Cover Page

Title of submission: Preserving Multiple Expert Voices in Scientific Knowledge Management

Category of submission: Design Case Study

Name and full contact address (surface, fax, email) of the individual responsible for submitting and receiving inquiries about the submission: Adria H. Liszka, P.O. Box 5800, Mail Stop 1137, Albuquerque, NM 87185-1137, USA, +1 505.844.8558, ahliszk@sandia.gov

Preserving Multiple Expert Voices in Scientific Knowledge Management

Adria H. Liszka
Sandia National Laboratories
P.O. Box 5800 Mail Stop 1137
Albuquerque, NM 87185-1137 USA
ahliszk@sandia.gov

William A. Stubblefield
Sandia National Laboratories
P.O. Box 5800 Mail Stop 1137
Albuquerque, NM 87185-1137 USA
wastubb@sandia.gov

Stephen D. Kleban
Sandia National Laboratories
P.O. Box 5800 Mail Stop 1137
Albuquerque, NM 87185-1137 USA
sdkleba@sandia.gov

Abstract

Computer archives of scientific and engineering knowledge must insure the accuracy, completeness, and validity of their contents. Designers of these sites often overlook the social and cognitive context of scientific activity in favor of highly distilled collections of theoretical findings and technical data, divorcing scientific information from its human origins.

In implementing a Glass-to-Metal Seals knowledge management system, we found the structure of expert communities, the patterns of communication across disciplines, and the informal representations, sketches and stories experts use in casual discussion to be essential to our efforts. Although these contextual factors seldom find their way into journals and other scientific forums, they often reveal the broader strategies behind the development and application of that knowledge. More importantly, preserving these "extra-technical" features in the system's content and organization gives users an implicit experience of the subtle interpretations, viewpoints and strategies that define engineering expertise.

Keywords

Cognitive Psychology, Ethnography, Information Architecture, Interaction Design, Knowledge Design, User Interface Design

Industry/category

Engineering Research and Development, Concurrent Design and Manufacturing.

Project statement

Designing and engineering large-scale, high-consequence weapons systems is the primary mission of Sandia National Laboratories. Doing so requires close collaboration between scientists, engineers, and designers across specialized areas of expertise. 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-to-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.

Over several decades, Sandia National Laboratories has accumulated vast knowledge of glass-metal sealing technology. This knowledge spans technical fields including glass-ceramic chemistry, computer modeling of material behavior, metallurgy, manufacturing, component design and engineering, and troubleshooting. Some of the sealing materials were designed at Sandia, and the laboratory remains the sole source of knowledge about their manufacture and use.

To structure this knowledge, 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 over time. It needs to preserve both theoretical knowledge and actual experiences (i.e. troubleshooting, lessons learned) across a range of practical problems.

- 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.

Our initial vision of the system was of a single knowledge-based advisor, or expert system for seal design. The design team has considerable experience in building such systems 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. We wanted our system to communicate a broader sense of the 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;
- links to experts and other knowledgeable contacts.

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. We think of these points of view as expressed in the *voice*, or the individual's distinctive style for sharing expertise. We have found that subtle differences in the way people talk about their work suggest much about their problem solving methods. Do they focus on general theoretical problems, or specific historical events? Are they more comfortable with graphics, theoretical summaries or narrative histories? Are the best interviewed alone or in a group setting? Do they characterize their work technically, or in terms of their interactions with other people? How do they gain confidence in their knowledge, through formal experiment, through theoretical argument, or through experiences? All of these factors define the expert's voice. This voice, in turn, reflects the subtle character of an individual's way of thinking about problems.

The top-level organization of the Glass-to-Metal Seals 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 building the GMS knowledge management system, we wanted to do more than record technical data. We wanted to help our users understand the origins, assumptions, limitations, and collaborative styles behind the application of glass sealing knowledge. Maintaining the expert's unique voice in the structure and presentation of the site gives us an intuitive way to accomplish this.

Project 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 case study. The scientific and engineering community 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. 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" [1], and Concurrent Design and Manufacturing (CDM), whose goal is to "concurrently design, procure/manufacture, and deliver technically complex, high reliability and low volume products" [2].

