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A STUDENT-EXECUTED INDUSTRIAL GAS TURBINE DESIGN PROJECT

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ABSTRACT

Practical training that readies the university graduate to deal with real life problems from the beginning of their engineering career is considered by many leading companies to be a critically important factor for future technological progress. An aggressive design project was undertaken by a unique collaboration between the Pennsylvania State University and Solar Turbines, Inc., an industrial gas turbine company. What made this project unusual was the requirement that the design effort had to be completed by students within the tight scheduling of this industry. It is becoming clear, as our students complete their formal education and leave, that the specific educational environment provided within this project to undergraduate and graduate level engineering students was effective, practical, and beneficial in terms of both educational value and practical outcome. Insights into undertaking such a project are described here.

INTRODUCTION

Collaborative research programs between the Pennsylvania State University (Penn State) and the gas turbine industry deal traditionally with isolated fundamental research topics focussing on either experimental or analytical/computational aspects of a specific problem. In this conventional mode of research environment (which is typical of most leading US engineering schools), graduate (and occasional undergraduate) students play a major role in the development and execution of the program. The duration of a typical project is usually more than two years. The final outcome of the research program involving graduate students is a final report, a thesis prepared by the student, and archival papers that contain novel ideas with contributory character. For some time, both industry and government have encouraged more industry/university interaction, and the involvement of more practical design experience in education. The same type of encouragement is often given by the "Industrial Professional Advisory Council" (IPAC) at Penn State (IPAC Report). At Penn State, this has manifested in the form of teaching (Lamancusa, *et al*, 1997)] laboratories and coop programs.

The current trends in the aero-engine and ground-based industrial gas turbine industry require very rapidly executed and effective engineering research and development programs that can not tolerate a time duration of two years or more. Although many industrial problems are less fundamental in nature, they require advanced engineering skills, dynamic scheduling, effective project management skills, and excellent team work. Industry has found that as the complexities of their designs increase, so must the functionality of the design tools and creativity of the designer. Today's computer-aided design (CAD) tool is much more than the electronic drafting board that was introduced 15 years ago. Today's designers not only need a foundation in good analytical practices, they must also be able to think in terms of components, systems, and 3-D geometry, communicate within a cooperative work group, and understand the impact of good cost and schedule management (Nicolai, 1993; 1998).

The Taurus 60, a mid-size gas turbine engine manufactured by Solar Turbines Inc. (Solar) of San Diego, served as the vehicle for a collaborative pilot project involving the Department of Aerospace Engineering (Aero) and the Applied Research Laboratory (ARL) of Penn State. The difference relative to other industrial-sponsored projects was that it promoted a much more intense practical interaction thus addressing the need for real-life problem solutions so often advocated by members of the gas turbine community (Glezer, 1996; Aerospace Education Workshop, 1996). This project was structured so that our students functioned in a professional engineering capacity. The students, guided by a principal investigator/technical manager and a consultant, worked on a real engineering problem as if they were part of an engineering team in a consulting engineering design firm.

The use of industry-standard software packages, having an actual deadline precisely monitored by the sponsor, establishing a regular video-conferencing link, meeting and collaborating with the engineering staff of the sponsor, and producing industry standard final drawings of the turbine components designed were a few of the real life experiences offered to the student team. A mix of undergraduate and graduate students, and academic and research faculty had the chance to learn,

design, produce, and disseminate in a real engineering environment that is not easy to simulate in the conventional, textbook-based, single-instructor classroom of our universities.

Figure 1 is a cross-section of the Taurus 60 engine, and identifies the two particular areas of technical interest selected for this project: the first stage nozzle and turbine blade. This figure shows the complicated internal structure required by these components for their survival in the high-temperature environment downstream of the combustor. Cooling is accomplished by diverting some of the compressor airflow to the passages shown inside of the nozzle and blade. The sketch of the nozzle shows the hollow internal manifold and heat transfer augmenting pins, while the sketch of the turbine blade shows the complicated serpentine passage. The project addressed design modifications that would be required to operate the engine at a higher turbine inlet temperature with improved cooling of the first stage nozzles and turbine blades immediately downstream of the combustor. Specifically, thermal/hydraulic analyses of several conceptual design modifications aimed at providing adequate cooling of the first stage nozzle were performed. Machining and casting drawings of the preferred design, using industry standard parametric CAD, were also required. The drawings produced had to be directly compatible with Solar's manufacturing requirements. Then, as a preliminary to follow-on work, three-dimensional solid models of the first-stage turbine geometry were also required.

