2018

Commercialization of the Carbon Nanotube Thermophone for Active Noise Control Applications

Steven A. Senczyszyn
Michigan Technological University, sasenczy@mtu.edu

COMMERCIALIZATION OF THE CARBON NANOTUBE THERMOPHONE FOR ACTIVE NOISE CONTROL APPLICATIONS

By

Steven A. Senczyszyn

A REPORT

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Mechanical Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2018

This report has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Mechanical Engineering.

Department of Mechanical Engineering – Engineering Mechanics

Report Advisor: *Dr. Andrew Barnard*

Committee Member: *Dr. Jason Blough*

Committee Member: *Dr. Andre Laplume*

Committee Member: *Mary Raber*

Department Chair: *Dr. William W. Predebon*

Table of Contents

Acknowledgments

I would like to thank all of those who have helped me throughout my research. First, I would like to thank Dr. Andrew Barnard for getting me involved in research and for giving me the opportunity to explore entrepreneurship. I would also like to thank Dr. Jason Blough, Mary Raber, and Dr. Andre Laplume for their support and agreeing to serve as my defense committee. I would like to thank Mr. Steve Mattson for his assistance and mentorship. Thank you to Jim Baker and Mary Raber for their help during the Michigan Tech Initial Customer Discovery program. Thank you to the Southwest I-Corps team for their guidance. And finally, thank you to the National Science Foundation for providing the tools and support for my efforts into research and commercialization.

Abstract

The rate of commercialization for technology developed in junction with academic institutions has risen dramatically over the past 30 years. Since the introduction of the Bayh-Dole Act in 1980, the amount of intellectual property owned by academic institutions has increased exponentially, and with that, there has also been an increase in the number of university spinouts generated. However, the increase of spinouts does not match the rate of increase in intellectual property. The National Science Foundation has created the Innovation Corps (I-Corps) program to help bridge this gap and provide academic professionals and students the tools necessary to commercialize technology and produce a better return on their investment into academic research.

Team NanoSound was composed of Dr. Andrew Barnard and Mr. Steven Senczyszyn from Michigan Technological University, and Mr. Steve Mattson of Great Lakes Sound and Vibration. The team participated in a series of I-Corps programs with the intent to commercialize technology being developed in Dr. Barnard's laboratory. The technology being explored for commercialization is the carbon nanotube (CNT) thermophone. A thermophone is a loudspeaker that generates sound using temperature fluctuations, which is made possible through the use of CNT thin-films. These thin-films allow the speakers to be flexible, lightweight, and have conformable geometries, making them an ideal solution to many noise control problems.

As a result of these programs, Team NanoSound has developed a business model following the Lean Startup method taught in the I-Corps program. The business model aims to prove the technology in the heating, ventilation and air conditioning (HVAC)

market by providing an active noise control (ANC) solution to reduce the sound generated by air handling units. HVAC is seen as an entry point into commercialization, with future prospects of expanding into the automotive and military industries by providing an ANC muffler to supplement and eventually replace traditional passive vehicle exhaust systems.

1 Introduction

Universities now serve more roles to students and academic professionals than ever before. What once began as a hub of knowledge, focused on education and research, has evolved to envelope a wide array of opportunities. One of the latest, and arguably most important, of these advancements has been the focus on commercialization of the technology being developed at universities around the world. Over the past 30 years, the number of university spinouts has grown exponentially with the introduction of the Bayh-Dole Act in 1980 [52]. This has also led to the formation of technology transfer offices at academic institutions, as well as an increase in intellectual property (IP) owned by the universities [56]. This IP comes in many forms, including patents, trademarks, copyrights, and trade secrets. In addition, with this increase, a relationship has been formed between academia and industry, bringing them closer together than ever before [61].

This collaboration between universities and industry has proven to be a mutually beneficial relationship. Many companies are pressured to remain competitive with fellow producers within their industry and need to continually innovate their product offerings, improve their quality, and increase cost effectiveness [52]. On the same note, these companies must also be mindful of how much they can afford in terms of technology and human resources they need to keep a competitive advantage. This is where academic partnerships become a key factor. This has led to an increasing trend over the past 25 years involving a collaboration between academic institutions and commercial industry to further advance these technologies [52]. To help facilitate these collaborations, academic

institutions have now created technology transfer offices (TTOs) which have become a staple in nearly every university across the country [46].

Despite these recent advancements and improvements to the TTOs, a disconnect still exists when bridging industry and academia. Academic professionals tend to lack the skills and experience required to successfully launch a scalable start-up business from the technology that they have developed in their laboratory, which is most often in collaboration with industry. The Innovation Corps (I-Corps) program through the National Science Foundation (NSF) aims to provide academics with these skills so that greater success can be had in commercializing the same technology that they help fund [20]. The hope is that this will in turn provide a greater return on the investment that they place in research by generating more spinoffs from universities and creating more jobs. Currently, the NSF provides over $7.5 billion of funding to academic research every year [75]. By investing in students and researchers financially, and funding the $50,000 grants for each I-Corps team to participate in the program, the NSF hopes that this will in turn increase their return on these investments in the following years [75].

This report will explore the I-Corps journey from the perspective of a team from Michigan Technological University with no prior experience in entrepreneurship, starting with the on-site Initial Customer Discovery (ICD), provided at Michigan Technological University (MTU), through the national level I-Corps program based out of the Houston Southwest I-Corps node. This team, Team NanoSound, is comprised of Dr. Andrew Barnard, an assistant professor of mechanical engineering at Michigan Technological University acting as the principal investigator (PI), and Mr. Steven Senczyszyn, a

mechanical engineering graduate student at MTU acting as the entrepreneurial lead (EL). The purpose of this research was to determine the commercial potential and, if validated, develop a business model for the commercialization of new loudspeaker technology for use in active noise control applications in industries such as automotive, military, and heating, ventilation, and air conditioning (HVAC). This technology has been developed in Dr. Barnard's laboratory for the past five years. Throughout this program, the team has conducted over 150 customer interviews to validate the commercial potential of the technology and the business model generated.

2 Background

Prior to 1980, relatively few patents were issued to academic institutions in the United States [26]. However, in 1980, the Patent and Trademark Law Amendments Act, better known as the Bayh-Dole Act, was passed in Kansas [52]. This act granted academic institutions the right to ownership of the intellectual property (IP) generated through research conducted with federal funding. This act led to a boom in the number of patents issued to universities, increasing from 300 in 1980 to over 2,000 in 1996, and over 80,000 patents issued to date, including 16,487 in 2015 alone according the Association of University Technology Managers (AUTM) 2016 report [10]. This has led to TTOs being a staple of nearly every university in the United States. Notable successes such as the formation of Google and Facebook have been the result of university technology commercialization efforts [42]. In total, academic technology has created over 11,000 startups, 4.3 million jobs, and added over $1.3 trillion to the US economy since 1995 [42].

In 2011, the National Science Foundation (NSF) created the Innovation Corps (I-Corps) program with the goal of providing academic professionals and students with the skills and experience needed to transition the research being funded by the NSF to market [19]. This program is focused around the concepts developed in Stanford University's Lean Startup course. To date, over 1,100 teams from universities around the country have participated in the I-Corps program at the nation level, as well as many more at the local level through university nodes [19]. A key teaching throughout the program is that in order to understand your target market, one must get out of the laboratory and talk to professionals in their respective industries so that they can better understand the needs of

their customers [20]. By understanding the needs of potential customers, their technology and research can be better guided and focused to meet them, thus creating a better chance at commercial success. At the national level, this program imparts the importance of this concept by requiring 100 customer interviews to be completed throughout the 6-week program. Funding is also provided to encourage the teams to get out of their comfort zone and travel to potential customers at their place of business, conferences, and trade shows.

2.1 Lean Startup

The NSF I-Corps program revolves around the Lean Startup method. The Lean Startup method was developed in 2011 by Steve Blank at Stanford University when he realized that startups needed their own unique approach to create a business plan [119]. His key discovery was that startups do not operate like smaller versions of large corporations, thus the traditional plans used by these companies will not work. Therefore, a new approach was needed that was more flexible and agile to accommodate the ever-changing nature of a startup. This Lean Startup approach relies on applying the scientific method to commercialization strategies to validate or invalidate hypotheses, incorporating customer feedback, and creating a repeatable and scalable business model. Since the introduction of this method, it has been adopted in over 100 universities worldwide and become the cornerstone of the I-Corps program.

2.2 Carbon Nanotubes and the Thermophone

The technology being explored for commercialization is the carbon nanotube (CNT) thermophone. A thermophone is a loudspeaker that generates sound through fluctuations

in temperature at acoustic frequencies, whereas a traditional moving coil loudspeaker which requires motion, or a velocity boundary condition, to produce the same effect [13]. This phenomenon was first discovered in 1898 when Braun found that sound could be produced when passing an alternating current through a bolometer [22]. Then, in 1917, this concept was further explored by Arnold and Crandall, who conducted the first scientific exploration into this technology when they attempted to create a telephone using a platinum thin-film [7]. However, this first attempt was limited by the high heat capacity per unit area (HCPUA) of the platinum films. Without a proper material to supplement it, this technology was left primarily untouched for nearly 90 years. That was until 2008 when researchers accidentally produced sound when passing an alternating current through a carbon nanotube (CNT) thin-film [82]. The CNT film possesses a sufficiently low HCPUA to produce tones up to 100 kHz [14]. Since the discovery of this material in 2008, significant research has been conducted towards the advancement of the CNT thermophone. Due to the nano-scale size of the CNT films, they are extremely lightweight compared to traditional loudspeakers, which require bulky magnets. The flexibility of the film and elimination of the velocity boundary condition also allow for unique geometries that would not be possible with a traditional loudspeaker. Additionally, due to the low HCPUA and dependence on temperature for operation, CNT thermophones are able to withstand high temperature environments, which are not optimal for the operation of traditional moving coil loudspeakers.

