Journal of Sol-Gel Science and Technology

Twenty Years of Aerogel Research at an Undergraduate Institution

--Manuscript Draft--

Manuscript Number:	JSST-D-22-00732
Full Title:	Twenty Years of Aerogel Research at an Undergraduate Institution
Article Type:	Invited Paper
Keywords:	Aerogels; Undergraduate research; Catalytic aerogels; Aerogel windows; Hydrophobic aerogels
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Funding Information:	
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Section/Category:	Educational aspects of sol-gel and hybrid materials
Additional Information:	
Question	**Response**

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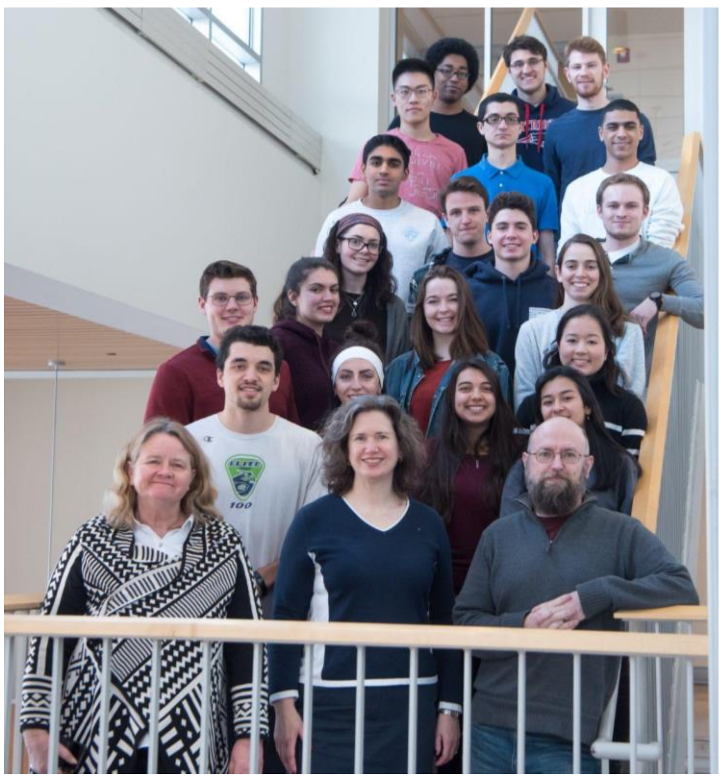
Graphical abstract



Caption: Photograph of Union College Aerogel Team: faculty (bottom row) and students, February 2020.

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Abstract

This paper celebrating the 30th Anniversary of the *Journal of Sol-Gel Science and Technology*, presents a retrospective of twenty years of aerogel research at Union College, a baccalaureate-granting institution. Development of a rapid supercritical extraction method for aerogel fabrication and subsequent contributions to the sol-gel literature in the areas of aerogel windows for sustainable buildings, hydrophobic aerogels for a variety of applications including drag reduction, and catalytic aerogels for automotive pollution mitigation are highlighted. Engaging in multidisciplinary research on remarkable materials that can contribute to addressing global challenges is inherently motivating for students early in their academic careers as well as for faculty members. Opportunities and challenges associated with establishing and maintaining a productive academic research program when most students are available to participate only in shorter-term projects are discussed.

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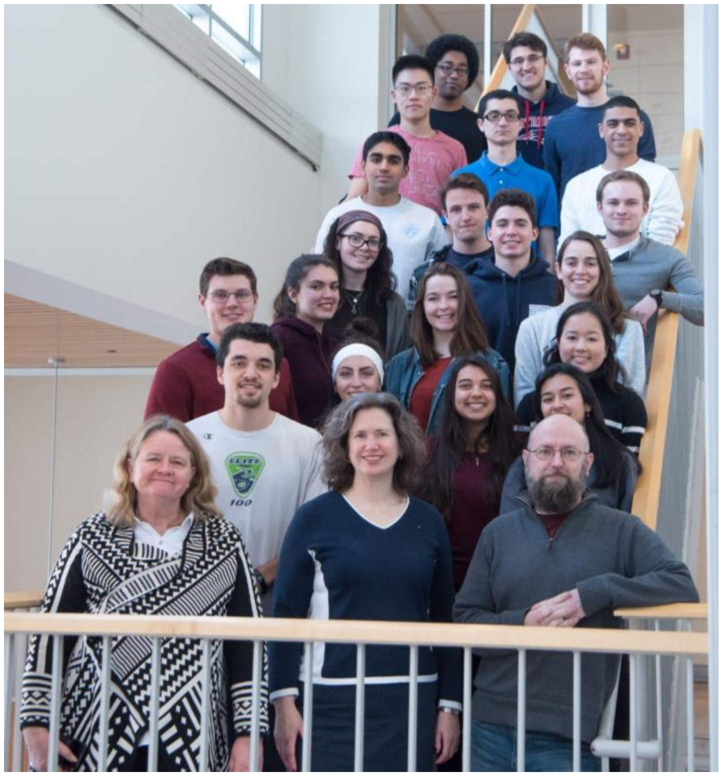

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Highlights

- A retrospective of 20 years of research in aerogel materials is presented.
- An overview of the Union College rapid supercritical extraction method is provided.
- Contributions in the areas of aerogel windows, hydrophobic materials and catalysis are described.
- Opportunities and challenges of research at an undergraduate institution are emphasized.

