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Using Rigid Silica Aerogel to Enhance Child Safety Near Gas-Fired Hearth Appliances

A Pilot Study

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***Abstract*—this paper presents the outcome of a pilot study to utilize rigid silica aerogel as a safety enhancement measure to insulate hot glass in hearth appliances. The aerogel provides a high temperature effective insulation material to lower the temperature of outside surfaces of hearth appliances (fireplaces and stoves). The process to investigate this study is purely experimental. This paper presents the results of this pilot study in the form of temperature measurements across the exterior surface of hearth appliance that is gas-fired. The preliminary outcome presents some challenges related to high aerogel hygroscopy while presenting a potential for enhancing the safety of hearth appliances when it comes to be touched by children during operation.**

Keywords—aerogel insulation; hearth appliances; child safety; heat transfer;gas-fired fireplaces and stoves (key words)

I. INTRODUCTION

Higher degree burns from hot fireplace glass has been a recently increasing safety hazard, more frequently with children touching the hot glass of fireplaces and stoves [1], [2]. Hearth industry in the USA is facing lots of litigation due to child first and second-degree burns from broiling glass fireplace doors [3]. The hearth industry produces gas-fired hearth appliances that utilizes glass doors to allow radiative heat transfer while keeping combustion products completely sealed from the chance to leak into the heated room. The industry mainly uses tempered soda-lime commercial glass on medium range hearth appliances and high-end ceramic glass on premium products. In 2012, American National Standard Association (ANSI) along with Canadian Standard Association (CSA) approved a new safety standard requiring maximum fireplace glass temperature not to exceed 172 F (77.78 ^{o}C). The standard took effect Jan 1, 2015. The manufacturers responded to these new requirements by adding permanent barriers and standalone barriers to enhance safety. The current work being presented in this paper demonstrates a pilot experimental investigation of using rigid silica aerogel as a transparent thermal insulation to fireplace glass doors. Rigid silica aerogel SiO2 in its primitive formulation is one of the lowest conducting solids known in industry. The following properties listed in Table 1 [6], indicates how rigid silica aerogel hold records properties compared to most know thermal insulation materials.

An aerogel is an open-cell solid foam that is porous and composed of a network of nano-sized pores. It exhibits porosity levels that are 50% or more by volume. Aerogel is classified as a mesoporous porous material since its pore size ranges between 2 to 50 nanometers.

TABLE I. SILICA AEROGEL RECORD PROPERTY [6]

Property	*Value*
Lowest density solid	0.0011 g cm^{-3}
Lowest optical index of refraction	1.002
Lowest thermal conductivity	0.016 W m^{-1} K^{-1}
Lowest speed of sound through	70 m s^{-1}
Lowest dielectric constant	1.008[a]

[a] For frequency range of 3-40 GHz

The use of silica aerogel as an insulation material has been demonstrated in numerous studies [14] and [16] are sample of these studies. Characterization of silica aerogel and its material properties were thoroughly studied over the past couple decades. Examples of these are found in [7], [8], [10] and [15]. In recent years, some commercial application of silica aerogel in fenestration insulation is being examined [16]. The use of silica aerogel in fireplace glass doors was not reported in the literature. This pilot study, presented in this paper, is an attempt to test the feasibility of using aerogel for this application. Samples of silica aerogel were acquired from LBL.gov lab. All samples used in this investigation are 1” in thickness.

II. EXPERIMENTAL SETUP

The test setup used for this investigation is constructed as shown in Figure 1 below:

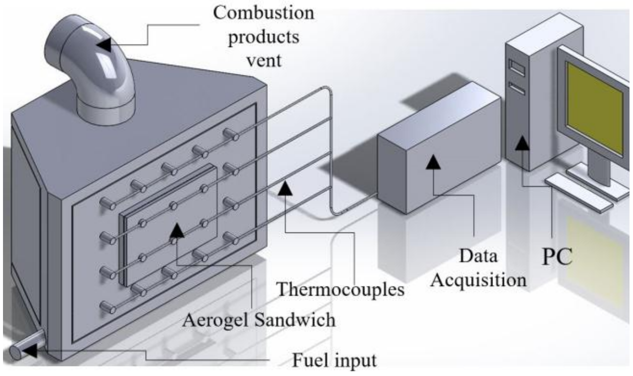

Fig. 1: Experimental Setup

The main components are as follows:

1- The Fireplace: Gas fired fireplace rated at 40,000 Btu/hr. is used. The fireplace fuel in natural gas with majority (97%) methane CH_4.

