The Passive Solar Greenhouse and the Fluid Column: Two Case-Studies in Integrated Design-Build Pedagogy

Danny Wills
Cal Poly, San Luis Obispo

Abstract

Poly Canyon is a 12-acre home to experimental student design-build projects, located less than a mile from California Polytechnic State University in San Luis Obispo's main campus. Scattered throughout the site are senior projects dating as early as 1961. Over time the site has gained a menagerie of experimental building forms, structural concepts, material techniques, and construction methods. Some have served very practical needs, such as bathroom facilities, housing, and pedestrian bridges, while others have crafted projects meant to push the boundaries of architectural science.

This paper will examine two specific case-study projects located in Poly Canyon and evaluate, through historical research, their performative value with regards to pedagogical intent. The first project, the Fluid Column, was a structural concept developed in 1970 by Dr. Jens G. Pohl that sought to use a pressurized rigid membrane as a column. The second project to be evaluated is the Passive Solar Greenhouse. Built over the course of seven years (1983-1990), this project was the conception of an Architecture graduate student Marc Jenefsky.

For this paper, formal research was conducted using the University's Senior Project collection, uncovering project timelines, photographic documentation, and unique perspectives from student researchers. Combined with informal searches through storage units, personal histories, and re-discovered documents, this research seeks to comprehensively tell the full story behind these unique case studies for design-build education.

Fig. 1. Photograph of the Fluid Column during under construction, 1975. Courtesy Cal Poly San Luis Obispo University Special Collections and Archive.

Structure and Nature of the Senior Project

A large majority of this paper relies on the information provided in students' Senior Project documentation. Each Senior Project at the time consisted of some form of abstract, goals, research, material selection, production documentation, test results, analysis, and a conclusion. This type of documentation offers a unique window into the projects via the student's own perspectives. The range of projects can be demonstrated through the range of outcomes; plans, site collages, data trees, network diagrams, photographs, donor letters, material budgets, brochures, and more line the pages of work.

Because of the dominate student narrative, it is difficult to ascertain the conceptual evolution of projects, let alone the physical changes in projects. Students' ambitions, combined with the pressures of graduation, often left project success up to the next torch carrier, yet language in their conclusions attempt to diminish those facts. After the author of this paper discovered approximately twenty Senior Projects and multiple newspaper articles, a timeline of building stories, project scopes, and student visions was organized and ordered into as factual as possible a timeline given the singular student perspectives on the project.

Fig. 2. Photograph of the Fluid Column during installation of the roof truss system, 1974. Courtesy Dr. Jens Pohl.

The Fluid Column

In 1973, as a recently hired Professor, Dr. Jens Pohl was determined to test his structural concepts of pneumatical support systems for multi-story buildings. Two small-scale prototypes were constructed using pressurized air, reflecting the experiments of other 'bubble-buildings' of the time. Interested in scaling up, Dr. Pohl also floated the idea of water as the pressurizing medium for structural components held in compression.

Gren Warner, a senior in the recently formed Construction Engineering department, studied Dr. Pohl's pneumatic theories with the goal to apply them to a single column multi-story building, with the goal of using water from the outset. From initial load calculations and material research, Warner selected steel and pre-fabricated the 24 foot tall, 4 foot 8 inch diameter column.[1] The hollow column was over-engineered within a "realistic safety margin," able to withstand the required loads unpressurized.[2]

Based on the photographs in his documentation, students helped move the column by hand after the shop's truck could not reach the project site. Meanwhile, three other students were tasked with the material selection, load calculations, stress-testing, and prefabrication of the columns' cantilever truss roof system. After testing one steel truss module in the shop's pneumatic stress bay, the students stated they "have gained self-confidence by proving that [their] truss can withstand the required load."[3] They fabricated eight identical segments fixed to a central frame. The system was stored in the shop until the day came to move both elements to the site – the last task before this senior class graduated and left the project.

The next year, with a new senior class, Dr. Pohl led the continuation of the building. The first task of the class was to check existing conditions and establish a Critical Path Method (CPM) for coordinating the construction process. With the column and truss system in place, students attempted to fill the column with over three thousand gallons of water. Two attempts at fixing issues with plastic liners eventually led the group to reconsider water as the fluid infill material and instead switch to sand. However, they defended the original concept by stating, "[d]ue to materials problems, not engineering problems, the fluid-support method became unfeasible."[4]

By the end of 1974, the completion of the project was on hold due to labor and safety concerns with filling the column with sand. In the Winter and Spring quarters, the project was now an open elective and able to accept an influx of interested students across not only the School's five new departments – Architecture, Architectural Engineering, Construction Management, Landscape Architecture, and City and Regional Planning – but also the University at large (including Business Administration, Agriculture, Environmental Engineering and Home Economics). Thirty-four students signed up for the class, and each was assigned a specific task for work completion.[5] Working days were kept to Fridays and Saturdays, and the group no longer kept a detailed CPM network to plan construction.