1 Introduction

The US higher-education landscape differs significantly from that of many other countries. A relatively high percentage of the population attends university (61.8% of US high-school graduates in 2021 [1]), and there are a variety of types of higher-education institutions, including (but not limited to) colleges that grant associates degrees, bachelors-degree-granting institutions, masters-degree- and doctoral-degree-granting universities [2]. Associate degree programs typically require two years of study, bachelor degrees require four years of study while the length of a masters degree will vary by discipline (typically 1-3 years). Moreover, there are private and public (state) schools in each of those categories. The various types of institutions have different expectations for faculty scholarship, and therefore different levels of resources dedicated to research.

Union College is a private undergraduate institution of approximately 2200 students offering majors in the humanities, social sciences, natural sciences, and engineering. It falls in the Carnegie classification 'Baccalaureate Colleges: Arts & Sciences Focus' [2]. Founded in 1795, Union was the first US college to be chartered in New York State, to create a bachelor's degree in science and mathematics (1822), and to establish an engineering degree program within the context of the liberal arts (1845). Union College has a strong history of achievement in undergraduate research and commitment to science and engineering education. Tenure-track faculty are expected to engage in high-quality scholarly activity. In the sciences and engineering, this typically takes the form of research activities leading to peer-reviewed journal publications (albeit fewer publications than would be expected at a doctoral university). Although it is not a requirement to involve undergraduate students in one's research, the chemistry and mechanical engineering departments have a strong tradition of doing so. Prior to starting our collaboration, each of us had established an independent research program (AMA in heat transfer, MKC in analytical spectroscopy) in which we involved undergraduate students and each had earned tenure at the college.

1.1 Initiation of aerogel research at Union College

In the fall of 2001, Ben Gauthier, an undergraduate mechanical engineering student, brought a well-known aerogel photo (see Figure 1) to AMA and indicated interest in making one for his senior project. AMA sent him to speak with MKC, who had begun working with sol-gel-based chemical sensors in the late 1990s and was, therefore, familiar with the literature. MKC was particularly interested in the potential of aerogel materials for gas sensor applications [4] and agreed to collaborate on the project. Because Union did not have the standard equipment – a critical point dryer – employed for supercritical CO_2 extraction, and available funds for student-initiated projects were not sufficient to procure

Figure 1. Classic Aerogel photo from NASA Jet Propulsion Lab. [3]

one, we looked into alternative methods for aerogel fabrication.

Over the course of the next year, using engineering equipment available in a colleague's laboratory at Union College and building off work on rapid supercritical extraction (RSCE) methods developed at Lawrence Livermore National Laboratory [5-7], we succeeded in developing a novel RSCE method capable of fabricating monolithic silica aerogel using a hydraulic hot press as shown in Figure 2a [8-11].

In the Union RSCE process (Figure 2b), a metal mold is filled with liquid precursor mixture or wet alcogel and placed between the platens of a hydraulic hot press. A restraining force is applied to seal the mold, which is then heated via the platens. As the temperature increases, the pressure within the mold also rises. The pressure-temperature conditions within the mold are brought above the critical point of the solvent (or solvent mixture) in the pores of the gel. The restraining force can then be lowered so that the solvent escapes from the matrix as a supercritical fluid, leaving behind an aerogel-filled mold. The mold is then cooled and the aerogel removed from the mold. Figure 2c plots actual pressure and temperature conditions during processing of a silica aerogel and clearly demonstrates achievement of supercritical conditions. The process can be used to make monolithic silica aerogels with essentially no shrinkage in as little as three hours [12]. (Some reviewers of our early papers were skeptical about the lack of shrinkage. We have received fewer questions about that since publishing a video protocol article on the process in which the lack of shrinkage is apparent [11].)