2- Aerogel Sandwich: This is the insulated section of the fireplace glass doors. It consists of the silica aerogel insulation sandwiched between the fireplace glass door and a tempered glass sheet on the outside that is 1/8” thick.

3- Thermocouples: J-type thermocouples with ceramic fiber isolation are used to sustain high temperatures of the fireplace glass door. Further details of thermocouple layouts are provided later in this paper.

4- Data acquisition system: National Instruments® data acquisition hardware and LabVIEW® data acquisition software were used to log data into the PC

5- Data acquisition Computer (PC)

The setup was housed in temperature-controlled room and fuel flow was gauged to maintain a 40,000 Btu/hr. operation of the fireplace. Figure 2 below details the size and layout of the fireplace glass door and the aerogel sandwich.

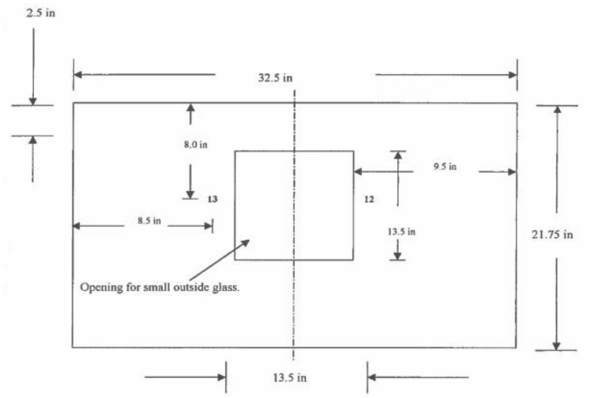

Fig. 2: Details of Fireplace glass door and aerogel sandwich showing location of thermocouples number 12 and 13

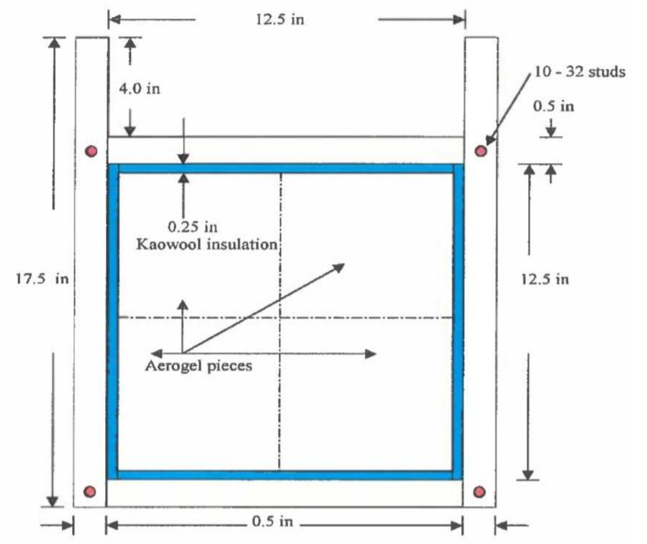

Fig. 3: Details of mounting aerogel sandwich

The aerogel sandwich was constructed by stacking four identical sheets of 1” thick aerogel that are 7” by 7” square in size. The 4-aerogel sheets generates a 14” by 14” square footprint for the sandwich. The experiments were also done on stacking four identical sheets of 1/2” thick aerogel that are 6” by 6” square in size where the 4-aerogel sheets generates a 12” by 12” square footprint for the sandwich. The aerogel is then framed by a ¼” thick ceramic blanket insulation (Kaowool ®) from four sides to minimize heat transfer from the sidewalls of the aerogel sheets. The sandwich is held together against the main fireplace glass door using the studded metal frame as shown in Figure 3.