With the addition of hanging floors, a wooden staircase, and a plastic membrane as enclosure, the prototype construction was completed. In the summary of their Senior Project, three Architecture students discuss implementation possibilities and application merits for the fluid-concept, including industry acceptability, aesthetics, and energy conservation. One advantage written by the students, aside from the structural applications, is the project's ability to allow for less material usage in residential construction - notably a concern of the time due to increased populations leading to material shortages.

The prototype was ready for public display by Spring 1975. Several media outlets covered the project, with one describing the column "filled with a semi-viscous material."[6] It is unclear if Dr. Pohl and the students were initially at peace with the last-minute switch to sand. However, plenty of effort was made to see its merits. In an LA Times article in 1976, a student was quoted with the suggestion of sand, "it acts like a liquid and is a lot cheaper."[7] Additionally, the incoming 1976 class decided to test the sand for its ability to store heat from solar collectors.

Undertaken by a group of seven students from multiple disciplines, and funded through a $12,700 National Science Foundation grant, the design consisted of a large flat plate solar collector installed on the roof and a collector-storage interface systems which connected the solar collector to the sand-filled column, acting as the heat store.[89] Unfortunately, as documented in a 1977 senior's project summary, the system failed to perform "due to failure of the piping system to withstand pressurization." The student also mentioned loose pipe fittings and connections due to "unsatisfactory glue" heated by the sun, as well as obstructions in the piping system. The total system ran for one hour, and little data was able to be collected. Ojeda documents the process and data nevertheless, but little is written on what real lessons were gained via this failure in the experiment.

Issues with the fluid prototype continued. Poor site drainage was causing pools of water to sit at the foundation and corrode the base connections, and the temporary materials were already showing their wear.[10] In their first proposal to the newly formed, student led Poly Canyon Quality Control Board, a new group of seniors proposed a demolition strategy for the prototype, with the intent to measure the ultimate loads the experimental structure could take. While they had plans for much of the later additions, the students could not figure out the best solution to deal with the column, sand, and its concrete foundation. One student suggestion of "carrying the problem to its most ludicrous extremes," cheekily wrote they "could all take the appropriate dosage and just simply hallucinate the damn thing away."[11] Not satisfied with this answer, the QCB requested an amended proposal that gave serious consideration to the environmental life-cycle of the materials and site once demolition took place.[12]

While lessons were learned all around, the students never followed up on their demolition documentation and it is unclear how much load this unique column could ultimately take before physical failure. Despite those lost lessons, the students emphasize the need to make room for other lessons. Citing potential crowding of project sites in the school's outdoor "laboratory for construction problems," they write that they "must be able to recycle the land in a manner which is beneficial to the Canyon, the School, and the Students. This facilitates the development of the Canyon to its fullest and at the same time making room for new ideas and development. It is with this in mind that we wish to remove the Sand-Supported House from Poly Canyon."[13]

Almost twenty years later, another student made project was built on the same base plate concrete foundation, still standing today.