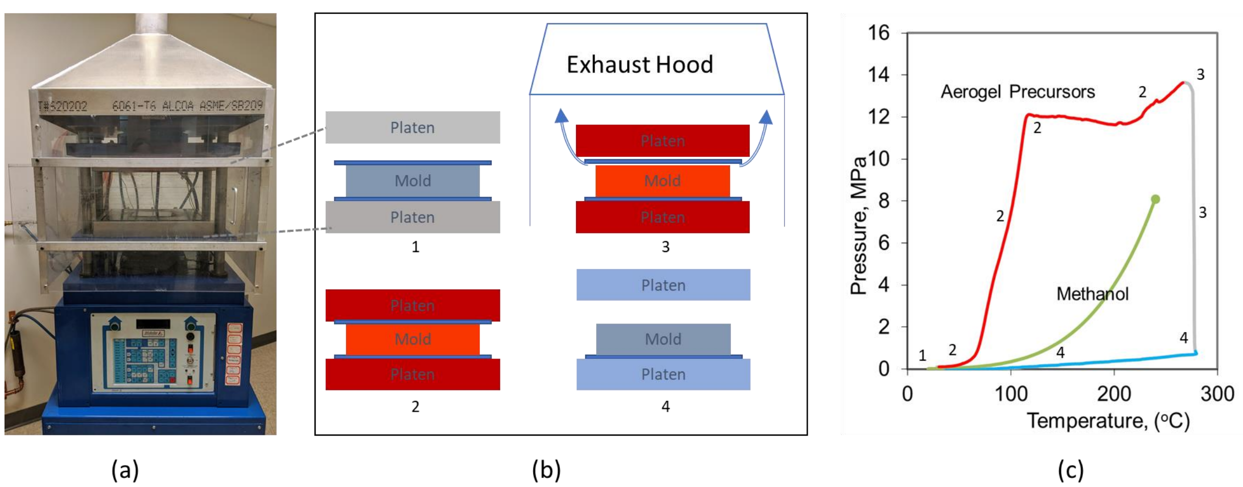


Figure 2. The Union College RSCE Process. (a) 30-ton hydraulic hot press. (b) Steps for making an aerogel: (1) Place mold/gasket assembly filled with aerogel precursors in the hot press. (2) Seal and heat mold using hot press. (3) Reduce hot press force and allow supercritical fluid to escape to the exhaust hood. (4) Cool the system and remove aerogel. (c) Process variables recorded during aerogel fabrication. The numbers on the plot refer to the step numbers in view (b).

What started as a 'side project' from our individual research agendas turned into a now two-decade-long productive, multidisciplinary research program. A timeline with highlights and milestones is shown in Figure 3.

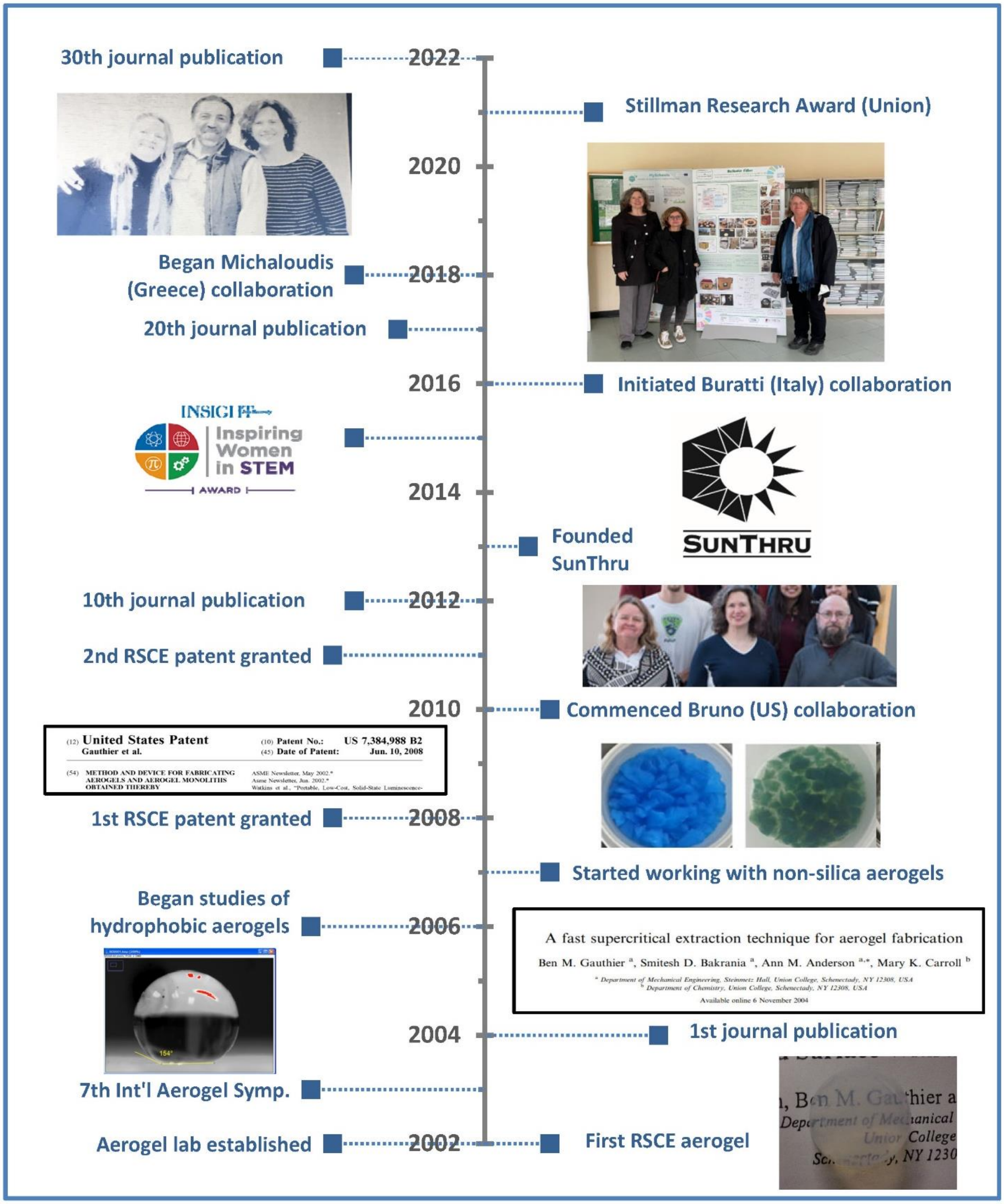


Figure 3. Timeline highlighting achievements in aerogel research at Union College.

2 Establishing an Aerogel Laboratory

In 2002, we secured funding from the US National Science Foundation (NSF)'s Major Research Instrumentation (MRI) program and Union College to establish an Aerogel Laboratory, with equipment for fabricating and characterizing aerogel materials. An ACS-PRF grant in 2003 to MKC for sensor work enabled us to collect preliminary data that led to our first NSF research grant (2005). We have subsequently had several additional NSF grants of various types (research, equipment and technology commercialization, as noted in the acknowledgments section).