The activity described in this paper explains the details of this unique engineering research and development program executed by a group of undergraduate and graduate students at Penn State. The key requirement of the project was the intimate involvement of students in the analysis and design process of the project, and its successful execution within a 4-5 month time frame. The objective of this paper is to describe the challenges of this project, and to address the questions: Can/did this project provide a significant educational experience?, and can this type of project be a regular part of the engineering curriculum if industrial partners and/or government organizations are committed to support them?

ORGANIZATION

Motives and Contributions

The Department of Aerospace Engineering has a strong interest in participating in industrially-supported educational projects if they provide a meaningful educational experience for its students. The time schedules and technical objectives planned for this project were more aggressive than typical university design projects. This project acted as an incentive for the department to upgrade its infrastructure by developing a CAD capability within the department geared toward interests that are particular to the aerospace industry. The successful

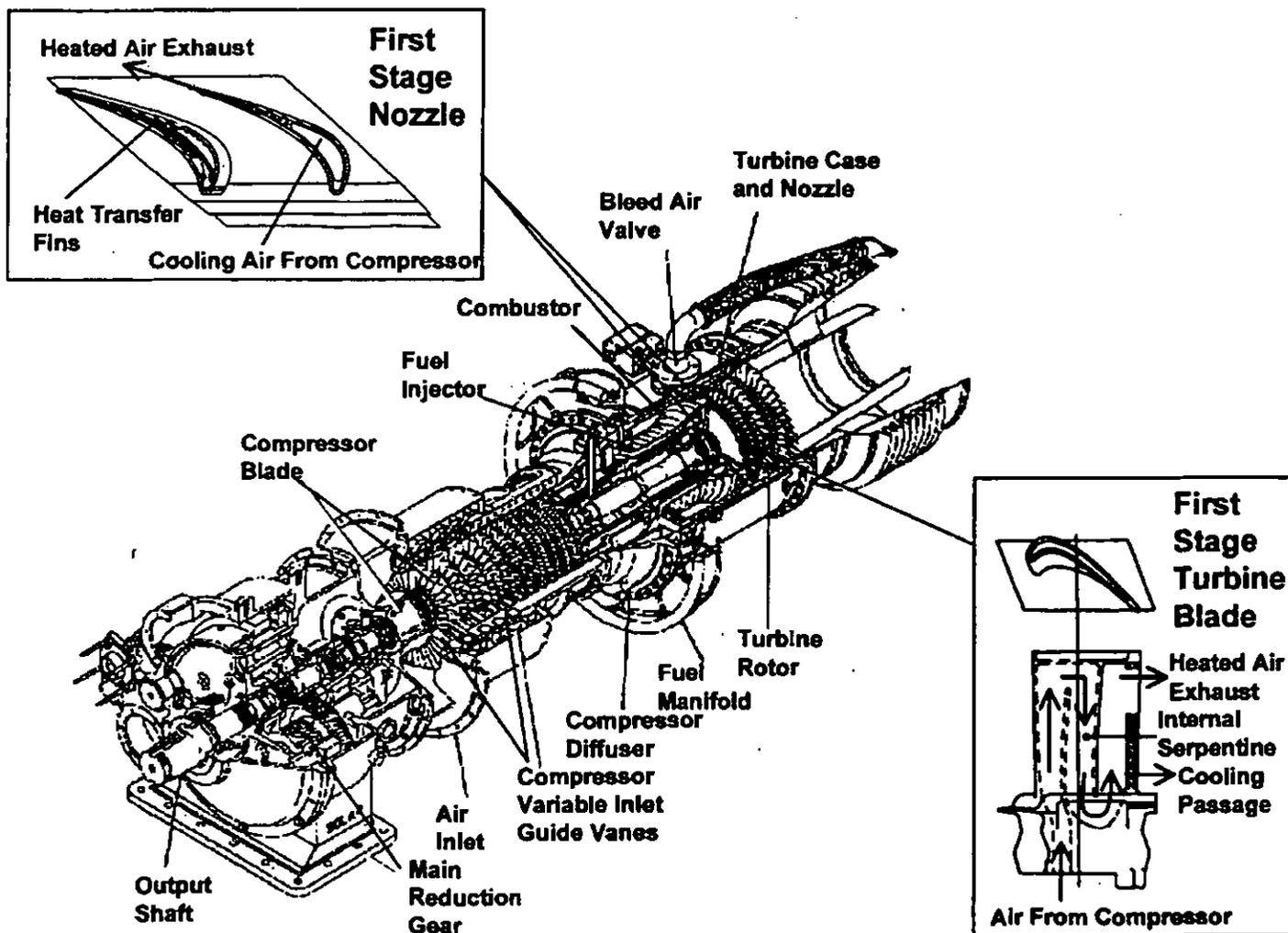


Fig. 1 - Taurus 60 Gas Turbine Engine

execution of this type of program acted as a motivator, morale booster, and as a recruitment tool for the department.