2.3 Potential Applications of the CNT Thermophone

The aforementioned features of the carbon nanotube thermophone lend itself to applications in a wide range of different industries that would benefit from weight reduction, high temperature resistance, and conformable geometries. Throughout this study, the focus of this technology is primarily on applications involving active noise control. The industries that have been identified with a potential need for this technology have been the oil and gas, automotive, HVAC, and military markets. In the automotive market, a thermophone has the potential to replace the traditional passive muffler in vehicle exhaust systems, which require a large amount of volume and weight, and are unable to adapt to changing frequency contents seen in modern vehicles with variable cylinders. In the military market, the thermophone is also a potential solution to reduce the noise generated in military ground vehicle exhausts, which will allow warfighters to travel undetected. In the HVAC industry, this technology could reduce the noise generated from air handling units in large buildings. Finally, in the oil and gas industry, this has the potential to reduce community noise pollution and withstand the harsh environments of these systems.

3 Methods and Materials

3.1 NSF I-Corps Programs

The methods presented here will lay out each of the individual programs of the overall I-Corps experience. This journey started with the Initial Customer Discovery (ICD) program provided at Michigan Technological University (MTU) in the spring of 2017, followed by the 2017 Midwest I-Corps Industry Innovation program in Traverse City, MI, which was in partnership with the Center for Automotive Research (CAR) Management Briefing Seminars (MBS). Finally, this program concluded with the National I-Corps program provided through the Southwest I-Corps Node in Houston, TX during the fall of 2017. Each of these programs built on the teachings of the one that came before it, continually leading to a greater understanding of the Lean Startup methods that are core to the I-Corps program.

During the Michigan Tech ICD program, Team NanoSound was tasked with creating and refining a business model using the Lean Startup method and conducting 40 customer interviews throughout the 4-week program. At this stage, Team NanoSound consisted of Dr. Andrew Barnard, the principal investigator, and Mr. Steven Senczyszyn, the entrepreneurial lead. The ICD program was led by Jim Baker and Mary Raber of the Michigan Tech Innovation Center for Entrepreneurship. Each week, the team was required to complete a minimum of 10 interviews and prepare a presentation summarizing their learnings from these interviews and how their business model had evolved using the Business Model Canvas. This course focused on the Value Proposition and Customer Segment blocks of the BMC, encouraging teams to focus on identifying their target

customer and what their technology will offer them. Overall, this program is geared towards preparing teams for the National I-Corps program by exposing them to the methods used in that program.

Following the ICD, Mr. Steven Senczyszyn then participated in the Industry Innovation program in July 2017 at the CAR MBS in Traverse City, MI, which regularly draws a crowd of over 1,000 key industry stakeholders in the automotive industry. This program is primarily geared towards teams that have either completed or are currently in the national stage of the program, but an invitation was extended for Mr. Senczyszyn to attend. During this program, the teams were led by mentors of the Midwest I-Corps node in exercises to refine their customer discovery skills, which were then put into practice when the teams conducted interviews with attendees of the seminar. Finally, each team was given the opportunity to present their technology and business model during a 10-minute pitch to those attending the conference, allowing them to reach a large audience and practice their professional presentation skills.

Ultimately, Team NanoSound participated in the National I-Corps program at the Southwest I-Corps node in Houston, TX. For this program, an industry mentor was required as a team member. For this role, Team NanoSound recruited Mr. Steve Mattson, president of Great Lakes Sound and Vibration, located in Houghton, MI. Mr. Mattson was the ideal candidate for this role, as he is a small business owner and his company's work revolves around noise control applications. This was a 6-week intensive program, requiring each team to complete a minimum of 100 customer interviews, present their findings and updated business models to the teaching team each week, and develop a feasible business

model canvas and strategy for the commercialization of their technology. The rigorous pace of this program requires teams to constantly be traveling and chasing their next interview. The teaching team requires a minimum of 20 interviews each week to keep teams on track to complete their 100 interview target. During this time, the teams are also required to watch weekly video lectures that cover additional Lean Startup methods, meet with members of the teaching team for office hours, and prepare additional market research information to supplement their proposed business strategy. Overall, this program was a fitting culmination of all of the previous I-Corps work completed, combining all of the teachings previously seen, and reinforcing the Lean Startup methodology.

3.2 Lean Startup and the Business Model Canvas

The primary tool used throughout this program in the development of the commercialization strategy is the Business Model Canvas (BMC). The BMC was first created in 2004 by Alexander Osterwalder and Yves Pigneur with the intent to provide a more versatile tool for startup businesses, as opposed to the traditional business model [58]. This tool has since been adopted by the Lean Startup method and the I-Corps program as the primary business development tool. The BMC contains nine basic building blocks that describe how a company will succeed and make money. These nine blocks cover four main areas of a business: customers, offering, infrastructure, and financial viability. Combined, these nine categories create a blueprint for the organization to follow and execute. The nine blocks can be seen in the blank BMC (Figure 3.1). The two primary building blocks that are core to the I-Corps program are the Customer Segment and Value Proposition, as the most important outcome of this program is identifying a product that customers need.

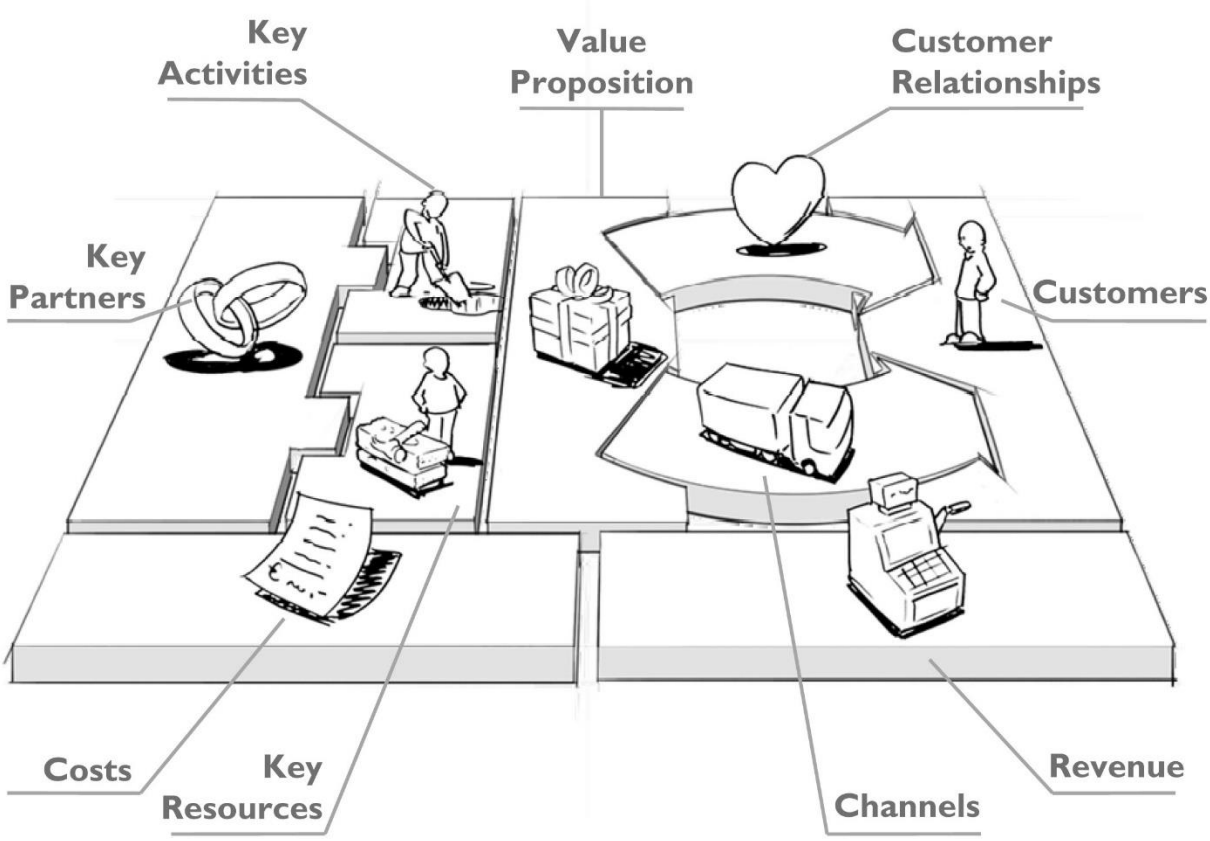


Figure 3.1. Business model canvas layout [58]

4 Results

4.1 Initial Customer Discovery

Over the course of the 4-week ICD program, Team NanoSound gained valuable experience conducting customer interviews after completing all 40 of the required interviews. The interview process was difficult at first, facing issues with biased questions and keeping interviews on track; however, after practicing many interviews, dissecting past interviews, planning out questions ahead of time, and learning to maintain focus on the topic of conversation, the interviews conducted later in the course of the program were able to produce more useful information relevant to the hypothesis being tested. Throughout the course of this program, the team conducted interviews in a variety of different industries to better understand the competitive landscape. In the automotive industry the team interviewed a wide range of professionals, talking with noise and vibration experts at Ford and Toyota, to car salesmen and mechanics at local dealerships and repair shops in Houghton, MI, as well as Porsche and BMW dealerships in Florida and Pennsylvania. The power sports market was also explored, interviewing salesmen at local dealerships, as well as engineers at Polaris. Interviews were also conducted in the heavy machinery industry, speaking with engineers at John Deere. Overall, these interviews gave the team great insight into various industries and the noise control problems they are faced with.

Using the information obtained from these customer interviews, an initial BMC was created and continually updated to improve upon and focus on the key offerings of the product and the target customers as more information was collected. The primary focus of the BMC for this program was on the Value Proposition and Customer Segment blocks.

Initially, it was thought that this technology would ultimately be an active noise control muffler for the automotive market, and that the target customer would be the end user, meaning the purchaser of the vehicle this technology would be implemented in. It was also thought initially that the value the product provided revolved around improving the overall experience of the driver, with value propositions such as, “Have a cool sounding car that you can interactively adjust,” and “A quiet and peaceful ride.”