Having invented a new RSCE method, we set out to develop a fundamental understanding of the process [13, 14], including investigating the effect of RSCE process variables on the physical properties of the resulting aerogels, which demonstrated the robustness of the method [12].

Although our initial work employed tetramethyl orthosilicate (TMOS) as the silica precursor, it was apparent that the RSCE method we developed would be suitable for processing gels prepared from a wide variety of sol-gel chemistries. (There are limitations: the high temperatures required for supercritical alcohol or alcohol/water mixtures preclude use of this method for thermally unstable gels.) We resisted the temptation to make many different types of aerogels to simply demonstrate that it is possible to do so and, instead, focused our efforts on preparing RSCE aerogels suitable for particular applications of interest.

The first application-focused paper from our lab, on the facile incorporation of luminescent complexes into TMOS-based silica RSCE aerogels for gas sensors [15], was related to MKC's ongoing interest in chemical sensing, and demonstrated one of the major advantages of our RSCE process: due to the lack of solvent exchanges, thermally stable dopants added to a precursor mixture remain trapped within the aerogel matrix. We have subsequently extended this approach, entrapping copper nanoparticles in silica aerogel [16] and platinum group metal nanoparticles in alumina aerogel [17] as part of our work with catalytic aerogels for pollution mitigation (described in more detail below).

2 Areas of ongoing research focus

Over time, we have gravitated to research projects that fall in three main areas: silica aerogel windows for sustainable building applications, hydrophobic aerogels for a variety of applications including drag reduction, and catalytic aerogels for automotive pollution mitigation. These topics are compelling to undergraduate students, who tend to be idealistic and motivated by projects that address sustainability and other global challenges. These areas of research are intellectually interesting for faculty, as well, and have led to productive collaborations with colleagues at our institution and others. Our contributions in these areas are described in more detail in the following sections.

2.1 Silica aerogel windows for sustainable building applications

The low density and thermal, electrical and acoustic insulating properties of silica aerogel monoliths render them attractive for building materials. There has been long standing interest in their use for highly insulating windows [18-26]. The Union College RSCE process shows particular promise for this application, because of the speed of the process (3-8 hours from mixing chemicals to obtaining a monolithic silica aerogel [12]) and the potential for scaling up the process [27] if industrial-sized hydraulic hot presses are employed (see Figs. 4a, 4e).

There are potential advantages to using the silica precursor tetraethyl orthosilicate (TEOS), which has ethanol (rather than methanol) as the byproduct of the hydrolysis and condensation reactions. We have demonstrated that high-quality monolithic aerogels can be fabricated from TEOS [28]; however, these are not as transparent as our TMOS-based aerogels [29].

In collaboration with Prof. Cinzia Buratti and her group at the University of Perugia, we have investigated the acoustic [30], optical and visual [31] properties of prototype aerogel glazing systems. We are currently undertaking a long-term study: evaluating the performance of aerogel monoliths under accelerated aging, employing a range of characterization methods including color rendering. The methodology of this study and preliminary results are the subject of a recent paper [32]. Through an Erasmus agreement between our institutions, we have hosted three of Buratti's graduate students in our laboratory, each for one to three months. Working alongside graduate students has benefitted the undergraduates at Union College and we believe the experience of engaging in research in the US at a very different type of institution has been positive for the Italian graduate students, as well. In spring 2022, AMA spent a month in Perugia through the Fulbright Specialists Program, giving lectures on aerogels in graduate and bachelors courses and working directly with research students.

In 2013, we co-founded a company, SunThru LLC [33], that is working to commercialize the aerogel technology developed at Union for fenestration applications. SunThru has been funded through NSF technology transfer grants and the New York Energy Research and Development Authority, among others. Some of these grants have included subawards to the Union College Aerogel Lab, and we have therefore been able to engage students in technology transfer and entrepreneurship activities at a formative stage in their academic careers.

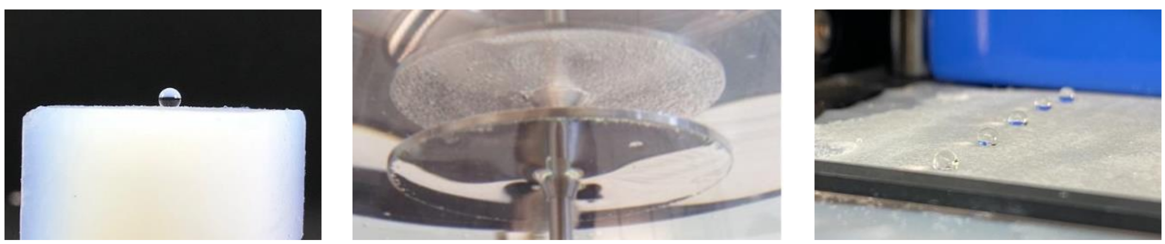
Recently, building on our experiences of incorporating luminescent species into silica aerogel for sensor applications [15, 34] and etching designs on aerogel monoliths using a laser engraver in collaboration with the aerogel artist Prof. Ioannis Michaloudis [35], we have explored the preparation of aesthetically enhanced silica aerogel windows that include dyes and/or etching [36, 29]. In this approach, small imperfections can be considered features that make each window pane unique, rather than flaws. Figure 4 shows examples of these aerogels.