Although part of Penn State, ARL has a somewhat independent identity as a research and development laboratory, and somewhat different mission than the academic departments. One of the traditional missions of ARL is to conceive, develop, design, and test non-nuclear power systems for undersea use by the U.S. Navy. Recently, there has been interest expressed by the laboratory management for developing expertise outside of its traditional defense area. This project provided an opportunity for ARL to gain experience in an area that is related to, but outside of, its traditional area of endeavor. It also fostered a closer relationship with an academic department, which may be mutually beneficial for future projects.

In support of Solar's strong commitment to engineering education, aggressive product and technology strategy, and development of the requisite staff of highly skilled and motivated designers and engineers, Solar has developed and maintained a comprehensive program with targeted universities and individual students. Under corporate and DOE sponsorship, Solar works closely with universities on research relevant to industrial gas turbine engines. The Solar Intern Program enables students to spend each summer at Solar to gain practical experience on meaningful technical assignments. The project described here added a new dimension to this corporate approach. Students were provided the opportunity to work on a design problem typical of the ones they would need to excel at in their professional career. They conducted the project from inception through final design review, under a realistic environment complete with tight schedules, execution of team-centered

and multidisciplinary design processes, acquisition of skills with technology and analytical tools representative of the industry, and the occurrence of unforeseen problems. An analysis of the benefits of these types of programs has been described elsewhere (Friel, 1995).

Personal commitments of the project leaders on both industrial and university sides played an important role in the successful execution of this project. This project allowed us explore the practical implementation of some new ideas about engineering education. For some of the university participants the project represented a first experience in technical management. The participation of multiple institutional participants caused some initial concern about conflicting allegiances. Consequently it was extremely important to focus on the primary objective of this project; the intimate participation of students, and the obligation to "do right by them."

Organizational Structure

The overall organizational structure of the project is shown in Figure 2. The five students (split into two teams) participated as engineers, two faculty members functioned as project engineers, and additional faculty and staff were closely involved in an advisory capacity at all levels. A goal was to promote as much cross-communication as possible between the student-engineers involved. Although, for this project, two relatively distinct project goals were required, in an actual industrial design process there is in fact much more communication required between thermal/fluid and mechanical designers. To emphasize this, we held semi-weekly project meetings for all participants.