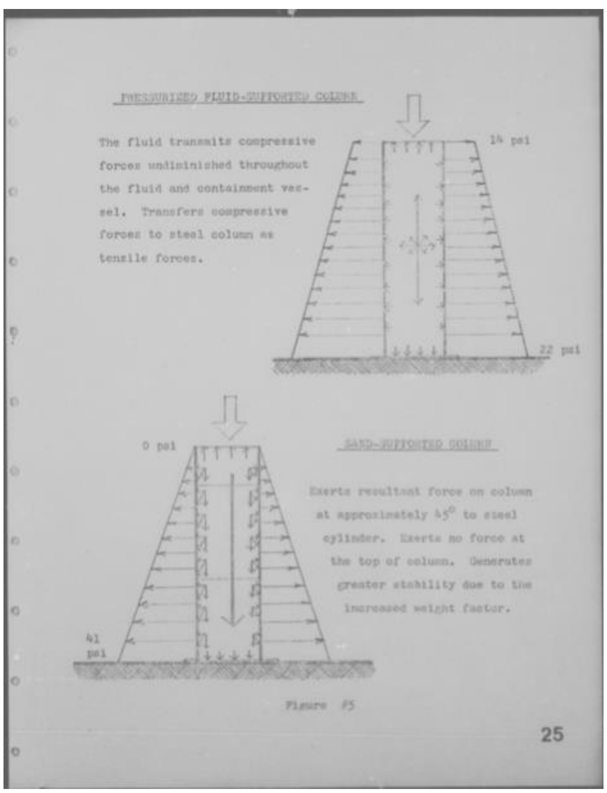

Fig. 3. Force path diagrams of fluid and sand-supported columns. From: Adams, Alvarez and Cauthon, "A Study," 25.

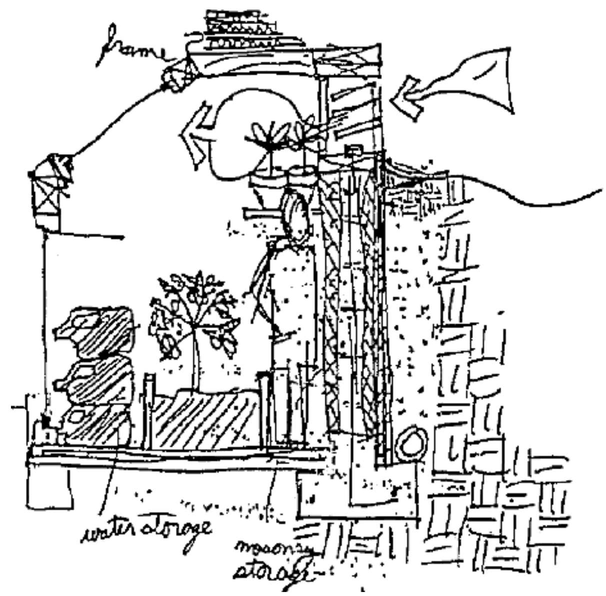

Fig. 4. The Original Design. From: Jenefsky, "The Process," 12.

The Passive Solar Greenhouse

In his 1991 Master's of Architecture thesis on the Passive Solar Greenhouse, Marc Jenefsky summarizes how, as a 1981 undergraduate, he "conceived the idea of building a passive solar greenhouse," and how, at the time, "the scarcity of examples of this rediscovered technology, both on campus and in the local community," drove him to build a demonstrative structure in Poly Canyon.[14] Jenefsky states his original intentions were for a "tiny lean-to greenhouse of inexpensive materials that could be built in one weekend."[15] Over the course of four-years (with bookmarked planning and documentation years), and according to Jenefsky, "over 200 students and two dozen faculty."

The project began in Spring quarter 1983 with a ceremonial groundbreaking. Jenefsky's graduation from the Bachelor of Architecture program was the same quarter, and he started the following Fall quarter as a Master of Architecture student. With this degree shift, Jenefsky was given a teaching elective, "CSTR 400: Special Problems," which gave support and momentum to his greenhouse goals.

The first Senior Project to emerge based on this elective course was Ron Radziner's study on site selection for the greenhouse, architectural design of the structure, as well as using the "CALPAS3" computer program to analyze and predict conditions within the designed greenhouse.[16] Radziner's clear documentation shows that three sites were analyzed for their elevation, site exposure, solar insolation, and distance from other projects for water utility connect ease. However, based on the timing of Radziner's documentation (in Winter 1974) and the actual known 'groundbreaking' in Spring 1983, it seems the final site was already pre-determined most likely due to a pre-existing rock foundation wall allowing for minimal site-excavation.[17] The site did, fortunately, also have one of the highest solar insolation possibilities.

Radziner first used the Passive Solar Design Handbook of 1984 to help with initial passive solar heating and cooling strategies, and then later refined them using a computer to analyze possible scenarios based on the greenhouse's location, size, and passive strategies expected.[18] The CALPAS3 program helped the student primarily understand the role of mass and volume related to solar capture and storage. Therefore, his original design, aside from the natural rock wall and CMU retaining wall, planned for twelve 50 gallon water-filled drums in a diagonal configuration." Perhaps he somehow learned that "water is a more efficient storage medium than rock," from the decade gone Fluid-Support Column turned Sand-Supported Solar House.[19]

Radziner's designs and site selection were approved by the Poly Canyon Quality Control Board, and at the time he stated that construction was "scheduled to be completed by mid-November and hopefully before the winter rains commence."[20] Little did he know at the time that these designs would trigger a snowball's effect of students and timelines that pushed the final project's 'completion' to 1989.