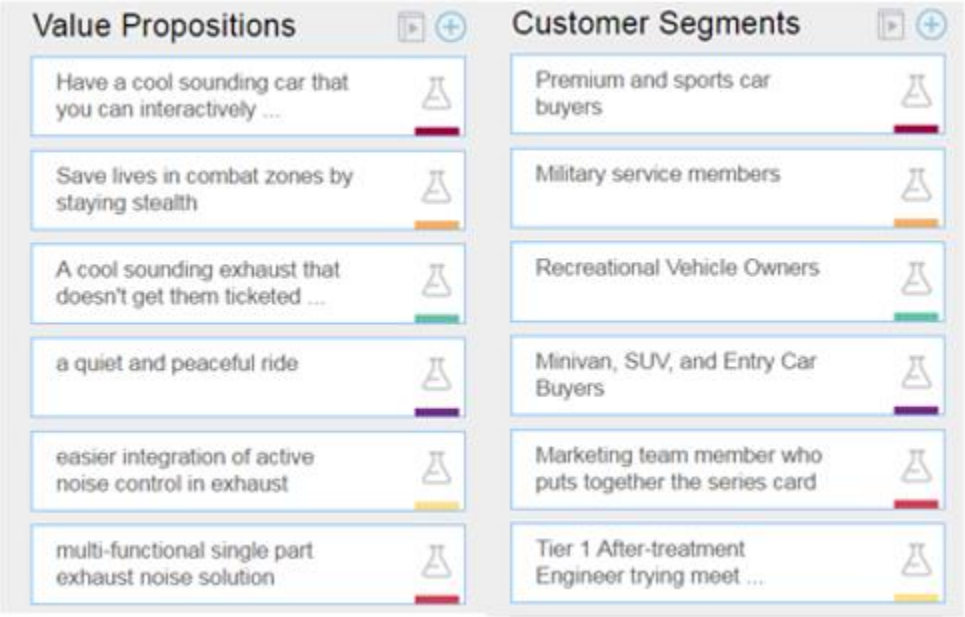


Figure 4.1. Initial ICD Business Model Canvas Value Propositions and Customer Segments

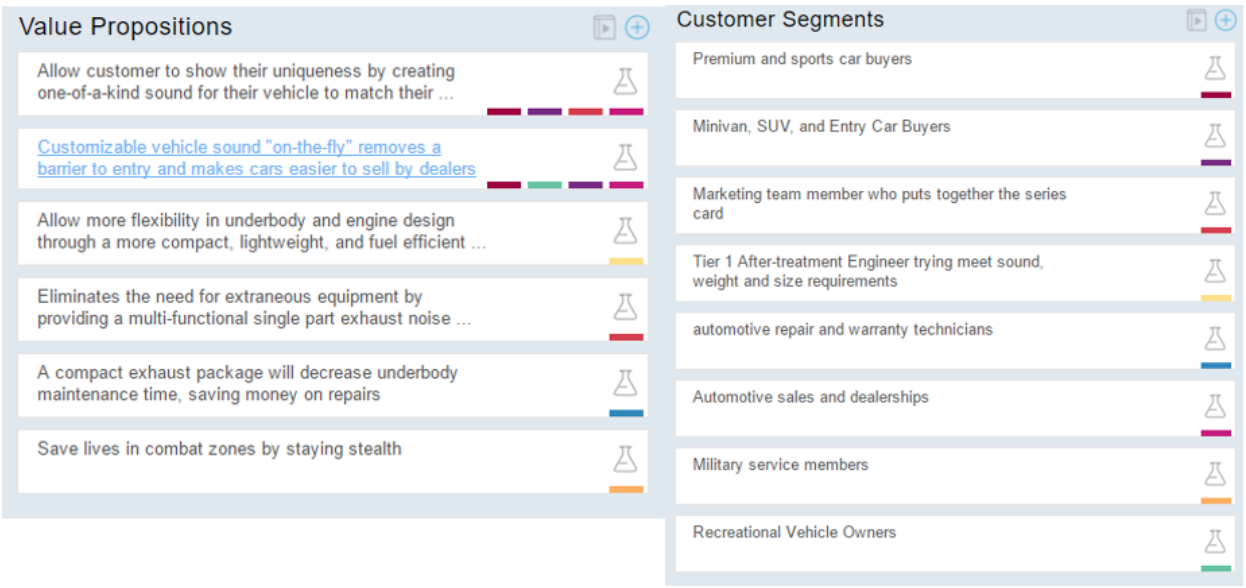


Figure 4.2. Final ICD Business Model Canvas Value Propositions and Customer Segments

Research was also done during this program to determine the size of the markets available in a chosen industry. First, the Total Addressable Market (TAM), or the overall revenue size of the market including all competing products, was determined for the automotive industry. According to market data, the TAM for the automotive exhaust market is nearly $30 billion. Narrowing this market down, the Served Available Market (SAM), or the portion of the market targeted by the team's specific technology, was determined to be approximately $3.5 billion for the luxury and sports car exhaust market. Finally, the Target Market that Team NanoSound chose to focus on was the Ford, GM, and Chrysler luxury and sports car exhaust market. This exercise was able to help the team narrow down which market they wanted to address as well as the financial opportunities that were present in the chosen market.

Another key development of this program was the archetype of the target customer. By identifying who the customer we are trying to reach is, the team is better able to focus its marketing strategy to optimize the chances of this target customer learning about the product. Through this process, four primary attributes of the customer were defined: the customer description, the customer attributes, the archetype highlights, and the acquisition guidance. A summary of these attributes that were identified for the target customer can be seen below (Figures 4.3 and 4.4).

Customer Description	Attributes
30+ years old	Disposable income
Male/Female	iPhone user
Hobbies: technology, cars	Not their first car
Key task: creative exclusive feeling/elevating social status	Brag about their technology to their friends
Fears: being like everyone else or being left behind	Want to be different from their neighbors and friends
Buys and services car at dealership	Big ego
Key decision maker	

Figure 4.3. Customer description and attributes

Archetype Highlights	Acquisition Guidance
Shop at Apple Store	iPhone integration/exclusive sounds
Shop exclusively at dealerships	Integrated into OEM product
High-tech junkie	Market CNT technology
Want to be different	Test drive different sounds
Key decision maker	Direct marketing
Want to feel exclusive	Price accordingly

Figure 4.4. Customer archetype highlights and acquisition guidance

Throughout this program, a business thesis was also crafted and improved for Team NanoSound. The business thesis is a one sentence pitch that aims to convey the overall goal of the company and its technology. The initial business thesis was “We deliver a great sounding exhaust system that is easy to install and maintain.” After completing the 40 customer interviews and digging deeper into the customer segments and value propositions, this business thesis was able to be improved throughout the program. At the end of the course, the final business thesis was “High performance active noise control in a low cost, lightweight, and compact package using carbon nanotube technology.” This final business thesis clearly presents the value that the technology is offering in the form of cost, weight, and volume savings, however it does not address who the target customer is.

4.2 Midwest I-Corps Industry Innovation Program

During the Industry Innovation program, Mr. Steven Senczyszyn, the entrepreneurial lead, was able to engage with and interview leading experts in the automotive field over

the 5-day course of the conference. During this time, over 20 interviews were conducted with managers and executives from automotive tier 1 suppliers and OEMs. The opportunity was also provided to present a 10-minute pitch in front of a group of these professionals. This provided exposure for the team and the technology, drawing in interest from several people involved in the automotive market. Building off of the results of the ICD program, the Industry Innovation was the perfect opportunity for Team NanoSound to continue their customer discovery in the automotive market. The interviews conducted at this conference drew in a lot of interest to the technology as a potential enhancement to future vehicle platforms.

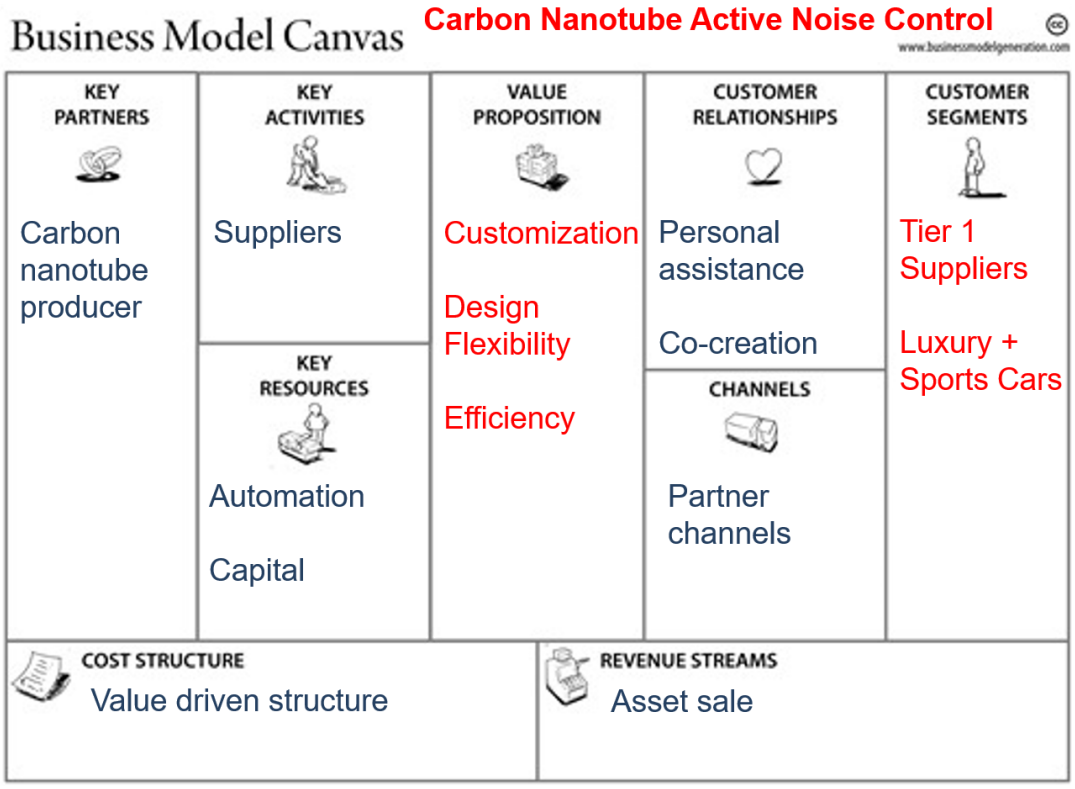


Figure 4.5. Business model canvas presented at the Midwest I-Corps Industry Innovation program

4.3 Southwest I-Corps National Program

Over the course of the 6-weeks of the National I-Corps program, Team NanoSound conducted over 110 interviews, with 103 of those interviews being in-person. The pace of the national program was much faster and more rigorous than the previous programs. As such, the team made substantial progress towards their commercialization strategy. Going into this program, the team has identified four major industries of interest: automotive exhaust, military, HVAC, and oil and gas. After the first three days conducting interviews in Houston, the oil and gas industry was quickly invalidated, leaving automotive, HVAC, and military as the primary industries. The first step to further explore these industries was to create a petal diagram, which identifies the financial size of the market and the major companies within each of those industries (Figure 4.6). The HVAC market was split into HVAC and industrial ventilation for this diagram.