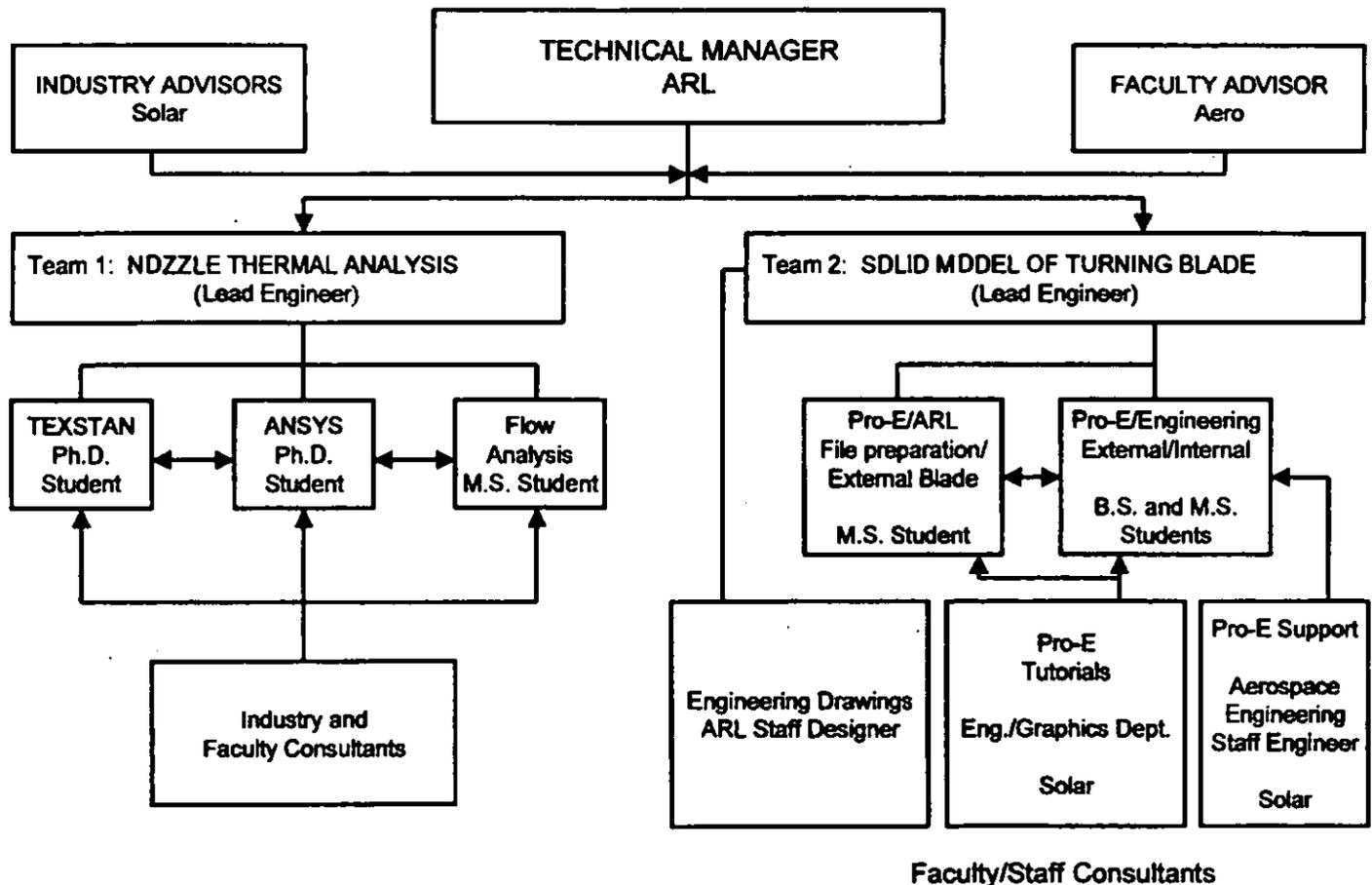


Fig. 2 - Project Organization

Because ARL maintains a professional CAD department, and has past experience with industrial research, manufacture, and development, ARL supplied technical leadership for the project. Some of the deliverables were industrial quality machining and casting drawings, and this aspect was undertaken at ARL as well. Aero provided administrative assistance and access to some of the college's CAD and workstation networks. Aero faculty also provided technical expertise for heat transfer/cooling issues particular to gas turbine technology. Solar initiated and funded the project, provided some conceptual design ideas, as well as a great deal of technical and instructional support.

PROJECT EXECUTION

Team 1

Figure 3 shows the overall analysis approach used by Team 1 to perform the thermal analyses. Solar supplied information about the external flow field as well as a temporary license for their proprietary

flow network analysis code. Initial parametric calculations of the external heat transfer coefficients were made with the academic version of the TEXSTAN boundary layer code (Crawford, 1986). The results of this parametric study showed that an important influencing variable was the free-stream turbulence intensity (it strongly affects both the magnitude and the location of the maximum nozzle temperature).

Simultaneously, different thermal-hydraulic circuits that modeled the cooling behavior inside the nozzle blade were built and exercised using the network program. A two-dimensional ANSYS finite-element model was constructed, and an iteration process was initiated between the flow and thermal student/analysts. The object of this was to obtain the nozzle temperature distribution for a range of free-stream turbulence intensities (the principal unknown). The proper intensity was inferred from comparisons with earlier thermal paint measurements made by Solar in the actual engine environment.

Correlations from the technical literature were used to supplement the numerical analysis. For example, the correlation for the leading edge, stagnation point heat transfer coefficient is shown in Figure 3.