It was perhaps the next student, Bradley Owens, who foresaw the beginning of the complexity of the project in terms of planning and management. His Senior Project, also published in Spring 1984, studied various construction management methods (MRP, Gantt, PERT, CPM), and developed his own creative method that could handle the "flexible schedule" that was the growing greenhouse.[21] His concept, named the "Greenhouse Project Organization Plan," was developed starting with the construction group listing what materials and equipment were needed on a large piece of butcher paper. Timelines, quantities, and any reliance on material donations was added. The butcher paper was transferred to letter sized paper, "for ease of display at meetings or for reference." The final part of the process involved a computer program assisting in timeline management. However, the student noted that the evolving project timelines were unable to be updated in the computer system because, "the person in charge of entering the data into the computer was unavailable to make changes."[22] Overall, it seems his planning of student's schedules also got the better of him, stating that:

"each member's school schedule was logged on a chart and the meeting was arranged during a common opening. Then a card was sent to each member informing them of the time and instructions to call a specified person to verify receiving the card and whether attending or not. Unfortunately, attendance was sparce and individual contact was the only time that coordination was accomplished. This is one reason the Greenhouse is slow in evolving."[23]

Owens, in evaluating the complexity of the project's planning, added that fundraising and donation soliciting often hampered timelines. Overall, he seems to place a majority of the inconsistencies on the students themselves. "The construction crew was also inconsistent. Often some wouldn't show up when scheduled to work or were unmotivated when they did show up."[24]

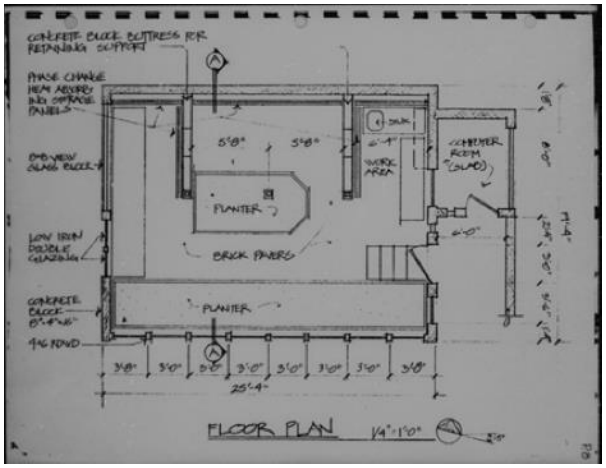

Fig. 5. Floor Plan of the Passive Solar Greenhouse. From: Yung, "Passive Solar Greenhouse," 9.

Perhaps related to this uncontrolled and unbalanced division of labor in this design-build project is the matter-of-fact presentation of the third Senior Project, by a Construction Management student. His documentation only contains a few pages, a foundation plan, and a very clear statement that he worked "every Saturday and Sunday from 9:00 A.M. to 3:00 P.M." assisting in the footing, foundation, formwork, reinforcing steel, concrete, concrete block, grouting and roof trusses.[25]

A year later, the project grew with a second round of Senior Projects. The 'passive' in Passive Solar Greenhouse began to take on a different interpretation, with a Construction Management student, Daniel Duke, designing and specifying an electrical power system. "[B]ased on the need for electrical power systems for the project expressed by Marc Jenefsky, I decided to undertake the project from the point of view of an electrical subcontractor."[26] Duke documented his research, design and layout, working days, bill of orders, and material expenditures in clear details. Duke graduated without the system being installed.

Based on the donation of 64 new phase change panels from DOW Chemical Company, arranged through Jenefsky, Robert Flory and Arthur Creef researched the potentials of these phase change panels, designed to assist in solar heating and cooling by reducing radical temperature swings.[27] Creef's methodical thesis constructed a black box to test a panel and compare data, while much of Flory's writing mimics the language of a catalog from DOW. However, his Senior Project importantly concluded that passive cooling via thermal mass and the phase change panels were not enough. Shade devices, operable windows, and stack ventilation were suggested as options to assist in the overall goal of overheating the future greenhouse plants.[28]

Douglas Herbert and Steven Eggemeyer, two Mechanical and Environmental Engineering students, were to address the problem of controlling the indoor environment. They used the CALPAS3 program again to calculate indoor temperatures and heating loads throughout the day, month and year. While the phase change panels could not be modeled into the program, "an increased water storage component was used to approximate their thermal behavior."[29] Additionally, the solar chimneys had to be modeled as simple vents twice the area. As a result of these computer analyses, the students concluded that a cooling problem still existed and proposed an evaporative cooler and an electric computer for controlling a damper on the solar chimneys. At this time in the construction, no windows have been installed to the greenhouse, but already the model simulations were dictating the need to forego the 'passive' nature of the greenhouse for energy intensive systems, simply to control the originally designed environment.