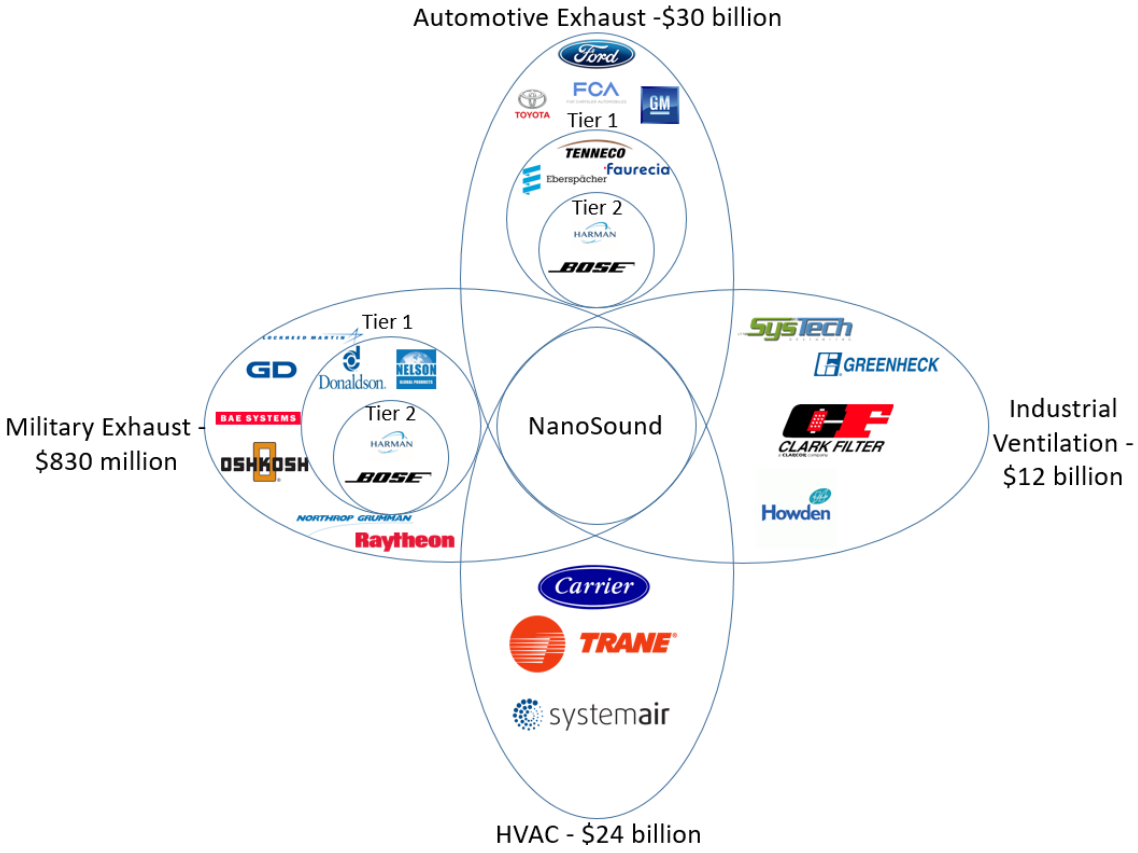


Figure 4.6. Petal diagram of automotive, HVAC, and military industries

After completing 30 interviews within the automotive industry, this market segment was invalidated as well. This was due to the large manufacturing capital required to produce the high volumes required in this industry at low profit margins, low tolerance for manufacturing errors, and strict requirements necessary to become a certified supplier to the OEMs and tier 1 suppliers. However, even though this market was invalidated as an entry point for a startup, a need for this technology was found in this industry and a lot of interest was generated. This industry will remain as an option for future growth, however just not for a market entry point.

The automotive industry was thought to be the perfect market fit for this technology after the ICD and Industry Innovation programs, however only the military and HVAC markets remained as viable options. The team conducted more interviews in the military market, and quickly learned that it was also a difficult landscape to break into as a startup, similar to the automotive industry. These findings led to the military market also being invalidated. With this information, the team decided to pivot away from exhaust systems and focus purely on HVAC applications. For the remainder of the National I-Corps program, the team focused on only conducting interviews with those involved in the HVAC market, ranging from engineers and architects, to general contractors, to HVAC subcontractors. Interviews in this market segment allowed the discovery to be made that there is a need for this technology in hospitals, theaters, and schools, areas which are extremely sensitive to noise, and excess amounts of noise in these areas can be detrimental. In hospitals, excess noise can inhibit patient recovery [30,34,50,55]. In schools, particularly elementary schools, noise has a known negative correlation with student learning outcomes [54,63,78]. Finally, in theaters, HVAC noise can distract from the performance and negatively impact the theatergoing experience [16,51].

After making the decision to pivot and focus purely on the HVAC market, further development of the business strategy was actively pursued. The first step was to create the customer workflow for construction projects. After talking to a range of professionals in the industry, a clear picture of the workflow was completed (Figure 4.7). By understanding this workflow, the team was able to pinpoint exactly where the technology fit. The key partner to enter the market would be with the HVAC manufacturer's representatives, who

supply components to the HVAC subcontractors. By understanding this connection as the entry point to the industry, the manufacturer's representatives could serve as evangelists, or promoters, of the technology. By creating exclusive deals for representatives of different areas, which is a standard practice for the industry, they would be incentivized to sell by offering them an advantage over their competitors.

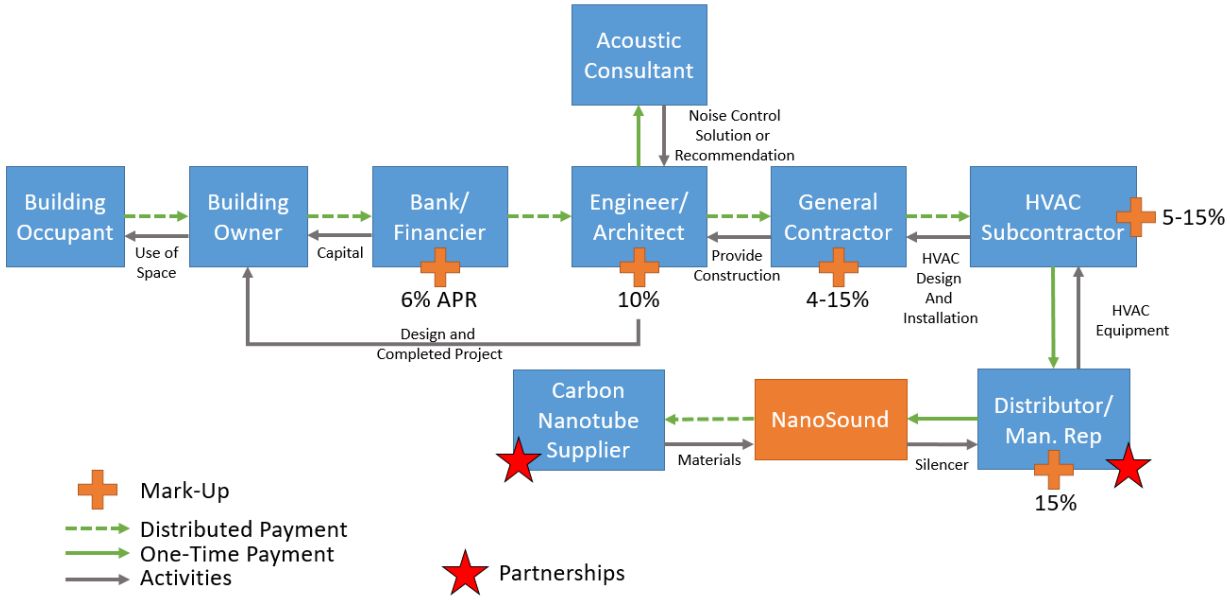
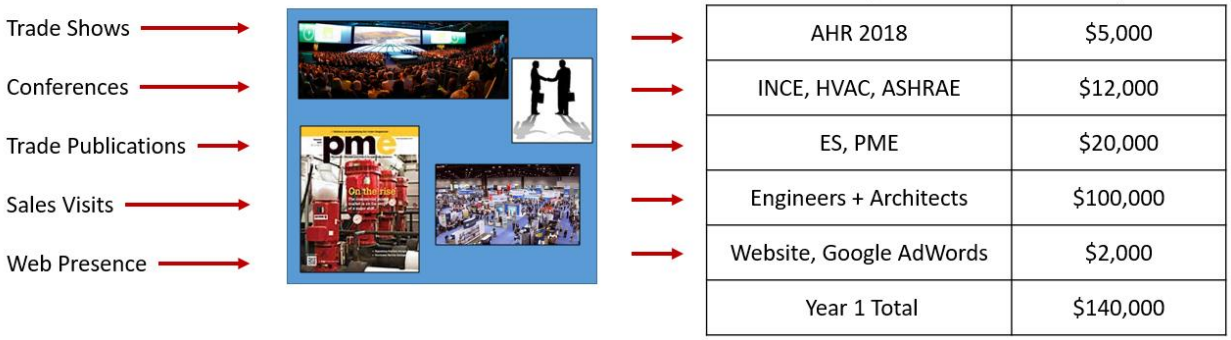


Figure 4.7. Customer workflow diagram for the HVAC industry

Once the customer workflow had been discovered, a more detailed marketing strategy was devised. First, the demand creation budget and forecast was created, which outlines the key areas of marketing and the costs associated with them (Figure 4.8). It was decided that the best places to market the thermophone technology would be at trade shows and conferences, advertising online and in trade publications, and through personal sales visits. The costs associated with each of these were estimated, coming to a total customer

acquisition cost (CAC) of $5,800 per customer for the first year, assuming that the business was able to acquire two new customers per month for the first year.