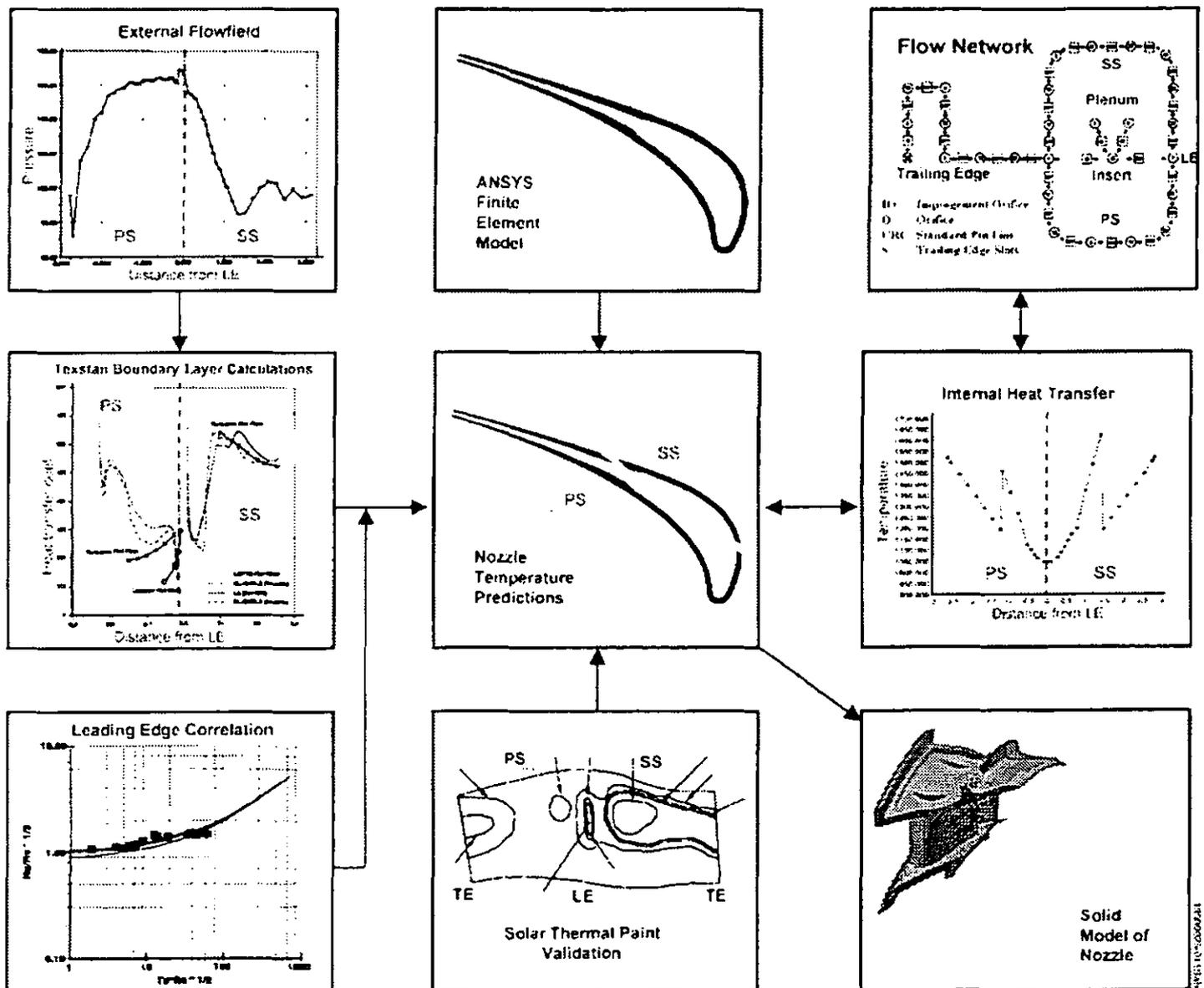


Fig. 3 - Pictorial Representation of Analysis/Design Method Followed by Team 1

Other correlations were used in subsequent calculations of film-cooling effects. After satisfactory nozzle temperature results were obtained, the casting and machining drawings were produced by an ARL CAD designer. Once the general procedure was validated for the baseline design, it was repeated for the various candidate cooling designs. Students rapidly became accustomed to the iterative nature of the design process.

Team 2

Figure 4 shows the development sequence pursued by Team 2. The objective of this team was relatively straightforward; the production of 3-D solid models of the internal, external, and combined geometry of the first stage turbine blade. The ability to think in 3-D is becoming an important requirement for engineering designers. The internal passage shape plays a very important role in cooling the turbine blade, and any future optimization of the interior for higher temperature operation would require close collaboration between Teams 1 and 2. A sequential construction of the turbine blade solid model is insufficient because of the multiple iterations required between thermal and mechanical designers.

Several mundane but difficult obstacles arose. For example, in common with many organizations (industrial and academic) and due to the rapidly evolving technology, Solar Turbines has its technical drawings on a variety of media. Currently, all new designs are performed using the 3-D parametric CAD program ProEngineer (ProE). Consequently, an additional de-facto technical objective formed: to develop a procedure for transitioning older 2-D CAD files to a format that was compatible with the 3-D parametric CAD package.

A second difficulty arose from the accelerated learning curve required by the students to come up to speed with ProE. Some students started with some familiarity with AutoCAD, others not (our technical managers were in similar condition). The project leaders sought to cope with this by arranging for students to sit in on ProE course lectures offered by Penn State's Department of Industrial Engineering. While this was useful in getting the students access to ProE and some initial instruction, the areas emphasized in these classes did not always coincide with the task. In retrospect, it might have served the project better by sending one or more of the students to a ProE sponsored accelerated short course, or to Solar for specific instruction.