Figure 4. Photo montage of various aerogel window projects: (a) view through an 8.9 x 8.9 x 1.3 cm aerogel; (b) 10 x 10 x 1.5 cm Rhodamine-B-doped aerogel with pattern cut through width of aerogel; (c) 10 x 10 x 1.5 cm fluorescein-doped aerogel with etched pattern on surface of aerogel; (d) view of a 2 x 2 style window prototype on black flocked paper with a variety of transparent plain and dye-containing aerogel monolith tiles, each of size 50 x 50 x 0.5 cm; (e) view through a 17.8 x 17.8 cm window prototype made from four 8.9 x 8.9 x 1.3 cm aerogel monoliths; (f), (g) and (h) various aerogel samples with patterns etched on front and back surfaces; and (i) transparent 13 x 12.5 x 0.5 cm aerogel monolith.

2.2 Hydrophobic silica aerogels

Silica aerogels' low density, high surface area and chemical stability are appealing for a wide variety of applications; however, unmodified silica aerogel is hydrophilic and upon exposure to water pore collapse occurs. Since many applications require water resistance, there has been considerable research effort expended on methods for making silica aerogel hydrophobic, which we have reviewed in [37].

Our own work with hydrophobic aerogels began with demonstration that the RSCE method could be employed to prepare monolithic, hydrophobic (in some cases, superhydrophobic) silica aerogels using co-precursor mixtures that include organically modified TMOS derivatives as well as TMOS (see Figure 5) [38]. We have employed a rotational viscometer to measure drag reduction from hydrophobic films, observing differences in drag reduction for simple films prepared with crushed hydrophobic silica aerogel and xerogel prepared from the same chemical precursor mixture, which implies that the differences are morphological rather than chemical (see Figure 5b) [39]. Recently we have begun work on the preparation of more robust superhydrophobic aerogel films (see Figure 5c).



(a) (b) (c)

Figure 5. Examples of hydrophobic aerogels made via RSCE. (a) 3-μL water drop on a hydrophobic silica aerogel monolith; (b) a spindle coated with hydrophobic aerogel powder captures an air bubble and reduces rotational drag; and (c) water droplets on a polyvinyl-butyral/aerogel-powder film.

The wide range of potential applications of hydrophobic and superhydrophobic aerogels are particularly motivating for students. We have worked with several students on projects related to use of hydrophobic aerogels for applications including oil spill clean-up, drug delivery and clothing insulation (see Fig. 5) but have not published in these areas.

We collaborated with the group of Prof. Desiree Plata (an alumna of our lab) on a life-cycle assessment (LCA) of aerogel manufacture for oil-spill remediation applications [40]. The LCA demonstrated that use of our RSCE method resulted in significant cumulative energy savings compared to two more conventional aerogel fabrication methods (alcohol and carbon dioxide supercritical extraction in autoclaves).

Over time, water vapor can enter and condense in window units, so commercially available granular aerogel products for use windows are typically hydrophobic (for example, Cabot's Lumira® aerogel particles for daylighting [41]). Monolithic aerogel inserts for windows would have enhanced visual and acoustic properties compared to the granular products available on the market [21-23, 30]. Our ongoing collaborative study of the performance of aerogel monoliths under accelerated aging with Buratti's group at the University of Perugia involves a comparison of hydrophilic and hydrophobic silica aerogels [32].

2.3 Catalytic aerogel materials for pollution mitigation

Solids with high surface area are particularly attractive for heterogeneous catalysis applications. Having met with considerable success using RSCE to prepare silica aerogels from a variety of silica alkoxide precursors, we extended this work to fabricating alumina- [42] and titania-based [43] aerogels, again using alkoxide precursors, with an eye to employing the alumina materials in automotive pollution mitigation and the titania aerogels for photocatalysis. Our subsequent work has focused on the use of catalytic aerogel materials for the automotive application, with the goal of either replacing or using substantially less of the platinum group metals (PGMs) currently employed in commercial "three-way" catalytic converters (TWC) to convert carbon monoxide (CO), unburned hydrocarbons (HC) and nitrogen oxides (NOx) to less harmful gases.

The first synthetic approach we employed to preparing alumina aerogels via the Union RSCE method, which was adapted from Armor and Carlson's aluminum isopropoxide recipe [44], resulted in high-quality aerogels but was relatively complicated and time-consuming [42]. We have subsequently employed the epoxide-assisted approach with metal salt precursors described by Baumann et al. [45] to prepare RSCE alumina aerogels [46, 47] and for much of our catalytic aerogel work.

In order to demonstrate the catalytic performance of these aerogels, it is necessary to expose them to simulated exhaust under conditions comparable to those experienced in a commercial catalytic converter, including temperature, oxygen level and humidity level, and monitor the conversion of the pollutants. To accomplish this, we began a long-term and ongoing collaboration with a Union College colleague who has expertise in internal combustion engines, Prof. Bradford Bruno of the Mechanical Engineering Department. The first experimental testbed was constructed by an undergraduate student in-house, in Bruno's laboratory, with funding from the college. After demonstrating that the materials and the testing approach had promise, we sought and were awarded an NSF MRI instrument development grant to construct a more sophisticated testbed: the Union Catalytic Aerogel Testbed, or UCAT [46, 48]. Over 15 undergraduate engineering students have been active participants in the design, construction and operation of the various components of UCAT.