Target	Yearly Cost
AHR 2018	$5,000
INCE, HVAC, ASHRAE	$12,000
ES, PME	$20,000
Engineers + Architects	$100,000
Website, Google AdWords	$2,000
Year 1 Total	$140,000

Figure 4.8. Demand creation budget and forecast

Following the creation of the demand creation budget and forecast, the get-keep-grow strategy was created (Figures 4.9 and 4.10). If the demand creation budget and forecast is the strategy for generating interest and awareness of the technology, the get-keep-grow strategy is the method to turn that interest into a growing business. Generating awareness is the first step in the get strategy. From this awareness, interest is generated, which can be quantified by the number of calls received, the number of clicks on the website, and the amount of requests for information (RFIs) received. This interest then feeds into consideration, which can be quantified through the number of requests for quotes (RFQs) received and the amount of demonstration requests received. Finally, all of this will ultimately result in the number of products that have been purchased. The word of mouth generated through these purchases and installations will again generate awareness, which creates a viral loop, continuing to generate more customers.

After the get strategy comes the keep and grow portion. Once a purchase has been made and a new customer has been acquired, the company wants to keep this customer returning by providing incentives. The keep strategy that was formulated involves keeping customers by offering routine software updates, providing continuous customer contact and support through a dedicated sales team, and providing manufacturers and extended warranties, which can cover routine maintenance and inspection. Once the keep strategy had been devised, a method to grow these existing customers and increase the lifetime value (LTV) of each customer must be developed. The first method is to unbundle additional services that may be provided, such as an extended warranty, and also by providing a training and certification program for local HVAC repair to become certified to fix the product. Additionally, the company will be able to upsell premium features of the technology that are not part of the minimum viable product (MVP). Some of the features that can be added are Bluetooth connectivity, a speech privacy mode, and major software updates. Eventually, the product line will be able to expand, allowing the opportunity to cross-sell these additional products. For example, a line of quiet diffusers, which could create a more quiet and peaceful environment in specific rooms. Finally, the last step of the grow strategy is to gain customer referrals. The goal is to have customer word-of-mouth generate interest and sales to additional clients, thus feeding back into the viral loop of the get-keep-grow strategy.

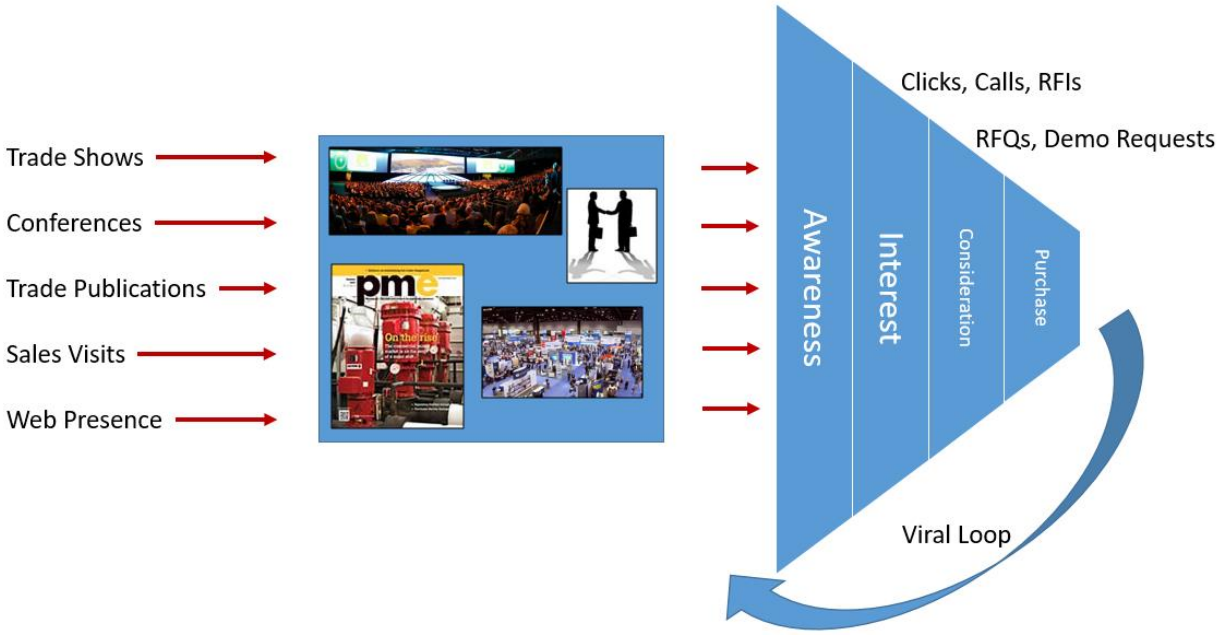


Figure 4.9. Get strategy for the HVAC market

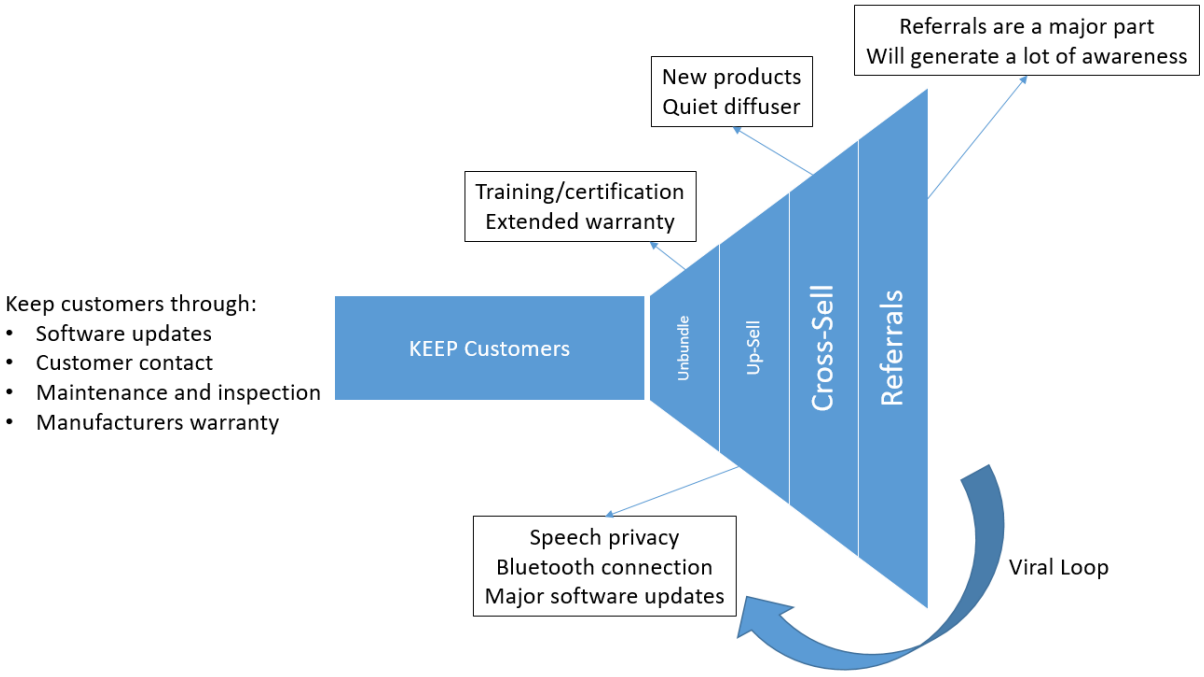


Figure 4.10. Keep and grow strategy for the HVAC market

After completing an additional 50 interviews in the HVAC industry and creating a marketing strategy, a final business model was created for the commercialization of the CNT thermophone (Figure 4.11). Team NanoSound plans to first create a minimum viable product (MVP) of the technology, capable of cancelling up to 20 dB of adverse noise in HVAC systems. Once an MVP has been identified and proven, the team will then begin the process of forming a company. After the company has been formed, the marketing strategy will then be implemented, creating advertisements and displaying the technology at trade shows and conferences. The goal for the first year of operation is to acquire customers that have noise control issues that cannot be solved with traditional passive methods, such as hospitals which cannot have any fibrous material present. By acquiring these customers, the company will be able to work with them to create a custom solution, providing both engineering services and the implemented solution. By starting with this low-volume hybrid approach, the company will begin to grow in size to the point where it is able to sustain a full manufacturing operation and expand into the commercial HVAC market. Once the technology has been proven in the HVAC industry, the team then plans to invest the earnings into expanding the manufacturing capabilities, eventually reaching the point where they are able to handle the high demand of the automotive industry and expansion of the product line.