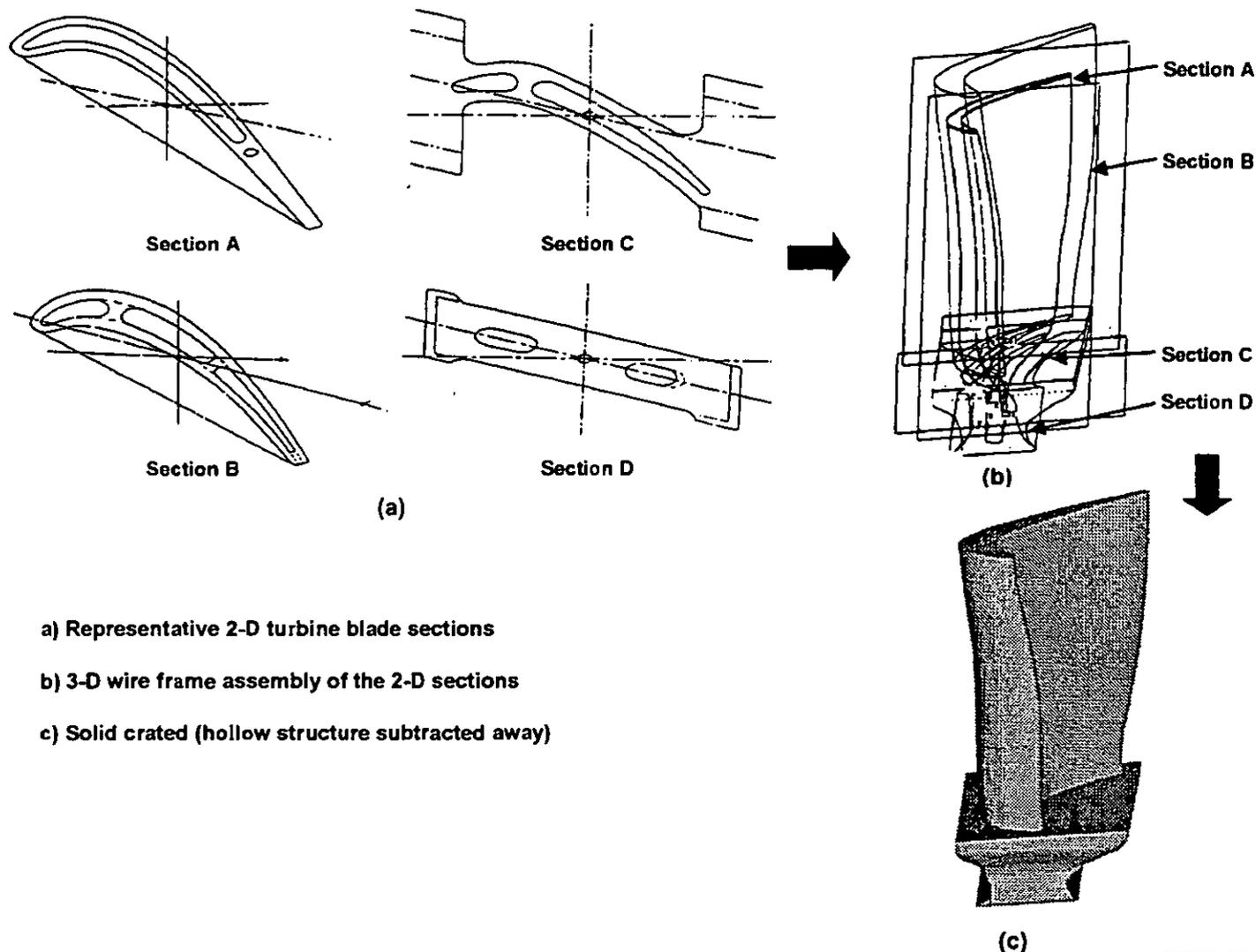


Fig. 4 - Steps in the Sequence Followed by Team 2

CHALLENGES

Personnel Recruitment

The student roster was more heavily-laden with graduate students than we had initially anticipated. One undergraduate and four graduate students participated in this project. There was a particular interest on the part of the graduate students to see practical application of their theoretical work. The graduate students were a mix of Ph.D. students finished with their research, and incoming students who had not yet started their principal research projects. An undergraduate student was interested in this project because of its similarity to a coop-type project, and the opportunity to participate while remaining in school was attractive to him as well. About half the participants were serendipitously available. The rest approached us after becoming aware of the project "through the grapevine."

