

Figure 7a. Browsable furnace schedule. This figure is a schedule-oriented view of processing. The user knows the cause (change in schedule), and explores possible effects.

Along with a browsable schedule, we also developed a troubleshooting advisor to address the impact of processing on seals. The success of S-glass seals is highly dependent on the proper sequence and duration of temperatures in the furnace used in processing, and any error in this schedule may cause seal failure. Manufacturing process engineers view the problem in terms of the symptom: if they process the seal correctly, there will be no failures. We designed the schedule browser (Figure 7a) for them. Failure analysts, however, view the problem in terms of the cause: once there are failures, they must determine the point of origin. We designed the Troubleshooting Advisor (Figure 7b), which lets the user select a symptom then provides possible causes, symptom then provides possible causes, for them. They are an example of the mentor-mentor relationship, linked to promote exploration and a broader understanding of processing as a whole.

Figure 7b. The troubleshooting advisor. This figure shows a problem-oriented view of processing. The user knows the effect (type of seal damage), and explores possible causes.

3.4 *Knowledge Synthesis*

Another useful technique of data delivery was a highly organized and linked set of static web pages for narratives. For example, the narrative history of the first material set summarizes each major stage of S-glass development. In this way, each stage has its own expert voice, but the collection of pages maintains the concept of the mentor-mentor relationships, which were necessary to develop this material. Figure 8 shows a page of history from the S-glass material set.

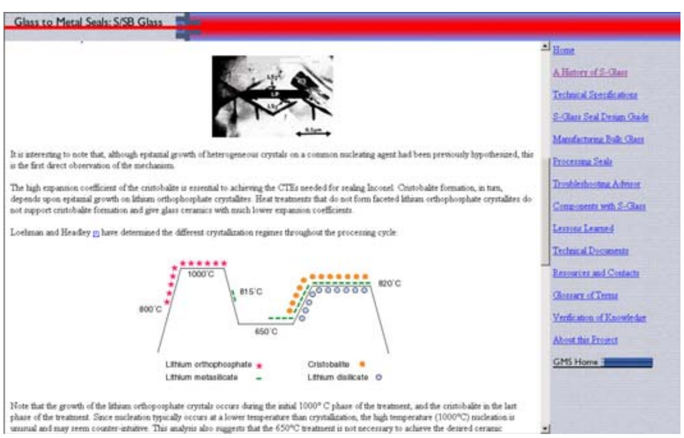

Figure 8. Narrative history. This is an example of knowledge integrated into a central place. The page, which discusses crystallization of the glass-ceramic, references more than five published papers and more than two expert interviews.

3.5 *Data Verification*

One of the most effective ways we used the social structure of the sealing community was in validation. To establish user confidence in the site's knowledge, we depicted our verification process graphically (Figure 9) and made it available to the user.

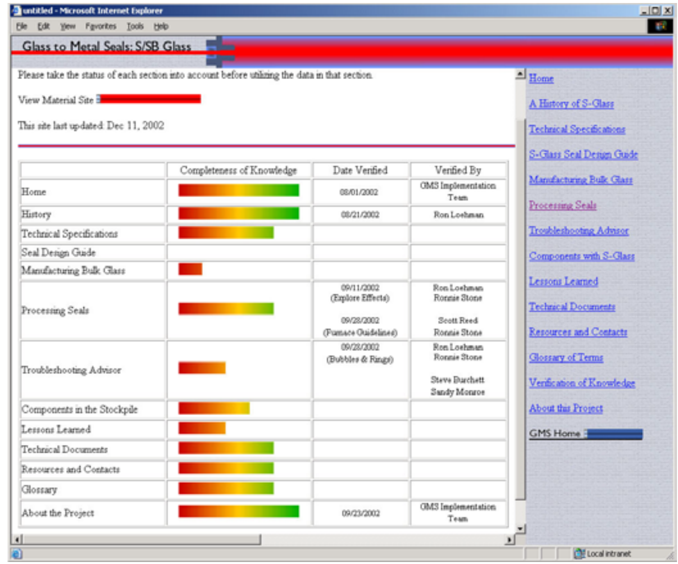

Figure 9. Verification of data. This page provides a graphical representation of the progress of each knowledge category. The date verified and the verifying scientist are included as well.

For each category on the toolbar, this page includes a graphical representation of the status of knowledge capture and validation, as well as the names of the subject-matter experts doing the validation. This conveys the experience of "science as actually practiced." Furthermore, it reflects the culture of Sandia National Laboratories, where the reputation of an individual scientist is important. If there is a question as to the verity of website, the user could simply contact the scientist who is responsible for that knowledge.

4 CONCLUSIONS

The usefulness of this system is in its ability to successfully address the challenges of concurrent design and manufacturing as laid out for this subject domain in Section 1.2:

- Diversity of target knowledge. As computer scientists, we had no initial knowledge of glass-metal sealing, so we easily stepped into the role as the student in the mentor-student relationship. Our technique of interleaving interviews and research based on our curiosity caused us to present both depth and breadth of knowledge simultaneously. Depth allows a new engineer to acclimate to a new field, while breadth educates the more experienced user on other areas of the production process.
- Multiple points of view. Subject-matter experts have their own vocabulary and points of view that differ from other subject-matter experts. Only by accumulating several points of view, however, can one person fully understand the domain. One example in this system is the collection of knowledge about the S-glass furnace schedule from the

points of view of the materials expert, the processing engineer, and the failure analyst.
- Broad system requirements. Requirements of the system include preserving part work, supporting current work, and fostering new work in the area of glass-metal seals. The site preserves past work by synthesizing the research and experiences of subject matter experts, as in the history (Section 3.4). Current work is supported in the careful explanation and verification of productions steps such as the sealing cycle (Section 3.3) and in the authorized access of external vendors to the site. The system fosters new work by highlighting existing controversies such as the theoretical furnace schedule (Section 3.2).
- Importance of experience and heuristics. The value of this system lies not only in its repository of technical information, but also in its focus on the expert as a intelligent, creative individual with an accumulated array of ideas, experiences, and techniques. For example, the system does not merely list the steps of processing an S-glass seal, but instead discusses the reasons why those steps exist as well as the scientific and engineering research that made those steps important (Section 3.3).

Although the system has been only partially deployed at this time, user feedback is very positive. Experts see the system as an efficient way to give new employees the background they need to contribute to a project. New engineers see it as an intuitive guide to learning about glass-metal sealing, as well as a nearly comprehensive desktop reference. Experienced users see it as a medium for sharing glass-metal sealing information with potential vendors. Potential vendors see it as a tool to explore the glass-metal sealing process before committing to a contract. Management sees it as a vehicle for streamlining production, thereby reducing component failures.

This system is not intended to replace a human expert. It cannot experiment with new techniques, hypothesize about new results, or suggest new avenues of research. Instead, our goal is to bridge the gap between different stages of glass-metal sealing with the idea that doing so will improve collaboration in the production process. By achieving this goal, we have shown that a prototypical web-based knowledge management tool can help to make concurrent design and manufacturing a reality.

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