Project dates and duration

There were four major milestones of this project. Our group received initial funding in the spring of 2002, starting conversations between the computer scientists and the scientific community. Initial progress was slow, because we could not discern any structure in the knowledge we were discovering. In the early summer of 2002, we shifted our efforts from designing tools and advisors to writing a comprehensive, narrative history of a single glass-metal seal material set, a high-strength glass-ceramic known as "S-glass," that was invented at Sandia National Laboratories. In the process of doing this, of blending the individual expert voices into a coherent story, we began to understand the deeper structure of the knowledge and expert communities. This guided our top-level organization of the site. By the late summer of 2002, a critical mass of knowledge was resident in the first glass-metal seal material set, and the process of verification began. Although not all the information was linked in at that point, we organized the principles and set the structure. Finally, by the mid-autumn of 2002, we had refined the first material set well enough to begin adding other material sets. We released the site to the user community in late autumn of 2002. Currently, we are 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.

Process

Although our development process followed the design-prototype cycle common to knowledge-based system development [3], we believe it is more informative to think of it as interleaving fieldwork and information design. There are several reasons we make this distinction. We have found that systematic fieldwork is much more effective in finding the deeper structure of human knowledge than focus groups, joint design sessions, and other approaches that rely on people's introspective accounts of how they work. Like many software development methods, such as eXtreme

Programming (XP) [4], we recognize the value of models and prototypes for communicating with our users, but feel that these methods place too much emphasis on the computer program as the sole or primary tool for doing so. Thinking of this cycle in terms of information design, rather than software prototyping, better reflects our use of multiple models of varying formality to communicate our emerging understanding of sealing technology with our experts.

Fieldwork

The key commitment we made in knowledge acquisition was to a lightweight form of ethnographic fieldwork [5]. We call it lightweight because we avoid becoming too involved in methodologies, but still emphasize:

- 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;
- avoiding rigid methodological prescriptions while interpreting our experts' knowledge in light of our own emerging understanding of that knowledge's context.

Normal ethnographic practice dictates a fair amount of subject observation [5]. However, we are primarily concerned with preserving historical information and other knowledge that is in danger of being lost, so we placed less emphasis on this technique. Instead, we reconstructed the history from multiple interviews and documents, requiring agreement among redundant sources to insure the accuracy of information.

We began by defining and interviewing a core or primary group of experts. We selected these individuals to represent the *network of practice* [6] in the glass-metal seals community. By network of practice, we mean the loosely-coupled technical communities (or communities of practice) that contribute to the development and application of sealing technology. They in turn directed us to other experts either in their field or outside of it who have specific knowledge about related topics. For example, a materials expert and a processing expert supplied much of the knowledge for the original narrative history, while failure and stress analysts directed us to several new groups of experts to interview.

Specific approaches we use to capture knowledge include interviews, some of which were taped and transcribed, joint evaluation (with experts) of historical documents, knowledge engineering sessions targeted at developing and evaluating low-fidelity, special purpose information models (see Solution details), and verification of both prototype software and other knowledge models. The historical documents, such as published papers and presentations, provide a vocabulary for us to use when conversing with our experts, but it is the knowledge engineering sessions that provide the core of the captured knowledge. These sessions are designed and prepared on a case-by-case basis depending on the expert's area of expertise, the number (group or individual) of experts involved, and the expert group type (breadth-centric or depth-centric).

Although we did not use a particular methodology, we did find many of the practices of Distributed Cognition (D-cog) [7] 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 have been determined, D-cog's next steps are to look at the operations through which people transform them, and the communication they enable. 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.

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 made it our goal, through the design process, to preserve this voice rather than distill it, and thus the concept of multiple mentors emerged.

Information Design

Information design deals with the logical, semantic and visual organization of the information in our site. It addresses everything from the global organization of knowledge, to the processes of navigating through the site, to the arrangement of text and images on an individual page.