To date, we have used the epoxide-assisted synthetic approach to fabricate alumina [46] and mixed-metal-oxide aerogel materials [50-52]. We have also explored vanadia-containing aerogels using $VO(acac)_2$ as the vanadia precursor [53] and using TMOS-based silica aerogel as a platform for catalytic metals, introducing metal salts [50, 52] or nanoparticles [16]. In each of these papers, the synthesis, fundamental physical characterization and catalytic characterization is presented. Table I presents a summary of our published work in this area. We also hold a US patent on the use of aerogels as three-way catalysts [54].

We extended the work with copper-alumina aerogels to include a study of copper loading on TWC activity [55] and to demonstrate the potential of these aerogels to survive a slurry process comparable to that used to wash-coat PGMs onto supports for commercial catalytic converters [56].

In our most recent work, we have shown that alumina aerogels doped with relatively low amounts of PGM nanoparticles have comparable catalytic activity to a commercial catalyst [17]. Figure 6 presents the temperatures at which 50% conversion ('light-off') occurs for HCs, CO and NO for copper-alumina aerogel and three PGM-nanoparticle-containing catalytic aerogels with comparison to the performance of a commercial catalyst under the same conditions.

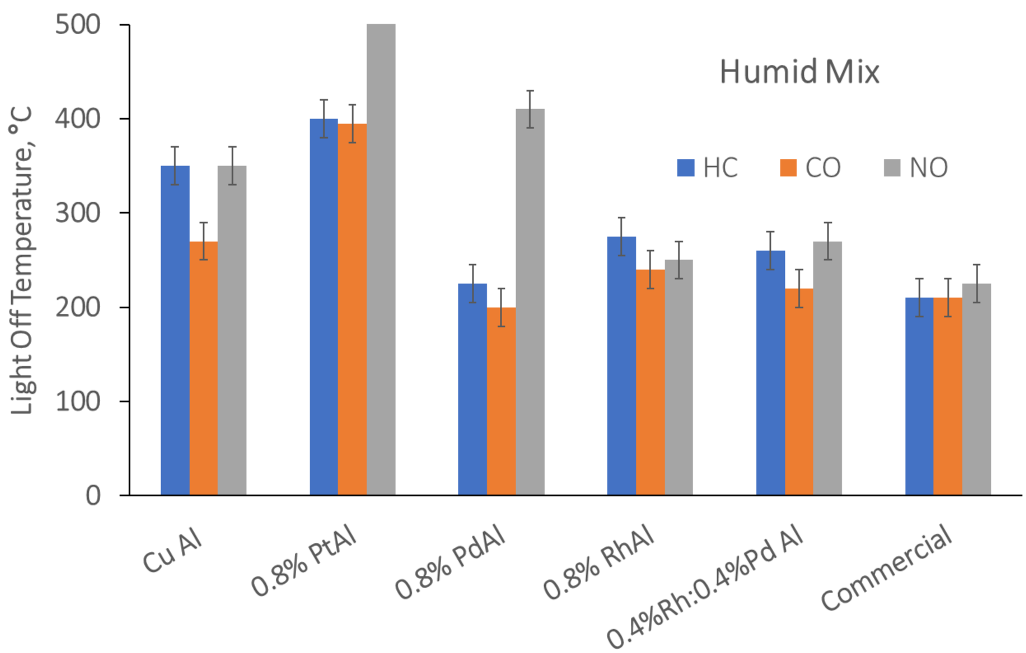
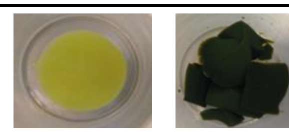


Figure 6. Light-off performance for a variety of alumina-based catalytic aerogels compared to a commercial catalytic converter (NAPA universal converter, part # 15037). Refer to Anderson et al. [17] for more information about the testing conditions.

Table I. Catalytic Aerogels fabricated using RSCE.

Aerogel Type	Surf. Area (m^2/g)	Bulk Density (g/mL)	Reference(s)	Images of as-prepared materials
Alumina	400-600	0.04-0.23	[46, 47]	
Nickel-Alumina	300-600	0.05-0.14	[47]	
Titania Ti-Si	120-190 530-650	---	[43]	 TiO_2 Ti-Si
Vanadia-Si	670-770	0.12	[53]	 Va-Si (low) Va-Si (high)
Vanadia-Ti-Si Vanadia-Al Vanadia-Co-Al	560 500 640	0.04 0.07 0.06	[53]	 Va-Ti-Si Va-Al Va-Co-Al
Cobalt-Al	680-705	0.07	[48, 51]	
Copper-Al Copper-Si Copper-Si-NP* Copper-Al (Slurry)	350-500 750-800 100-450 340	0.09-0.11 0.11 0.08-0.10 0.12	[16, 48, 50, 55, 56]	 Cu-Al Cu-Si Cu-Si-NP
Ceria-Si Ceria-Al	400-500 112	0.09 0.06	[52]	 Ce-Si Ce-Al Ce-Cu-Al
Pt-Al Pd-Al Rh-Al	510-630 420-660 650	0.06 0.05-0.06 0.05	[17]	 Pt-Al Pd-Al Rh-Al

3 Engaging in productive research at a baccalaureate-granting college

3.1 Moving long-term projects forward with short-term student involvement

Colleagues in the sol-gel community frequently ask how we have been able to contribute in such substantive ways to the aerogel literature when our group is primarily composed of inexperienced students who are available to participate for only relatively short-term student projects.