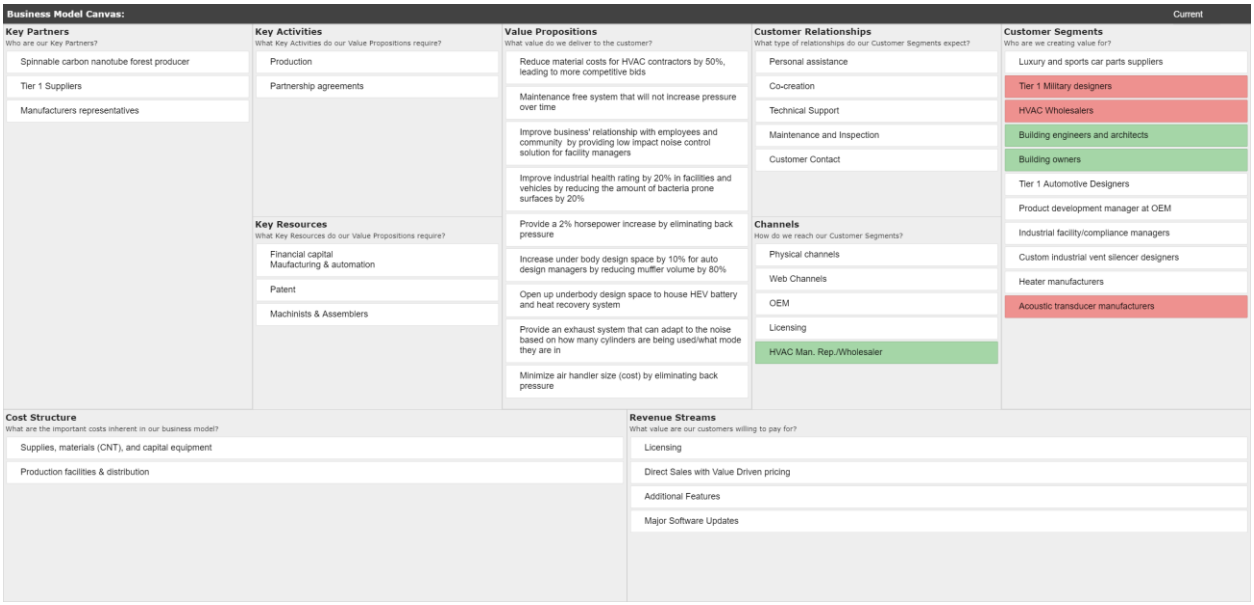


Figure 4.11. Final business model canvas

5 Discussion

5.1 I-Corps Lessons Learned

Over the course of these three I-Corps programs, valuable lessons were learned not only in navigating the business landscape, which is a challenge coming from an engineering background, but also in professional communication and how to guide research. The business concepts that were taught throughout this program were easily understood as each lesson was put into practice the following week. This gave the team a firsthand understanding of how it applied to their business strategy in real time. Additionally, these topics were reinforced throughout each of the three I-Corps programs, providing opportunities for them to be understood in detail. The professional communication skills taught in this program have been extremely valuable. By engaging directly with industry professionals at all levels and over a wide range of industries, the customer interviews have led to improved conversation and listening skills. Along the same lines, there has been a marked improvement in presentation quality as well. By learning to create engaging media, such as videos and PowerPoint presentations, the technical concepts of the thermophone and the overall business strategy have become easier to convey to those unfamiliar with the technology. Overall, the lessons on focusing research into areas that are not only interesting from an academic perspective, but also from a commercialization standpoint have been invaluable.

5.2 Personal Growth/Tips and Tricks for Successful Interviews

The NSF I-Corps program helps promote not only academic growth through lectures and readings, but also personal development throughout each course. Looking

back on the beginning of the ICD program at Michigan Tech, a dramatic increase has been seen in the presentation skills, interpersonal skills, and confidence of the EL. These improvements can be attributed to the supportive nature of the I-Corps program and teaching team. While they can be tough at times, the uncomfortable situations that they create help promote personal growth. One of the best learning situations that they put the EL in is requiring that they are the only team member to speak during the team presentations, while the PI and IM remain silent. This puts the spotlight purely on the EL, not allowing them to fall back on to their team members. This practice was stressful at first, but after the first sessions were over, it created a large confidence boost being in control of the team image and message.

One of the most challenging tactics to understand throughout this program was how to conduct a good interview. Ideally, during the interview process, one does not want to ask guided questions, such as "Would you be interested in a product that was less expensive?" The majority of the responses to this type of question are always going to be "Yes." Instead, it is important to allow the customer to lead you to this information by digging deeper into the root cause of their issues and what features are a necessity to them. Another beneficial tactic to practice is to learn to talk less and listen more. It may be uncomfortable at first but allowing for pauses in conversation can be beneficial. This allows the customer a chance to think further on the subject and can lead to valuable learnings. Overall, these lessons could not have been learned without the amount of interviews that the program requires the team to complete.

Another key learning in the interview process was to conduct as many in-person interviews as possible. The information obtained from meeting in person far outweighs that gained from phone or web interviews. When meeting in person, it is possible to observe the body language of the customer and better read their facial expressions. This can lead to deeper insight by understanding when they get excited or emotional about a certain topic, which allows you to ask further questions and discover their burning issues. Meeting in person also presents opportunities to see the facilities first hand. If a customer presents the offer to tour the facilities, a much better understanding of the manufacturing processes and issues can be found. Finally, it is beneficial to have two team members present at the interview whenever possible, one to conduct the interview and one to take notes. Allowing the interviewer to focus purely on the line of questioning they are pursuing without having to focus on note-taking is extremely beneficial. Once these interview tactics are learned and properly applied, a significant increase in both the amount and quality of data collected will be seen.

5.3 Benefit to the University

Participation in this program not only benefited the participating team, but has also brought many benefits back to Michigan Tech. The practice of customer discovery can be highly beneficial as a teaching tool to help students dig deeper to find the core issue to solve a problem. Whether it be in senior design projects, enterprise interaction with industry, or research projects, teaching students to engage with their customer will not only reflect more positively on the university, but also lead to better results in these projects. For example, Dr. Barnard has discussed implementing these techniques into his courses

where students are given design projects that interface with industry professionals. He has also discussed incorporating this process with his graduate students to help them better understand and convey the true purpose behind their research and the benefit it will provide. The team's participation in the I-Corps program also drew the attention of the local news channel, ABC 10 News. A local report picked up the story and interviewed Dr. Barnard and Mr. Senczyszyn. This segment further spread the awareness of this new technology and the role that the university played in pursuing its commercialization.

5.4 Evolution of the NanoSound Business Model Canvas

Looking back on the evolution of the business model canvas that was originally developed in the ICD, the business model for Team NanoSound has improved tremendously by learning the fundamentals of the Lean Startup method. Two of the biggest areas of improvement have been the customer segments and the value propositions. The understanding of what makes a good value proposition has increased dramatically, and through over 150 customer interviews, the target customer segments have been thoroughly explored. In the case of active noise control technology, the end user is not likely to be the target customer. Initially, it was thought that the target customer in the automotive market was going to be the purchaser of the vehicle, however it was learned through the development of the business model, the customer of interest is going to be the manager making the decision on which product to spec into the vehicle platform and who the supplier for that product will be. By gaining a better understanding of the customer workflow, the chain of decisions is able to be seen, and from that the entry point for the technology can be identified. Additionally, the improvement in value propositions has been

notable as well. The initial value propositions were vague and qualitative. This is just one example of the many improvements that have been made. In the final BMC, it can be seen that the value propositions have specified results and a quantitative measurement along with each.

5.5 Technical Design Challenges

Going into the I-Corps program, the team knew that there were still questions regarding the CNT thermophone technology that were not yet answered. The three primary concerns were the thermal cycling of the CNT, the challenge of finding a suitable material to protect the CNT thin-film, and improving the efficiency of the thermophone. During previous research done in Dr. Barnard's laboratory, the CNT thermophones have only been operated for relatively short durations. In commercial applications, these systems will be in operation for extended periods of time, ranging from hours to months, or even years at a time. There was also concern in finding a suitable material to separate the CNT thin-films from the external environment while still remaining acoustically transparent. In previous testing, the barrier material had been the point of failure in high flow environments. Finally, there were initial thoughts on how the efficiency of the thermophone could be improved. When operated in air, the CNT thin-films can fail when particulate falls on the surface and combusts, which leads to cascade failure. There has been interest from the team in operating the thermophone in different ambient gases that are inert, such as argon, which would allow the thermophone to operate at higher temperatures.

After talking with professionals in the automotive, HVAC, and military industries, some concerns and questions were raised that the team was not prepared to answer based on previous research. In automotive and military exhaust applications, many of the engineers were concerned with system's ability to withstand multiple environments. For instance, many times a vehicle will need to start in freezing weather, after which the exhaust components rise to high temperatures in a short period of time. Another concern was raised about the fragile nature of the CNT thin-films, as they can be easily destroyed when exposed to airflow or moisture. Many vehicle components have difficulty remaining sealed from moisture and debris, with engineers citing headlights as an example. Finally, questions were also asked regarding the durability of the CNT in response to external shock and vibration, as vehicles must be able to withstand the vibration from multiple road surfaces. In the HVAC industry, similar concerns arose when discussing the long-term effectiveness of the ANC system. Currently, customers expect a traditional passive silencer to last upwards of 15 years with low maintenance requirements. However, once installed, these systems are unmoved until they are replaced. Finally, concerns were also raised in the HVAC industry about the effects of nanoparticles on the human body, and how this would affect the adoption of this technology in sensitive areas.

Learning the concerns voiced from an industry perspective has altered the team's research priorities both in understanding concerns and how they should be approached for each industry. To address these issues, research plans have been developed to gain a better understanding of the technological needs that are needed to succeed in commercialization efforts. For the automotive and military exhaust technology, a research plan has been

developed to investigate the effects of road vibration and environment on the CNT. This will be accomplished by taking a measured profile and exciting a prototype system using the Dongling shaker at Michigan Tech. To understand the environmental factors, a test chamber will be created that can be used to continuously cycle the system from freezing conditions to warm weather conditions. In pursuing the HVAC market, a research plan has been developed to understand the long-term durability of the CNT thermophone. Performing an accelerated lifetime test can help provide a prediction of how these systems will hold up over time, and whether they can compete with the traditional passive silencer in terms of durability. Lastly, more research will also be done looking into regulations on nanoparticles in environments such as hospitals. Understanding these regulations will provide the necessary knowledge to create a design that will remain compliant with future regulations. Performing customer discovery allowed for valuable insights into both the needs and concerns that each industry has. Without this insight, the research plan for the technology would not be focused in areas of high necessity.