One of the first decisions we made was to decide on a web-based environment for the GMS tool. Other options included a comprehensive technical report, which is a common vehicle for preserving technical knowledge at Sandia Laboratories, or a knowledge-based expert system or advisor, with which the authors have extensive experience. However, when we realized that we needed to capture extensive diversity in knowledge and in information sources, it became clear that we needed a large and more structurally flexible approach. The resulting system includes advisors, documents, narrative histories, technical specifications including vendor links, and databases for material set usage, lessons learned, and technical terms.

We began with "S-glass" (a contraction of Stainless Steel Sealing glass), an extremely high strength glass-ceramic developed at Sandia [8]. We chose it for three reasons: it is one of our more frequently used technologies, the people who developed it are at our location, and most of the experts will be retiring soon. Our first action was to condense the story our experts told us into a narrative history of the material's development and use. This history is a central part of the web site, and provides a valuable introduction to the material that is particularly suitable for training new engineers or even scientists from other domains. What is equally important was its role in exploring the structure of the knowledge domain. Carroll [9] has argued for the power of scenarios and other informal, narrative structures in exploring a design space. Our written history provided the same help in exploring a knowledge domain. We also used it as a measure of our own understanding: our experts could easily review it and detect any misinterpretations on our part.

Based on our experiences in writing this history, we next designed the overall organization of the site. Because we used the web as a vehicle to share this knowledge, we express this organization in a navigation panel to help direct the user. This panel preserves the structure of the mentoring relationships we had established with our own experts, giving each expert or associated group his or her own item on the panel. These groups are discussed more in Solution details. Figure 1 shows an example material set home page with the navigation panel. After we designed the navigation panel, we reviewed the organization with our experts and target users.

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

Process Effectiveness

Although our process was informal, it proved highly effective and also includes a number of generally useful practices. These include the importance of background research before doing fieldwork, targeted collaborative environments, and custom information representations.

Before meeting with that expert, we read reports and completed other background research on that expert's topic. The purpose of this was to absorb technical setting and language before interviewing expert so as not to waste time with explanation of rudimentary details. This way, we appeared like a student in front of our mentor, the expert: we knew the basics about the subject matter, but did not have the depth of knowledge like our mentor.

An interesting aspect of our approach was our reliance on targeted collaborative environments as a vehicle for interaction with our experts. This successful technique resulted from some earlier failed work with focus groups of experts. In the beginning, we tried to use groups of experts for in-depth topic exploration. This lacked structure, 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. We also found that the success of these groups depended on the structure we brought to them. The most effective structuring tool was the use of both software prototypes and primitive representations of the subject matter as a focus for discussion.

In the early stages of development, web-based prototypes worked: for example, the navigation panel was a valuable tool for refining the site's overall layout. However, as we got into more detailed design, the overhead of navigating the site made it hard for our experts to get a global sense of the completeness of knowledge we were placing in the site. For example, trying to understand the knowledge content of a troubleshooting advisor by asking it one question after another proved nearly impossible. Instead, we began to rely on targeted, low-fidelity representations to convey the structure and content of this knowledge. These representations do not appear in the web site, as they are strictly tools for structuring the knowledge engineering sessions.

Grids and other abstract representations were essential to capturing our experts' ways of thinking structurally. One simple yet powerful tool was the furnace schedule grid (Figure 2).

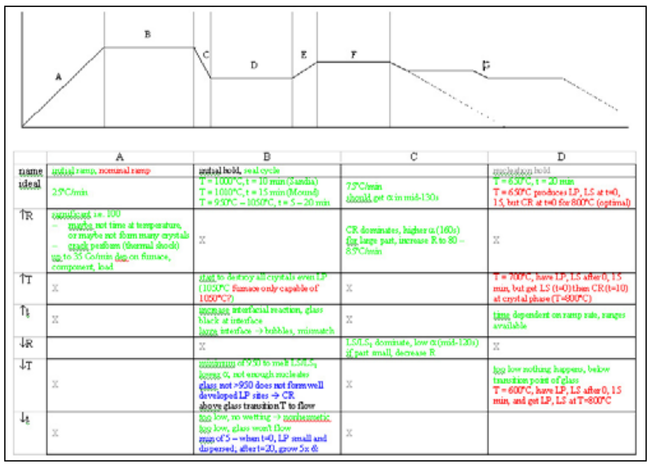

Figure 2: Furnace Schedule Grid. This intermediate prototype was used to discuss the effects of changing the processing schedule for S-glass. The columns of the table are different stages in the furnace schedule, and the rows are changes in rate, time, or temperature. Colored fonts differentiate information sources, so experts know our interpretation of their contribution.