For our major ongoing research efforts, our strategy is to break down the work into manageable segments and set goals for each student that are ambitious but potentially achievable in the time available (for example, a summer or two academic terms), in order to move our overall research agenda forward. A student with no prior research experience can be trained on one or more experimental methods (for example, fabrication of silica-based aerogels, or design of metal molds for RSCE) and either apply those to a particular project or become the 'go-to' person for a particular type of analysis (SEM imaging, surface area measurements) during their time in the lab. Working in a group with students and faculty members from different disciplines is engaging and rewarding.

Most of our research students are pursuing bachelors degrees in chemistry or mechanical engineering. We tailor projects to student interest and experience. For example, our approach to developing a new type of RSCE aerogel begins with modifying synthetic procedures from the literature. Engaging in this type of project is better suited to the students who have more chemistry laboratory course experience. Once we have an established recipe and protocol for a particular type of aerogel, other members of the group are trained to make them. Similarly, we recruit students who have taken engineering courses for projects involving a considerable amount of graphical design, computational modeling, or device construction (including the work with the UCAT system). Other aspects of the research, including use of the various physical characterization methods we employ, are well-suited to either science or engineering students.

It is important to note that without the ability to prepare aerogels quickly that is afforded us by the RSCE process, it would be substantially more difficult for undergraduates working in our laboratory for a limited number of weeks (as described in the next section) to make significant progress.

When grant funding permits, we hire a full-time 'post-baccalaureate researcher' (technician) to assist with day-to-day research activities. This aids in continuity of research effort; however, we note that these employees have typically been recent BS-level graduates of Union or other institutions so require a considerable amount of mentoring.

3.2 How research with undergraduate students is structured at our institution

Students at Union College can participate in research via several mechanisms (Table II), three of which are part-time and involve academic credit. Senior research courses for fourth-year students can be taken through either the chemistry or mechanical engineering departments, and are the option for fulfilling the college's senior writing requirement that is most often chosen by students in these disciplines. The culmination of the two- or three-term project is a detailed report (a thesis). Second-year students in the college's Scholars (honors) program are introduced to research through engaging in a two-term project of interest to them. Those projects are often, but not always, related to the students' major area of study. Research practicum, which is open to students in any class year, is a low-time-commitment opportunity used in some cases to introduce students to research and in other cases to continue work begun in the summer. The fourth main approach is paid, full-time research for four, six or eight weeks of the summer, with funding provided by Union College or external grants. Frequently, students participate in more than one of these over the course of their studies and, therefore, can spend up to three years engaged part-time in aerogel research. All of these experiences, whether credit-bearing or not, are included on the students' academic transcripts.

Table II: Mechanisms for structured undergraduate student research at Union College

Category	**Credit or Compensation**	**Duration (weeks)[a]**	**Hours/week**
Senior Thesis Project	Credit for 2 or 3 courses	20 or 30	12-15
Scholars (Honors) Project	Credit for 1 course[b]	20	6
Research Practicum	Credit for 1 course[c]	10, 20 or 30	4
Summer	Pay	4, 6, or 8	35

[a] Union has three ten-week terms per academic year (fall, winter, and spring trimesters)
[b] Credit awarded after successful completion of a two-term project
[c] Credit awarded after three terms; some students participate for one or two terms only

Students can apply for small amounts of funding through the college in support of research projects. We have supervised students on short-term, academic-year projects that come about when a student approaches one of us with an application-focused idea ("Can I use aerogels to …?") that is unrelated to (and, therefore, can't be supported by) our grant-funded research. Generally, those projects lead to presentations by the student but not publication. Examples include a hydrophobic-aerogel-coated high-performance swimsuit, and a small demonstration model of a house with an aerogel window and aerogel blanket insulation on the walls and roof (see Figure 7). The enthusiasm and optimism that students bring to their first research experiences spurs creative discussions and, occasionally, a student-initiated project leads to a new and productive research focus for the lab.