With the new need for a damper system, Gene Mancebo, a Mechanical and Engineering Technology student, designs a programmable system, complete with damper, stepper motor and driver chip. At the time of Mancebo's project publication and graduation, he writes, "[a]t this time, no computer has been selected."[30]

Jenefsky recruited two Landscape Architecture students to develop a promotional package for the project, seeking to gain both donors and more project volunteers. The brochure created touts the mechanical, electrical, and computerized devices “to control and monitor plant growth,” including PV systems, automatic drip irrigation, and thermosiphon solar chimneys all controlled automatically via a computer run by an anemometer and environmental simulation software.[31] These systems were never procured or installed.

The following year, 1986, saw only one student publication produced. Perhaps returning to the passive intent of the project, Maggie Selig, another Mechanical and Environmental Engineering student, designed, tested, and installed three ventilator caps for the greenhouses’ solar chimneys. The student based her designs on the Bernoulli air pressure equation and fabricated them through a GE donation of Lexan polycarbonate.[32] Selig also used a variation of CALPAS3, called Micropas, to analyze the building’s energy. Micropas was chosen for its ability to incorporate the donated Enerphase phase change panels.

According to Jenefsky’s summary thesis, he graduated in Spring 1985 and left the project in Winter 1986, sometime after the installation of the ventilator caps. It was the unfinished nature of the project that led Jenefsky to shift his report to “focus on process rather than technical research and data.”[33] At the interest in the project grew, the project objectives “moved from the actual carrying out of the tasks at hand to the management and logistical problems of dealing with large numbers of people who came and went, working on a volunteer basis.”[34]

During this time, and documented later in a 1989 Senior Project by a Management and Business Administration student (Alida Brandi), another student Jim Gates was brought on to oversee the transition. Brandi expands on the growing ambitions:

“Variables such as temperature, humidity, and carbon dioxide content would be closely monitored by computer and fed into a control loop. This control loop would then compensate for changes in the environment before they occur. Such tight control of the environment allows for in-depth studies of what affects the growth of various plant species. The growth rate of a plant could be speeded up or slowed down. This would make it possible for a grower to target his crop’s rate of maturity for greater profits. It would be possible to grow food all year since a person is controlling the environment not Mother Nature.”[35]

While Jim Gates was able to complete the construction of the enclosed greenhouse (roof, doors and glass windows) by 1987, all of the students with the ambitious goals of monitoring and studying the add-on systems had graduated. According to Jenefsky’s document, the Enerphase panels were still in storage, and still no computer system was installed. In the following years, the glass was broken out. Today, it stands an open shell; it is unclear if a single plant was ever grown in the greenhouse.

Fig. 6. Photograph of the unfinished roof. From: Selig, “Delta Wing Ventilator Caps,”43 .

Legacy of Lessons Learned

Con E 461 (Fall) and Con E 462 (Winter) were two senior class Construction Engineering courses that kickstarted the practical development of Dr. Pohl's pneumatic designs starting in 1973. The following year, the course was turned into an Arch 400 elective course open to any student in the University. Similarly, Jenefsky's greenhouse project was developed using the CSRT 400 "Special Problems" course (starting in the Fall of 1983) and then transitioned to rely on the extracurricular enthusiasm of University students outside of the Construction Management program.

Two identified reasons for these shifts from department requirement to general elective are design inheritance and excessive labor demands. Incoming seniors were un-enthusiastic about the previous group's design, which now they were left to simply execute. Combined with critical moments of excessive labor, the students in both projects were pushed to physical limits and many protested or left the project. From the perspective of the seniors who stayed behind and finished - including publishing a Senior Project on the subject – there is much resentment towards those protesting unrealistic labor requests. In the case of filling the fluid column with wet sand up three stories on a piecemeal scaffold, three Architecture students wrote:

"During this sand filling operation rainy weather was encountered and several of the students protested the working conditions, and indicated that they were unwilling to continue with the project. As an alternative to their working on the project these (7) students were assigned the task of preparing a report on how to construct and manage the project. The result was a letter to the University and School administration, describing the unsuitability of the project as a Senior Construction Engineering exercise and at this time the construction process, was once again, stopped.