5.6 Future Work

The National Science Foundation I-Corps program has instilled the entrepreneurial spirit in the NanoSound team. After completing the national I-Corps program, the team has decided to continue pursuing the commercialization path for this technology laid out in the previous sections. In the coming months, the team plans to participate in several pitch competitions in Michigan, such as the Central Michigan University New Ventures Competition and the Greenlight Michigan Business Model Competition. The team has also applied for additional funding to continue this pursuit through the Michigan MTRAC

program, the NSF PFI-TT, and T3N funding. With these funds, the team will be able to collaborate with Great Lakes Sound and Vibration to produce a prototype for the HVAC industry, improve the current design of the automotive exhaust system, and continue customer discovery. If these ventures prove successful, the team plans to form a company in the next 12-18 months. The team is still actively pursuing customer discovery as well to find the best entry point for commercialization. Since the completion of the I-Corps programs, Mr. Senczyszyn has attended the AHR Expo and ASHRAE conference in Chicago, IL, where he conducted an additional 25 customer interviews. These events regularly attract upwards of 70,000 HVAC professionals, providing ample opportunity to understand the needs of the industry and explore the product offerings of competing companies. The team plans to continually pursue customer discovery, as this is a process that never ends and can always provide additional benefits.

6 Conclusion

Overall, participation in this series of National Science Foundation I-Corps programs has proven to be beneficial not only for the team of Dr. Andrew Barnard, Mr. Steve Mattson, and Mr. Steven Senczyszyn, but for Michigan Technological University as a whole. By completing the Initial Customer Discovery, Industry Innovation, and National I-Corps programs, the team has developed an understanding of the Lean Startup methodology and the business model canvas and put these learnings to use in developing a sustainable business model to pursue the commercialization of the carbon nanotube thermophone technology. After completing over 150 customer interviews in the automotive, HVAC, military, and oil and gas industries, the team has decided that the best market for entry is the HVAC market, where the active noise control technology can reduce the system footprint, lower operating and construction costs, and reduce the backpressure on the air handling system. The automotive market, which was initially thought to be the ideal entry point, was found to be a non-starter due to the high volume production requirements, stringent supplier requirements, and low profit margins. However, this does not mean that the automotive market is out of the business model for good. By establishing the technology in the HVAC market, this allows the opportunity to incrementally grow the business to the scale that would be necessary to become a serious competitor in the automotive market. Participation in this program has instilled the entrepreneurial spirit in the team, and progress has been moving forward in pursuing this opportunity further since the conclusion of the I-Corps program. The team has applied for additional follow-on funding through the Michigan PFI-TT, T3N, and MTRAC programs, continued customer

discovery at conferences and trade shows, and been accepted to pitch competitions to pitch their business model against others. Overall, this program has been successful in its goal to help commercialize technology and bridge the gap between academia and industry.

7 Reference List

1. Aliev AE, Lima MD, Fang S, and Baughman RH, “Underwater sound generation using carbon nanotube projectors.” Nano Letters, 2010. 10: 2374-2380.
2. Aliev AE, Gartstein YU, and Baughman RH, “Increasing the efficiency of thermoacoustic carbon nanotube sound projectors.” Nanotechnology, 2013. 24: 233501.
3. Aliev AE, Lima MD, Silverman EM, and Baughman R, “Thermal conductivity of multi-walled carbon nanotube sheets: radiation losses and quenching of phonon modes.” Nanotechnology, 2010. 21: 035709.
4. Aliev AE, Mayo NK, Baughman RH, Avirovik D, Priya S, and Zarnetske MR, “Thermal management of thermoacoustic sound projectors using a free-standing carbon nanotube aerogel sheet as a heat source.” Nanotechnology, 2014. 25: 405704.
5. Aliev AE, “Thermophones using carbon nanotubes and alternative nanostructures for high power sound generation and noise cancellation.” InterNoise and NoiseCon Congress and Conference Proceedings: Institute of Noise Control Engineering, 2014. 3938-3947.
6. Anderson RA, Daim TU, and Lavoie FF, “Measuring the efficiency of university technology transfer.” Technovation, 2007. 27: 306-318.
7. Arnold H and Crandall I, “The thermophone as a precision source of sound.” Physical Review, 1917. 10(1): 22-38.
8. Asadzadeh SS, Moosavi A, Huynh C, and Saleki O, “Thermoacoustic study of carbon nanotubes in near and far field: Theory, simulation, and experiment.” Journal of Applied Physics, 2015. 117(9): 095101.
9. Asgarisabet M, Barnard AR, and Bouman TM, “Near field acoustic holography measurements of carbon nanotube thin film speaker.” Journal of Acoustical Society of America, 2016. 140(6): 1-9.
10. Association of University Technology Managers, “Statistics Analysis for Technology Transfer (STATT).” AUTM, 2016.
11. Barnard AR, Brungart TA, McDevitt TM, Aliev AE, Jenkins DM, Kline BL, and Baughman RH, “Advancements toward a high-power, carbon nanotube, thin-film loudspeaker.” Noise Control Engineering Journal, 2014. 62(5): 360-367.
12. Barnard AR, Jenkins DM, Brungart TA, McDevitt TM, and Kline BL, “Feasability of a high-powered carbon nanotube thin-film loudspeaker.” The Journal of the Acoustical Society of America, 2013. 134(3): EL276-EL281.
13. Barnard AR, Brungart TA, McDevitt TM, and Jenkins DM, “Background and development of a high-powered carbon nanotube thin-film loudspeaker.” Proceedings of Inter Noise, 2012. 1513-1524. New York, USA.

14. Barnard AR, Brungart TM, McDevitt TM, Jenkins DM, and Kline BL, "Advancements towards a high-powered carbon nanotube thin-film loudspeaker." Proceedings of Noise Control, 2013. 796-802. Denver, USA.
15. Barnard, AR, "Solid State Transducer, System, and Method," US Patent Pending, PCT/US2018/012061, 2 Jan. 2018.
16. Basner M, Babisch W, Davis A, Brink M, Clark C, Janssen S, and Stansfeld S, "Auditory and non-auditory effect of noise on health." The Lancet, 2014. 383 (9925): 1325-1332.
17. Beck BS, Zugger ME, Brungart TA, Fredley JE, Kline BL, and Yoas BW, "Increasing the efficiency of carbon nanotube, thin film loudspeakers." InterNoise 2015. San Francisco, USA.
18. Bin J, Oates WS, and Taira K, "Thermoacoustic modeling and uncertainty analysis of two-dimensional conductive membranes." Journal of Applied Physics, 2015. 117: 064506.
19. Blank S and Dorf B, *The Startup Owner's Manual*. Pescadero CA: K&S Ranch, Inc. 2012.
20. Blank S, "Embrace failure to start up success." Nature, 2011. 477: 133.
21. Bouman TM, Barnard AR, and Asgarisabet M, "Experimental quantification of the true efficiency of carbon nanotube thin-film thermophones." Journal of the Acoustical Society of America, 2016. 139: 1353-1363.
22. Braun F, "Notiz über thermophonie (Note on thermophonie)." Annalen Der Physik, 1898. 65: 358-360.
23. Busch-Vishniac IJ, West JE, Barnhill C, Hunter T, Orellana D, and Chivukula R, "Noise levels in John Hopkins Hospital." Journal of the Acoustical Society of America, 2005. 118: 3629-3645.
24. Carnes TN, Pelton HK, and Saenz DW, "Environmental noise issues associated with medical facility HVAC equipment." Journal of the Acoustical Society of America, 2003. 114.
25. Daschewski M, Boehm R, Prager J, Kreutzbruck M, and Harrer A, "Physics of thermos-acoustic sound generation." Journal of Applied Physics, 2013. 114: 114903.
26. Djokovic D and Souitaris V, "Spinouts from academic institutions: A literature review with suggestions for further research." Journal of Technology Transfer, 2008. 33: 225-247.
27. Eklund P, Ajayan P, Blackmon R, Hart AJ, Kong J, Pradhan B, Rao A, and Rinzler A, "International assessment of carbon nanotube manufacturing and applications." World Technology Evaluation Center, 2007.
28. Evans GW, "Community noise exposure and stress in children." Journal of the Acoustical Society of America, 2001. 109: 1023-1027.
29. Fei W, Zhou J, and Guo W, "Low-voltage driven graphene foam thermoacoustic speaker." Small, 2015. 11(19): 2252-2256.
30. Freedman NS, Gazendam J, Levan L, Pack AI, and Schwab RJ, "Abnormal sleep/wake cycles and the effect of environmental noise on sleep disruption in the intensive care