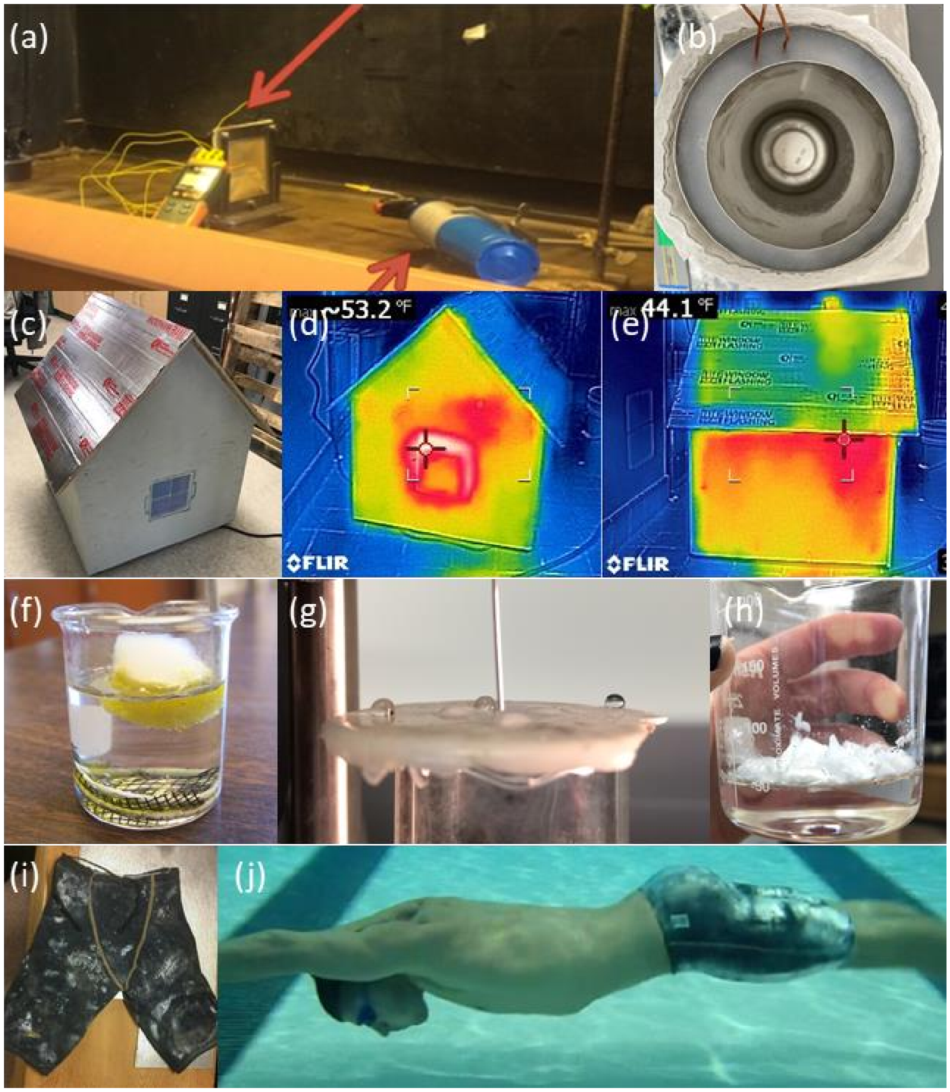


Figure 7. Photo montage summary of aerogel projects proposed by undergraduate students in which they used aerogels to: (a) insulate firefighting protective wear; (b) reduce hydrogen tank boil-off; (c) (d) (e) insulate a model house with an aerogel window and aerogel-blanket-covered wall studs; (f) soak up oil; (g) coat fabric; (h) deliver ibuprofen; (i) make a hydrophobic swimsuit. View (h) shows a student swimming with the aerogel coated swimsuit demonstrating the development of an air layer.

4. Concluding remarks regarding the impact of research at an undergraduate institution

We readily acknowledge that ours is not the only laboratory that engages undergraduate students in aerogel research. Many doctoral-granting universities and national laboratories offer research opportunities or internships for undergraduates; however, at those institutions students are typically working as part of a team that includes graduate students, postdoctoral researchers and full-time professional researchers. We know of two other faculty members at baccalaureate institutions who engage students in aerogel research: Colonel F. John Burpo at the US Military

Academy (West Point) [57-60] and Professor Amanda Harper-Leatherman at Fairfield University [61, 62].

We have the benefit of being at a liberal-arts college that has a history of strength in bscience and engineering, and both high expectations and strong support for faculty and student scholarship. The RSCE method we invented and developed facilitates short-term student involvement in projects with long-term goals. We have been successful in attracting to our group students from a wide variety of backgrounds, engaging them in rigorous experiments in a supportive, collaborative environment, and in motivating students to consider graduate studies and careers in industry.

To date, we have involved 170 undergraduate students and 13 high-school students in aerogel research projects at Union College. 43 of the undergraduates and two high-school students, have co-authored peer-reviewed journal articles and six undergraduates are co-inventors on patents. Of the 160 students who have graduated from Union, >40% have subsequently earned doctorates (30 alumni) or masters degrees (at least 38 alumni) in STEM-related fields, and another 6% have earned doctoral degrees in medicine or law. Several are currently enrolled in graduate programs in science or engineering. Most of the other graduates went directly to jobs in STEM-related industries. We have launched a company, SunThru LLC, whose leadership includes alumni from our group, that is working to commercialize products based on aerogel technology developed at and patented by Union College.

So it is apparent that, in addition to the contributions made by our research group to the aerogel literature, we have had a disproportionate impact (for an academic institution of our size) on both STEM workforce development and technology development. We are grateful to have received recognition for this both externally (100 Inspiring Women in STEM Award [63]) and internally (Stillman Prize for Faculty Excellence in Research) and we look forward to continuing to contribute to research in the sol-gel community.

Acknowledgments

The Union College Aerogel Lab has received external funding from the US National Science Foundation (Grant Nos. CTS-0216153, CHE-0514527, CMMI-0722842, CHE-0847901, DMR-1206631, CBET-1228851, IIP-1332456, DMR-1828144 and IIP-1918217) and the ACS Petroleum Research Fund (Grant No. 39796-B10), as well as subawards from grants to SunThru LLC from the NSF (Grant Nos. IIP-1415359 and IIP-2025800) and the New York State Energy Research & Development Authority (Grant No. NYSERDA-87381). We are grateful for the contributions of our students, postbaccalaureate researchers, and colleagues to the work reviewed herein. We acknowledge support of that work from Union College through the Faculty Research Fund, Student Research Grants, Student Summer Research Fellowships and the Chemistry Department's Kane Fund.

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Statements and Declarations

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

Both authors contributed to writing and editing the manuscript. Both authors read and approved the final manuscript.