Instead of trying to resolve management and personality problems at the source this indirect method was chosen. It is often easy to avoid the real issues and write a letter; it is much more difficult, but at least more positive, to stay and try to solve the real problems. This was the climax of the unwillingness of some students to not complete the building."[36]

During a recent interview with Dr. Pohl, this paper's author asked about this moment of protest. Dr. Pohl said all concerns were discussed, addressed, rectified and "the class made it through."[37] Dr. Pohl, after meeting with the University V.P. and Provost, bought a personal liability policy for up to $1,000,000 as assurance that the project and conditions were safe.

With the Passive Solar Greenhouse project, students wrote about the inconsistency of labor especially during the foundation and retaining wall construction, built primarily out of repetitive concrete masonry units filled with buckets of concrete. "Because of differing demands by various school departments, it was difficult to enforce any requirements upon the project members of the construction crew."[38] This statement, written by a student in their project summary, acknowledges the exchange of credits and labor but unfortunately only suggests enforcement as a mediator.

Jenefsky acknowledged the growing complexity of his own project as a main contributor to individual failure but insisted on overseeing and coordinating the projects to a level of control that seemed to push away students. In her evaluation of the course, one of the Landscape Architecture student writes:

"When the opportunity came to join this interdisciplinary project, we weren't sure of our role in the undertaking. It seemed that since the project had already begun and we were joining in, that it was Marc's project and we were working for him… This attachment was also a hinderance at times because it was hard for him to step back and see

the project objectively or to understand other people's views. Sometimes he would become a little pushy and we were important in directing his actions in a more positive way."[39]

A large portion of Jenefsky's Master Thesis devotes itself to this dynamic nature of interest, labor, and willingness to participate in a project not their own. Jenefsky, responding to the issue of failure by other students, said, "[I] approached the above problems by requiring smaller individual scopes of research projects and a firmer commitment to complete the research while trying to make people aware of how their effort contributed to a more meaningful greenhouse." Yet, it was Jenefsky's own ambitions that built large expectations for a project that began with very simple intentions. Another student notes, "clearly Marc was wearing too many hats."[40]

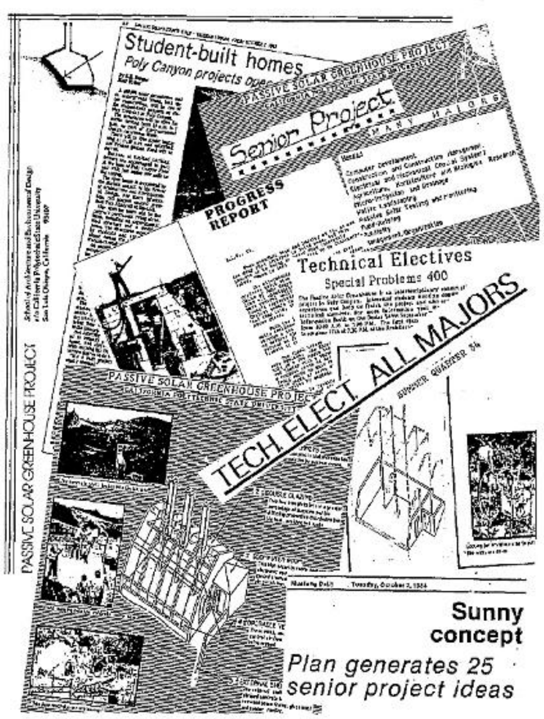

Fig. 7. Publicity Materials. From: Jenefsky, "The Process," 84.

Conclusion

Would it have been more educationally performative to build the original lean-to greenhouse and study its resultant environment, or produce a series of simulation models, material tests, and planning experiments examining the potential of a continuously unfinished project? Inversely, was the Sand-Supported column successful because of the closed scope of the project, despite the inability to gather any experimental data? The answers are not so black and white.