unit." American Journal of Respiratory and Critical Care Medicine, 2001. 163 (2): 451-457.
31. Gregorio DD and Shane S, "Why do some universities generate more start-ups than others?" Research Policy, 2003. 32: 209-227.
32. Grimpe C and Fier H, "Informal university technology transfer: A comparison between the United States and Germany." Journal of Technology Transfer, 2010. 35: 637-650.
33. Hsu DWL, Shen YC, Yuan BJC, and Chou CJ, "Toward successful commercialization of university technology: Performance drivers of university technology transfer in Taiwan." Technological Forecasting & Social Change, 2015. 92: 25-39.
34. Hsu T, Ryherd E, Waye PK, and Ackerman J, "Noise pollution in hospitals: impact on patients." Journal of Science Communication, 2012. 19 (7): 301-309.
35. Hu L, Hecht DS, and Grüner G, "Carbon nanotube thin films: fabrication, properties, and applications." Chemical Reviews, 2010. 110(10): 5790-5844.
36. Hu S and Rajamani R, "Carbon nanotube thin films for active noise cancellation, solar energy harvesting, and energy storage in building windows." University of Minnesota, 2014.
37. Hu S, Rajamani R, and Yu X, "Directional cancellation of acoustic noise for home window applications." Applied Acoustics, 2013. 74: 467-477.
38. Hu S, Rajamani R, and Yu X, "Active noise control for selective cancellation of external disturbances." American Control Conference, 2011. San Francisco, USA.
39. Ijima S, "Helical microtubules of graphite carbon." Nature, 1991. 354: 56-58.
40. Jakubinek MB, White MA, Li G, Jayasinghe C, Cho W, Schulz MJ, and Shanov V, "Thermal and electrical conductivity of tall, vertically aligned carbon nanotube arrays." Carbon, 2010. 48(13): 3947-3952.
41. Kim CS, Hong SK, Lee JM, Kang DS, Cho BJ, and Choi JW, "Free-standing graphene thermophone on a polymer-mesh substrate." Small, 2016. 12(2): 185-189.
42. Kirchberger MA and Pohl L, "Technology commercialization: A literature review of success factors and antecedents across different contexts." Journal of Technology Transfer, 2016. 41: 1077-1112.
43. Kozlov ME, Haines CS, Oh J, Lima MD, and Fang S, "Sound of carbon nanotube assemblies." Journal of Applied Physics, 2009. 106: 124311.
44. Lim CW, Tong L, and Li Y, "Theory of suspended carbon nanotube thin film as a thermal-acoustic source." Journal of Sound and Vibration, 2013. 332(21): 5451-5461.
45. Lockett A, Siegel D, Wright M, and Ensley MD, "The creation of spin-off firms at public research institutions: Managerial and policy implications." Research Policy, 2005. 34: 981-993.
46. Manap A, Ismail N, and Sidek S, "The roles of technology transfer offices to facilitate intellectual property commercialization in the university: Issues and challenges." The Social Sciences, 2017. 12(6): 919-924.
47. Markman GD, Gianiodis PT, Phan PH, and Balkin DB, "Innovation speed: Transferring university technology to market." Research Policy, 2005. 34: 1058-1075.

48. Markman GD, Siegel DS, and Wright M, "Research and Technology Commercialization." Journal of Management Studies, 2008. 45: 1401-1423.
49. Mason BJ, Chang SW, Chen J, Cronin SB, and Bushmaker AW, "Thermoacoustic transduction in individual suspended carbon nanotubes." ACS Nano, 2015. 9(5): 5372-5376.
50. Messingher G and Ryherd E, "Hospital noise and staff performance." Journal of the Acoustical Society of America, 2012. 132.
51. Moudon AV, "Real noise from the urban environment: how ambient community noise affects health and what can be done about it." American Journal of Preventive Medicine, 2009. 37 (2): 167-171.
52. Mowery DC and Sampat BN, "The Bayh-Dole Act of 1980 and University-Industry Technology Transfer: A Model for Other OECD Governments?" Journal of Technology Transfer, 2005. 30: 115-127.
53. Muscio A, Quaglione D, and Ramaciotti L, "The effects of university rules on spinoff creation: The case of academia in Italy." Research Policy, 2016. 45: 1386-1396.
54. Nelson P, Kohnert K, Sabur S, and Shaw D, "Classroom noise and children learning through a second language: Double Jeopardy?" Language, Speech, and Hearing Services in Schools, 2004. 36: 219-229.
55. Notbohm G and Siegmann S, "Noise stress for patients in hospitals – a literature survey." Acoustical Society of America, 2013. 19.
56. O'Kane C, Mangematin V, Geoghegan W, and Fitzgerald C, "University technology transfer offices: The search for identity to build legitimacy." Research Policy, 2015. 44: 421-437.
57. O'Shea RP, Allen TJ, Chevalier A, and Roche F, "Entrepreneurial orientation, technology transfer and spinoff performance of U.S. universities." Research Policy, 2005. 34: 994-1009.
58. Osterwalder A and Pigneur Y, *Business Model Generation*. Hoboken NJ: Wiley, 2010.
59. Peng ZE and Wang LM, "Effects of noise, reverberation and foreign accent on native and non-native listeners' performance of English speech comprehension." Journal of the Acoustical Society of America, 2016. 139: 2772-2783.
60. Pöhls JH, Johnson MB, White MA, Malik R, Ruff B, Jayasinghe C, Schulz MJ, and Shanov V, "Physical properties of carbon nanotube sheets drawn from nanotube arrays." Carbon, 2012. 50(11): 4175-4183.
61. Rasmussen E and Borch OJ, "University capabilities in facilitating entrepreneurship: A longitudinal study of spin-off ventures at mid-range universities." Research Policy, 2010. 39: 602-612.
62. Rasmussen E, Mosey S, and Wright M, "The influence of university departments on the evolution of entrepreneurial competencies in spin-off ventures." Research Policy, 2014. 43: 92-106.
63. Ronsse LM and Wang LM, "Relationships between unoccupied classroom acoustical conditions and elementary student achievement measured in eastern Nebraska." Journal of the Acoustical Society of America, 2013. 133: 1480-1495.

64. Sharma M, Kumar U, and Lalande L, “Role of university technology transfer offices in university technology commercialization: Case study of the Carleton University foundry program.” Journal of Services Research, 2006. 6: 109-139.
65. Shield BM and Dockrell JE, “The effects of environmental and classroom noise on the academic attainments of primary school children.” Journal of the Acoustical Society of America, 2008. 123: 133-144.
66. Sidhu S, “Implementation of active noise cancellation in a duct.” Simon Fraser University, 2013.
67. Stanfield SA, Berglund B, Clark C, Lopez-Barrio I, Fischer P, Ohrstrom E, Haines MM, Head J, Hygge S, van Kamp I, and Berry BF, “Aircraft and road traffic noise and children’s cognition and health: a cross-national study.” The Lancet, 2005. 365 (9475): 1942-1949.
68. Sternberg R, “Success factors of university-spin-offs: Regional government support programs versus regional environment.” Technovation, 2014. 34: 137-148.
69. Sugimoto T and Nakajima Y, “Acoustic characteristics of a flexible sound generator based on thermoacoustic effect.” Acoustical Society of America, 2013. 1aEA4. Montreal, Canada.
70. Suzuki K, Sakakibara S, Okada M, Neo Y, Mimura H, Inoue Y, and Murata T, “Study of carbon-nanotube web thermoacoustic loud speakers.” Japanese Journal of Applied Physics, 2011. 50: 01BJ10.
71. Swamidass PM, “University startups as a commercialization alternative: Lessons from three contrasting case studies.” Journal of Technology Transfer, 2013. 38(6): 788-808.
72. Tian H, Ren TL, Xie D, Wang YF, Zhou CJ, Feng TT, Fu D, Yang Y, Peng PG, Wang LG, and Liu LT, “Graphene-on-paper sound source devices.” ACS Nano, 2011. 5(6): 4878-4885.
73. Tong LH, Lim CW, and Li YC, “Gas-filled encapsulated thermal-acoustic transducer.” Journal of Vibration and Acoustics, 2013. 135(10): 051033.
74. Tong LH, Lim CW, Lai SK, and Li YC, “Gas separation effect on thermoacoustic wave generation by heated suspended CNT nano-thinfilm.” Applied Thermal Engineering, 2015. 86: 135-142.
75. United States National Science Foundation, “FY 2017 Agency Financial Report.” 2017.
76. Vesterinen V, Niskanen AO, Hassel J, and Helisto P, “Fundamental efficiency of nanothermophones: modeling and experiments.” Nano Letters, 2010. 10: 5020-5024.
77. Visintin F and Pittino D, “Founding team composition and early performance of university-based spin-off companies.” Technovation, 2014. 34: 31-43.
78. Wang LM and Brill LC, “Relations between acoustic quality and student achievement in K-12 classrooms.” Journal of the Acoustical Society of America, 2017. 141.
79. Wei Y, Lin X, Jiang K, Liu P, Li Q, and Fan S, “Thermoacoustic chips with carbon nanotube thin yarn arrays.” Nano Letters, 2013. 13: 4795-4801.
80. Winberg M, Johamsson S, and Lagö T, “Speaking panels – new actuators for active noise control.” InterNoise 2005. Rio de Janeiro, Brazil.

81. Wright M, Birley S, and Mosey S, “Entrepreneurship and University Technology Transfer.” Journal of Technology Transfer, 2004. 29: 235-246.
82. Xiao L, Chen Z, Feng C, Liu L, Bai ZQ, Wang Y, Lan L, Zhang Y, Li Q, Jiang K, and Fan S, “Flexible, stretchable, transparent carbon nanotube thin film loudspeakers.” Nano Letters, 2008. 8(12): 4539-4545.
83. Xiao L, Liu P, Li Q, Feng Z, Fan S, and Jiang K, “High frequency response of carbon nanotube thin film speaker in gases.” Journal of Applied Physics, 2011. 110(8): 084311.
84. Yu X, Rajamani R, Stelson KA, and Cui T, “Carbon nanotube-based transparent thin film acoustic actuators and sensors.” Sensors and Actuators A: Physical, 2006. 132(2): 626-631.
85. Yu X, Rajamani R, Stelson K, and Cui T, “Active control of sound transmission through windows with carbon nanotube-based transparent actuators.” IEEE Transactions on Control Systems Technology, 2007. 15(4): 704-714.
86. Zhang M, Fang S, Zahkidov AA, Lee SB, Aliev AE, Williams CD, Atkinson KR, and Baughman RH, “Strong, transparent, multifunctional, carbon nanotube sheets.” Science, 2005. 309: 1215-1219.
87. Zhu C, Cheng C, He YH, Wang L, Fung KK, and Wang N, “A self-entanglement mechanism for continuous pulling of carbon nanotube yarns.” Carbon, 2011. 49: 4996-5001.
88. Zhu H, Rajamani R, Dudney J, and Stelson K, “Active noise control using a distributed mode flat panel loudspeaker.” ISA Transactions, 2003. 42: 475-484.