Solution details

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. 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. It involves multiple tools and representations ranging from simple static web pages to databases of lessons learned and technical documents to targeted knowledge-based systems.

The top-level page (Figure 3) 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. The cost of qualifying a new material set is somewhat prohibitive, so this organization is stable. In addition, the page has a link to a materials selection advisor. Users may either go straight to a material set, or use the advisor to select the set best suited to their needs.

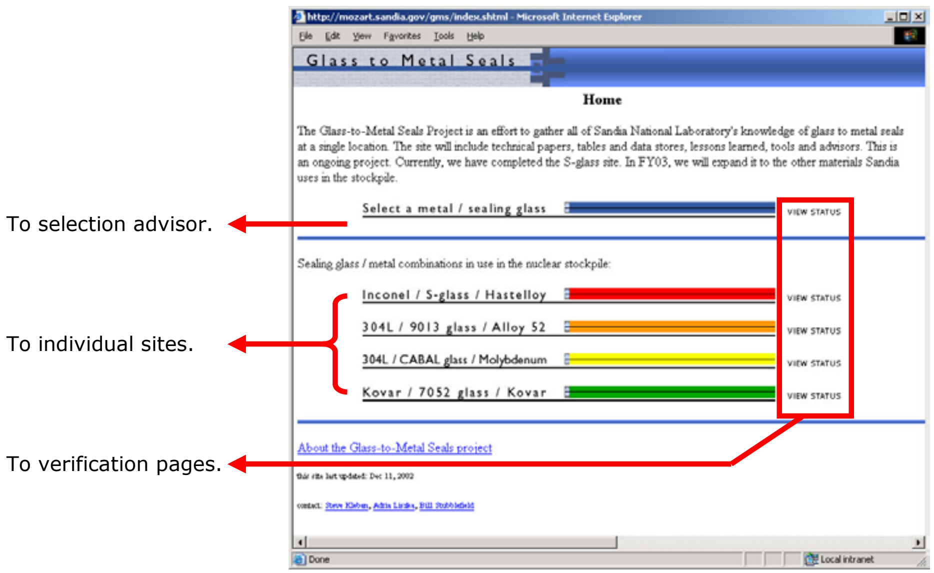

Figure 3. Top-Level Page. This is the home page for the GMS system. From this site, users can seek advice on which sealing system to use, go directly to a sealing system home page, or view the verification status of a particular sealing system.

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

- Technical specifications. A straightforward compilation of material properties.
- Seal design guide. Narrative descriptions and knowledge-based question-answer tools containing knowledge of component designers and of engineering analysts.
- Processing seals. Advisors and narrative discussions focused around concerns of manufacturing engineers, 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 and processing.
- Glossary. A comprehensive database of terms for the material scientist through the designing engineer.

The navigation panel conveys the central metaphor we used in designing the system: multiple mentor-student 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. In a successful mentoring relationship, the mentor not only answers the student's questions, but also steers the student towards a broader perspective. Essentially, a good mentor infers the broader patterns of understanding (or misunderstanding) in a question and speaks to that more general context.

For these qualities of a good mentor to be apparent, we studied the relationship between 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 also essential in these. 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 4).