Over 30 students were documented having some role in the Passive Solar Greenhouse, and almost 20 students were able to publish a Senior Project on the Sand-Supported Column. Both performed well in terms of reach. Both projects engaged a wide variety of students from different disciplines, and both projects took on current industry questions and experimented with modern technologies. Unlike most pedagogical projects, these two unique case studies in design-build education stretched across several years and classes, perhaps reflecting more clearly the realistic timelines of professional building projects. With those realities of external professions, students learned the messy 'real-life' lessons including interpersonal relationship management.

Notes:

1 Warner, "Application of Pressurized Rigid Membrane Columns to Building Construction," Senior Project (1974), 11.

2 Warner, "Application," 22.

3 John Hickman, Kris Reiswig and Windell Reynolds, "Development and Evaluation of Cantilever Truss System," Senior Project (1975), 29.

4 James H Adams, Sergio S. Alvarez and Charles F. Cauthon, "A Study of a Prototype Fluid-Supported Building," Senior Project (1975), 28.

5 Adams, Alvarez and Cauthon, "A Study," 32.

6 Kent Promeneski, "Fluid building is not all wet," *Mustang Daily*, March 5, 1975, 1.

7 "The Liquid Principle," *Los Angeles Times*, August 29, 1976, L9.

8 David Quattrone, Eric Farmer, Dan Smith, Mike Carson, Tony Kannry, Greg Smith and Jerry White, "Sand-Supported Solar House: A Student Project," Senior Project (1977), 1.

9 "Students can turn ides into profit," *Mustang Daily*, September 27, 1977, 5.

10 Bruce S. Elster, Keith B. Foiles, Marney Mintz and Peter D. Van Matre, "Demolition Proposal: Ultimate Load Test of Sand Structure," Senior Project (1978), 1.

11 Elster, Foiles, Mintz and Van Matre, "Demolition Proposal," 2.

12 Bruce S. Elster, Keith B. Foiles, Marney Mintz and Peter D. Van Matre, "Amendments to Quality Control Board Proposal," Senior Project (1978), 3.

13 Elster, Foiles, Mintz and Matre, "Demolition Proposal," 3.

14 Marc Allen Jenefsky, "The Process of a Design-Build Solar Greenhouse in Poly Canyon," Master Thesis (1991), 10.

15 Jenefsky, "The Process," 11.

16 Ronald R. Radziner, "Poly Canyon Passive Solar Greenhouse Project," Senior Project (1984), 6.

17 Radziner, "Poly Canyon," 8.

18 Total Environmental Action, inc, Los Alamos Scientific Laboratory., Los Alamos National Laboratory., and Bruce Anderson, *Passive Solar Design Handbook* (New York: Van Nostrand Reinhold Co., 1984).

19 Radziner, "Poly Canyon," 15.

20 Radziner, "Poly Canyon," 8.

21 Bradley B. Owens, "Management Supervision for the Passive Solar Greenhouse Project," Senior Project (1984), 5.

22 Owens, "Management Supervision," 32.

23 Owens, "Management Supervision," 15.

24 Owens, "Management Supervision," 17.

25 Jason Yung, "Passive Solar Greenhouse," Senior Project (1984), 3.

26 Daniel E. Duke, "Electrical Power Systems for the Passive Solar Greenhouse," Senior Project (1985), 5.

27 Robert D. Flory, "Cooling with Solar Enerphase Panels," Senior Project (1985), 5.

28 Arthur Creef, "Performance Analysis of a Phase Change Panel," Senior Project (1985), 4.

29 Douglas P. Herbert and Steven L. Eggemeyer, "Controlling the Passive Solar Greenhouse Environment," Senior Project (1985), 16.

30 Eugene G. Mancebo, "Design Proposal for Air Flow Control Device," Senior Project (1985), 45.

31 Julianne Patterson and Rebecca Gurr, "Passive Solar Greenhouse," Senior Project (1985), 12.

32 Margaret V, Selig, "Delta Wing Ventilator Caps for the Passive Solar Greenhouse Project," Senior Project (1986), 22.

33 Jenefsky, "The Process," 11.

34 Jenefsky, "The Process," 18.

35 Alida T. Brandi, "The Passive Solar Greenhouse – A Project Management Experience," Senior Project (1989), 43.

36 Adams, Alvarez and Cauthon, "A Study," 50-51.

37 Dr. Jens Pohl, interview by author, January 15, 2024.

38 Owens, "Management Supervision," 17.

39 Patterson and Gurr, "Passive Solar Greenhouse," 106.

40 Brandi, "The Passive Solar Greenhouse," 10.