Time Scales and Schedules

Industrial time scales are typically much more compressed relative to those with which academia is accustomed. Academia is typically used to operating on multi-year time scales, without the "time is money" deadlines of industry. One major unknown was whether it was possible to produce an industrial caliber result within an industrial time constraint (4 months). The ARL functioned here as an intermediary. Although ARL does not operate under the extreme time constraints of industry, it is still accustomed to having to produce a design or physical product under a deadline.

Industry, when a commitment is made, can perform work on a continuous basis. The university partner is typically constrained by the academic calendar. The work-load of the participating students must be tailored to their examination and classroom project schedules. This was of particular importance if undergraduates were to participate in a meaningful manner. (Students may have to contend with unsympathetic instructors.) We were wary of obtaining a Pyrrhic victory where the material objectives were achieved, but the students were so exhausted that they would want nothing more to do with the engineering profession in the end. Preliminary work was initiated at ARL prior to the academic start to bring the faculty/staff advisors up to speed with some of the computational tools.

Proprietary Elements

Arrangements were required for using the proprietary nozzle and blade drawings supplied by Solar. The ARL has experience dealing with confidential DoD material, and a similar document handling protocol was implemented at ARL. The drawings were kept locked in Aerospace Engineering's main office, and signed out to the appropriate students working on the project. However, we were sensitive that one of the desired outcomes of this project was to get other students interested. This is typically most effectively done via word of mouth between students working in the common workstation laboratory area. It would have been counterproductive to be too secretive about this project.

Several computational tools were required to undertake this project, some of them proprietary. For example, Solar uses a proprietary one-dimensional flow network code. A temporary license was obtained to enable students to use it on an ARL workstation.

Computational Tools, Software Compatibility, and Learning Curves

The ARL uses the parametric CAD package UNIGRAPHICS for solid modeling and mechanical design work. The college of engineering, however, maintains a large number of ProE seats, which Solar Turbines uses as well. However, Solar's principal casting supplier prefers

UNIGRAPHICS. This type of software heterogeneity is a common problem (in all sizes and types of organizations). UNIGRAPHICS was used at ARL to produce the electronic solid models, casting and machining drawings of the first stage nozzle. Hard copies of the drawings were supplied to Solar, and the electronic copies to the casting supplier. We discovered that for the most part, the CAD models developed using UNIGRAPHICS ported completely to ProE (this was demonstrated at the final design review held in San Diego). The push to use ProE resulted from the desire to make the solid models immediately compatible with Solar's system. Given that the educational goal of the solid modeling effort was to encourage a general thinking ability, rather than a specific software capability, we will reconsider the insistence on using a specific parametric CAD package in the future.

These types of software compatibility and communication issues are part of the rapidly maturing area of "simulation-based design." As engineering software tools improve, compatibility issues between older and newer software become more important. This project represented a first attempt at using drawing files from an older 2-D CAD package as input into the parametric ProE package. The ability to read in and manipulate these files while still on the ProE learning curve represented the most challenging technical part of the project. Although this was done successfully in the end (and this new information passed on to Solar for future reference) it is clear that steps could have been taken by the faculty advisors to minimize the effort required by the students.

Because of ease of access, the student development of the solid models of the turbine blade exteriors and interiors were undertaken using ProE in the College of Engineering's student laboratory. We found that the student laboratory was a fertile environment to work in. Students and teaching assistants, not involved with the project, would observe some of the work being undertaken, become interested, and offer suggestions. During this period we also established a ProE site in the Aerospace Engineering Department which allowed us to pursue a more intense effort when required.

Strengths typical of industry, that Solar brought to the table, are accumulated design experience, specific design codes, and experience with making rapid parametric studies. For thermal analysis we used the TEXSTAN boundary layer code, as well as Solar's flow network code. One of our students was already using TEXSTAN for his thesis work. Although some of the faculty had experience with some of these codes, it was necessary for the faculty to work as hard as the students to gain familiarity in order to provide the necessary advice and guidance.

Communication

The establishment of lines of communication between the project supervisors and the students, and between the project supervisors and the participants at Solar, represented one of the most important and, on occasion, one of the most exasperating aspects of the project. E-mail was the primary means of communication with our student participants. However, when students had examinations or other academic work due, they would often "go to ground" and virtually disappear. It took some effort to convey to our students that the need to communicate with them came not from a desire to load them with more work, but rather from our need to be keep aware of their availability. It was important for us to convey to the students that their course work took precedence, and that we were willing to work around their schedules.

External access through the Internet was limited to one person at Solar to maintain security. Given the extremely fast-paced schedule, the ability to exchange e-mail progress reports, data, and design files, was absolutely essential. Unfortunately, the faculty project advisors did not go far enough to encourage more direct participation between our students and the industrial participants. The frequent communication

between project supervisors and industrial participants would have been more effective if students were directly involved in this communication.