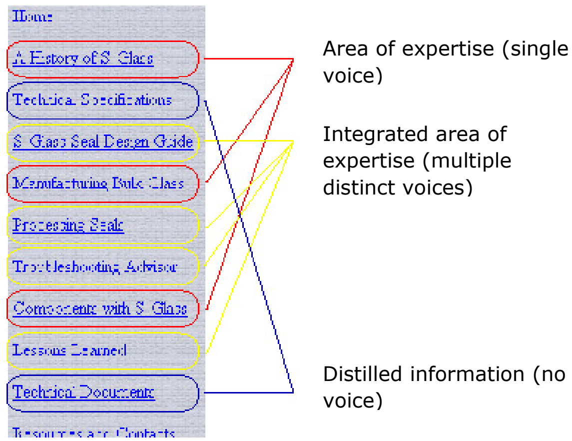

Figure 4: Navigation Panel. This illustration breaks up the navigation panel into areas of expertise, integrated areas of expertise, and distilled information. Remaining items such as the glossary are complementary details.

We instantiate expert voices in different ways throughout the site. For example, our material selection advisor followed 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. 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.

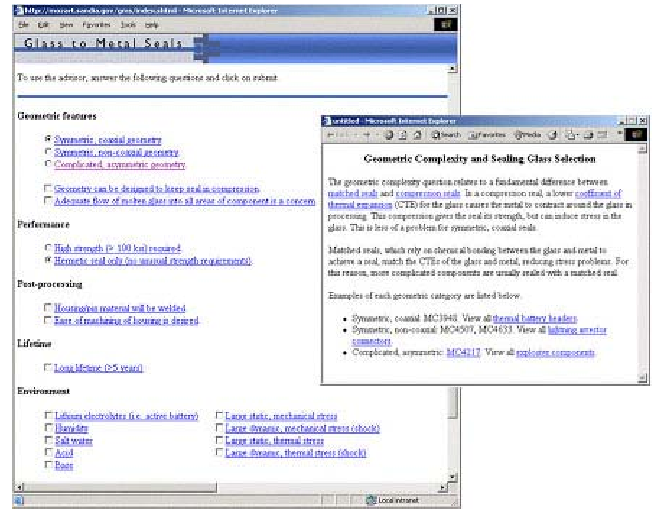

Figure 5: Question-Answer Style. The Material Selection Advisor demonstrates the question-answer technique in a mentoring relationship. The pop-up window describes one question, geometric complexity, in detail.

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).

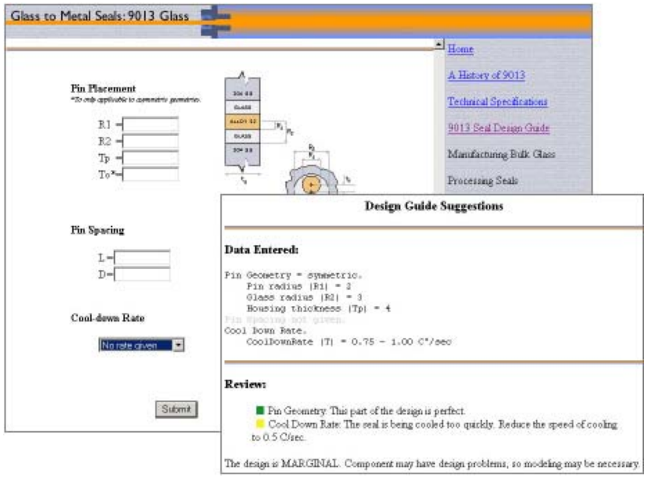

Figure 6: Design Advisor. The design advisor imitates the question-answer pattern inherent in the mentor-student relationship, but uses real-valued data. The inset shows the layout of advice.

In contrast to the question-answer format, our discussion of the effects of furnace schedule changes on seal quality is centered around a browsable graphic of the furnace schedule (Figure 7a). This was the way our experts discussed the processing schedule, as stages focused on temperature and time. In our tool, a user can click on any stage of the cycle to read the effects of modifying the parameters of that stage.

This schedule browser also illustrated the way in which we handled controversies about seal processing. In particular, theoretical work by Sandia's ceramic chemists suggests that the fourth stage of the processing cycle (Stage D in Figure 7a) could be omitted without harming seal quality. However, manufacturing experts expressed reluctance to try the abbreviated processing cycle, even though it would save money in the long run. This reluctance was based on the fact that thousands of seals had been processed using the longer schedule, and they had high confidence in the ability of their engineers to implement it. Although they accepted the theoretical possibility of changing the cycle, they preferred to use the proven manufacturing method rather than possibly waste money trying a new, unproven schedule. In our site, the discussion of the growth hold stage mentions the controversy, and provides a link to the section of the history that discusses it in detail. This interleaving of advisors and narrative discussions is typical of the ways we captured different expert voices in the site.