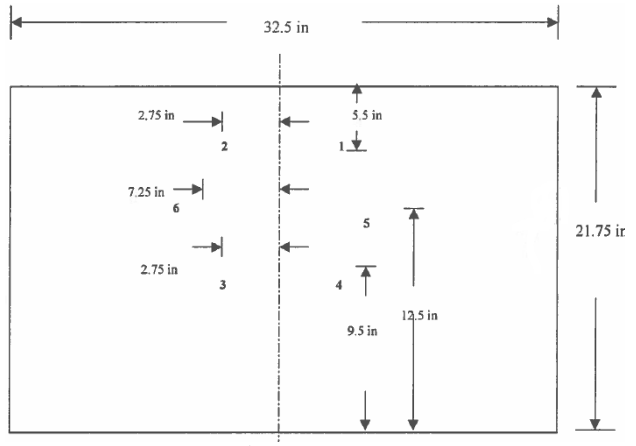

Fig. 4: Details of mounting thermocouples 1 to 6

J-type Thermocouples where mounted on the fireplace glass door and on the outside tempered glass sheet sandwiching the aerogel sheets. Locations of the thermocouples on the fireplace are detailed in Figure 4. Nineteen thermocouples were used with thermocouple number 14, 15 and 16 were dedicated to measure room temperature which was kept at 77 F (25 °C) using air-conditioning system. All data reported in this paper refer to the data-acquisition channel number assigned to reach thermocouple in the experimental setup. For example, CH-1 temperature measurements represent temperature data acquired by thermocouple number 1 and so on.

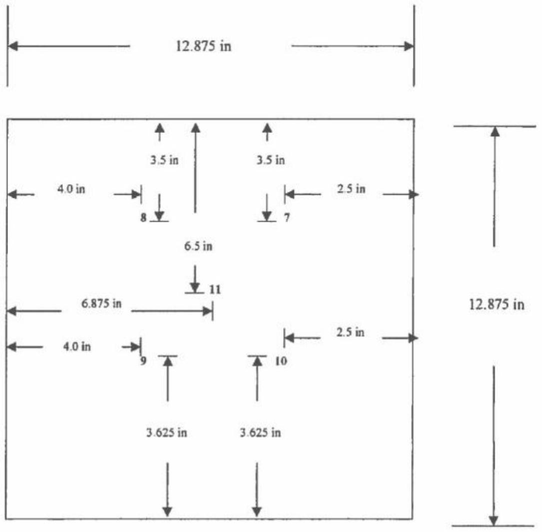

Fig. 5: Details of mounting thermocouples 7 to 611

Figures 4 to 6 details the mounting location of all thermocouples on the fireplace glass door behind the aerogel sheets and in front of the aerogel sandwich. More thermocouples were mounted to measure skin temperature of the firebox of the fireplace for reference purposes. The details and location of mounting the thermocouples 17, 18 and 19 are shown if Figures 6.

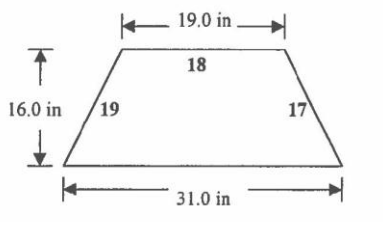

Fig. 6: Details of mounting thermocouples 17 to 19

III. MEASUREMENT PROCEDURE

The fireplace equipped with aerogel sandwich insulation was fired at the start of each test and a period of one hour was used to bring the fireplace glass door to its highest level. Both 1" and 2" thick aerogel sandwiches were tested.

J-type thermocouples were located at the same locations as shown in Figures 4 to 6 during all aerogel testing. The temperature data acquisition logged large amounts of continuous readings. The process for each case was repeated to improve confidence. The temperature data were logged as a function of time.

Temperatures across the thickness of aerogel samples were used to calculate the effective thermal conductivity of aerogel under a practical application.

Calculations of effective heat conduction resistance and the enhancement of child safety of fireplace glass doors are observed. The measurement of temperature variation with time was observed for a maximum of 120 minutes after the first hour of operation of the fireplace.

IV. EXPERIMENTAL RESULTS

The measurement procedure outlined above was repeated for the two cases of aerogel insulation thickness of 1" and 0.5". Table II lists a sample of temperature measurements for the 1" thick aerogel case at three different times 15, 25 and 30 minutes.

Table III shows sample temperature measurements for the case of 0.5" thick aerogel at times 20, 40 and 60 minutes. Temperature difference between inside fireplace glass and outside glass insulated with 1" aerogel and 0.5" aerogel are listed in these two tables.