Although the Internet provided an effective means of exchanging information, face-to-face meetings between Aero, ARL, and Solar were essential for conveying a sense of urgency of this project. Scheduling and financial constraints made personal meetings impossible between all participants. However video-conferencing provided a very satisfactory compromise. A video-conferencing room was not readily available on campus during this project; instead we used one from a local copy center. Although other groups at Penn State have not found video-conferencing to be as effective (Lamancusa, et al., 1997), the effect of the more personal interaction was very beneficial as a morale booster during some of the more frantic periods.

A final design review was held near the completion of the project on site at Solar. Solar flew the students involved in the project to San Diego. The students participated in a professional caliber design review in which they made technical presentations to members of Solar's technical management and engineering staff, including the vice-president for engineering and other functional managers. The review was very effective at giving the students a perception of the implications of their work in the larger technical, financial, and marketing arenas.

RESULTS

Benefits for Student Participants

Some direct benefits to the student participants included:

- Familiarization and practice with design and analysis codes (thermal-flow network, finite element, boundary layer, parametric CAD) used in the industrial design process.
- Practical application of some of their theoretical research work.
- Familiarization with multi-disciplinary industrial design practice and methodology.
- Experience with the intense group dynamics of a high-speed project.
- Interaction with a corporate culture and structure, including a professional design review presentation on site at Solar to the vice-president of engineering and other functional technical managers and engineering staff.
- Developing confidence in their ability to perform a challenging engineering task and meeting a tight production schedule.
- Receiving a plant tour of the Solar Turbines production and research facilities.

Benefits for Institutional Participants

Specific benefits to the industrial participant included:

- Performing a cost effective thermal analysis of several alternative first-stage nozzle cooling concepts, and the identification of a preferred design.
- Establishing parametric CAD machining and casting drawings of the first-stage nozzle, including the alternative cooling concepts.

- Obtaining parametric CAD solid models of the interior and exterior of the first-stage turbine blade.
- The identification of specific difficulties related to transitioning older 2-D CAD files to 3-D ProE solid models, and the development of a procedure for accomplishing this.
 - Access to enthusiastic potential hires with experience in team work, and some industrial design practices.

Specific benefits to the university participants included:

- Better understanding of the technical issues associated with the commercial gas turbine industry.
- Recognition of the importance of real life problems and experience with their solutions as part of the engineering curriculum.
- Experience in initiating and executing a heterogeneous collaborative project.
- Establishing a technical infrastructure for future work.
- Training students that may act as instructors for industry standard software packages (ProE).

Observations

Some observations that we feel may facilitate such an accelerated program in the future include:

- Recognizing and resolving the university (semester-based) time scale with the more flexible industrial time scale.
 - Our undergraduate is now an instructor for parametric CAD classes offered by the College, thus providing another route for the wider dissemination of his industrial experience.
- The participation of an intermediate participant that is more accustomed to accelerated time scales was an important bridge between industry and the academic teaching university for this type of accelerated project.
- For this project the key to success was a very keen, very personal commitment to this project by all of the parties involved.
 - Establishing and proactively encouraging easy, personal, and blame-free methods of communication between all parties involved with the project. Encourage E-mail lines of communication with the industrial participant (especially including the student participants). Video conferencing is an easy, cost effective, and can serve as very important morale booster for this type of accelerated project. The college/university should enable ready access to this equipment.
- Facilities must be available for turning over industrial caliber drawings to the industrial participant; either from the intermediate partner, or developed by the department

participant. Easy access to the technical infrastructure (CAD workstations) is necessary. Comments and suggestions from interested onlookers can help the project and should be encouraged.

- We must explore the option of using commercial short courses (preferably on site so as not to affect student schedules) to quickly bring students (and participating faculty/staff) up to speed. Future projects of this type may not require this if a corporate memory is established and easily accessible.
- The emphasis should be most strongly directed toward general knowledge and ability rather than relying too heavily on the use of a particular software package.

SUMMARY

This project was challenging. As to the initial question posed in the Introduction, yes, this project did provide a significant educational and personal experience, and we think that all involved benefitted from it. Can this type of project be institutionalized as part of a curriculum? The levels of personal energy and dedication required by the participants were high. However, by developing some infrastructure and corporate memory within the academic department, such a project can be successfully performed when it becomes available. Two-way exchange between university and industry with representatives from both sides physically working for a certain time in a different environment (leading seminars or giving lectures), may be an effective strategy for improved engineering education.

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