An example of the relationship between different voices is our development of this furnace schedule browser as well as 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, for them. These tools are linked to promote exploration and a broader understanding of processing as a whole.

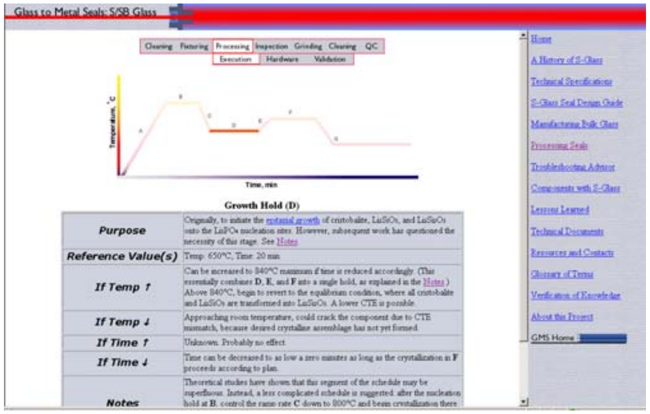

Figure 7a. Browsable Furnace Schedule. This tool gives a schedule-oriented view of processing. The user knows the cause (change in schedule), and explores possible effects.

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

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 network of practice, which was necessary to accomplish the development of this material. Figure 8 shows a page of history from the S-glass material set.

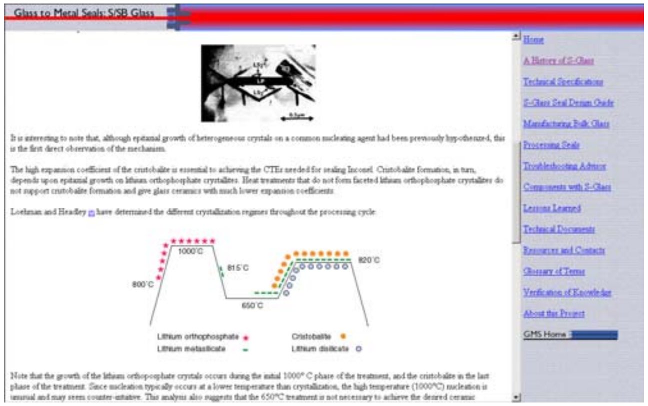

Figure 8: Narrative History. This screen capture is an example of knowledge integrated into a central place. The page, which discusses crystallization of the glass-ceramic, references more than five published papers and more than two expert interviews. Images are enlarged and easier to understand.

One of the most effective ways we used the social structure of the sealing community was in validation. To increase user confidence in the site's knowledge, we depicted our verification process graphically (Figure 9) and made this available off the main navigation toolbar. 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, and it gives the user a sense of closer connection with that scientist.

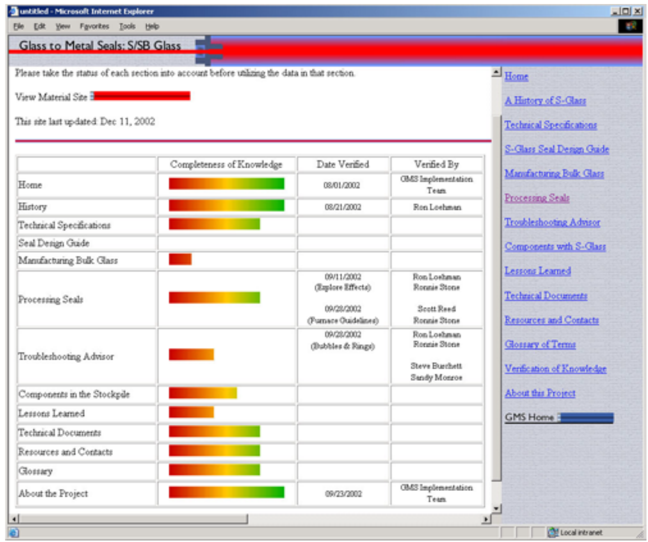

Figure 9. Verification of Data. This page provides a graphical representation of the progress of each knowledge category. The date and scientist associated with the verification process are included as well.

Results

We measured the impact of the deployment of this system using feedback from users on the site's usefulness, from our experts on the correctness and presentation of their knowledge, and from informal observations of the way in which people used the site.

Both our experts and guidance groups testified to the effectiveness of the development process. The experts described the knowledge development process as "painless" owing to the way we prepared and structured interviews. In evaluating the quality of the site's knowledge and presentation, they not only recognized our efforts to maintain the expert voice, but also commented on its usefulness in helping train new engineers. Their commitment to the project, shown as a willingness to answer our questions, demonstrates to us that they are as invested in providing the knowledge as we are in understanding, organizing, and displaying it.

Our current users, having never witnessed a demonstration of the tools, find the site well-developed and intuitive to use. They point to ease of navigation and simplicity of design as two major characteristics of the display. These users are mostly searching for background and information on the S-glass material set, for which they find a wealth of knowledge. However, this deployment has affected us as well: the probing by these users has brought to the forefront some problems, such as holes in current knowledge and disputed knowledge, which we thought were settled.

This project is ongoing. Future work will include populating the items in the navigation panel for the remaining three material sets, but will center mainly on broader topics such as project maintenance and reusability.

We are currently working on tools to support site maintenance. The outline structure, in the form of a navigation panel, lends itself to proper packaging and intuitive maintenance. The structure of this outline is unlikely to change: since this project reflects a knowledge community and not organizational configuration, it will be augmented but probably not structurally altered. Other maintainability work focuses on the ability to port structured parts of the site, such as lists of lessons learned, from static web pages to a database. This will not change the user's view of the site but will simplify maintenance.

Reusability of code has been a goal since the onset of the project. We have made an effort to construct each software tool for reusability not only within the project but also, if possible, outside of it. Examples of these large-scale endeavors include the lessons learned database, a context sensitive glossary, and the process verification page. Reusable within the project are the concepts and techniques for creating a design advisor, the navigation panel structure, some static page structure (i.e. technical specifications), and some software components. Although the content of our work on this project is specific to the glass-metal sealing problem, the structural components and organization are more general.

Acknowledgements

We would like to thank Neil Lapetina and Cesar Lombana, as well as our managers Steve Humphreys and John Mitchiner and other managers at Sandia National Laboratories who provided "big picture" comments. Our primary experts deserve special accolades for their willingness to share their knowledge. These include: Sandy Monroe (failure analysis), Ron Loehman (materials), Ronnie Stone (processing), Steve Burchett (stress analysis), Mike Kopczewski (component design), and Dick Massey (production). We are also grateful to our referenced experts in the areas of materials, processing, and component design.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94aAL85000.

References

[1] Sandia National Laboratories Technical Business Practices Definitions. Internal website.

[2] Sandia National Laboratories Concurrent Design and Manufacturing. Internal website.

[3] Luger, G. and Stubblefield, W.A. Artificial Intelligence: Strategies and Structures for Complex Problem Solving. Reading, MA: Addison-Wesley, 1998.

[4] Astels, D., Miller, G., and Novak, M. A Practical Guide to eXtreme Programming. Upper Saddle River, NJ: Prentice Hall, 2002.

[5] Randall, D. and Rouncefield, M. The theory and practice of fieldwork for systems development. Tutorial at CSCW (New Orleans, November 2002).

[6] Brown, J. S. and Duguid, P. The Social Life of Information. Cambridge, MA: Harvard Business School Press, 2000.

[7] Hutchins, E. Cognition in the Wild. Cambridge, MA: MIT Press, 1996.

[8] Kleban, S.D. and Stubblefield, W.A. Personal Interview of R.E. Loehman. April 1, 2002.

[9] Carroll, J.M. Making Use: Scenario-Based Design of Human-Computer Interaction. Cambridge, MA: MIT Press, 2000.