TABLE II. SAMPLE TEMPERATURE MEASUREMENTS AT THREE DIFFERENT TIMES 15, 25 AND 30 MINUTE, THE CASE OF 1" THICK AEROGEL INSULATION

Time (min.)	Inside glass T CH2 (°F)	Outside glass T not insulated with Aerogel CH4(°F)	Outside glass T insulated with Aerogel CH11 (°F)	T difference across the Aerogel CH2 - CH11 (°F)	Air gap T difference CH2 - CH4 (°F)
15	434	185	85.8	348	249
25	554	262	120	434	292
35	621	312	167	454	309

The experiments were repeated at different days to account for variation in the natural gas supplied to the lab. Table IV shows sample data for the case of 0.5" thick aerogel insulation ate five different measurements times. Variation between Table III and Table IV data for the same 0.5" thick aerogel indicates the difficulty in the repeatability of the measurements due to instability of aerogel samples along with decay in transparency over time. Time dependent temperature data of Table IV are plotted in Figure 7. It is clear that aerogel insulation reduces temperature of outside surface glass over 380 F at 120 minutes.

TABLE III. SAMPLE TEMPERATURE MEASUREMENTS AT THREE DIFFERENT TIMES 15, 25 AND 30 MINUTE, THE CASE OF 0.5" THICK AEROGEL INSULATION

Time (min.)	Inside glass T CH2 (°F)	Outside glass T not insulated with Aerogel CH4(°F)	Outside glass T insulated with Aerogel CH11 (°F)	T difference across the Aerogel CH2 - CH11 (°F)	Air gap T difference CH2 - CH4 (°F)
20	504	212	145	359	292
40	528	242	201	327	286
60	564	262	220	302	302

TABLE IV. SAMPLE TEMPERATURE MEASUREMENTS AT FIVE DIFFERENT TIMES 15, 25 AND 30 MINUTE, THE CASE OF 1" THICK AEROGEL INSULATION

Time (min.)	Inside glass T CH2 (°F)	Outside glass T not insulated with Aerogel CH4(°F)	Outside glass T insulated with Aerogel CH11 (°F)	T difference across the Aerogel CH2 - CH11 (°F)	Air gap T difference CH2 - CH4 (°F)
20	404	177	93.9	310	227
40	533	263	150	383	270
60	571	294	181	390	277
120	599	320	211	387	278
140	599	323	213	386	277

As expected, the experimental observation for the 1" thick aerogel insulation produced lower outside glass temperatures compared to that of the 0.5" thick aerogel. Figure 8 shows a sample plot of temperature readings on significant locations of the aerogel sandwich and fireplace glass door.

It is important to notice that the density of aerogel used in this investigation varies with sample thickness. This is indicated in Table V. The difference in density between the two thicknesses is driven by the variation in the process to produce the aerogel samples.

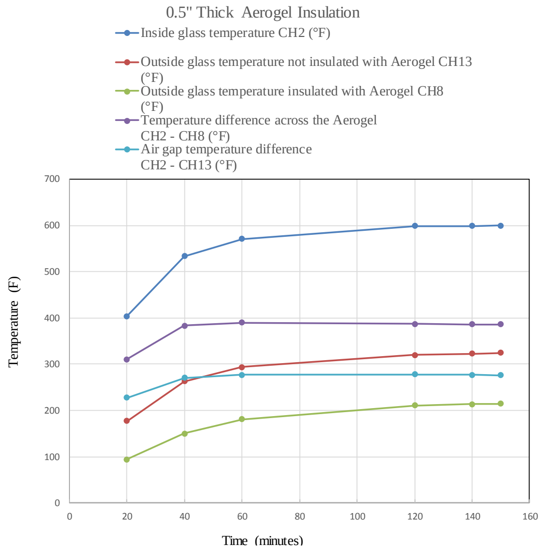

Fig. 7: Temperature variation with time for five significant location of the aerogel sandwich. The case of 0.5" thick aerogel.

TABLE V. VARIATION OF AEROGEL DENSITY WITH THICKNESS

Aerogel Thickness (inch)	Density (grams per cubic centimeter)
1.0	0.21
0.5	0.13

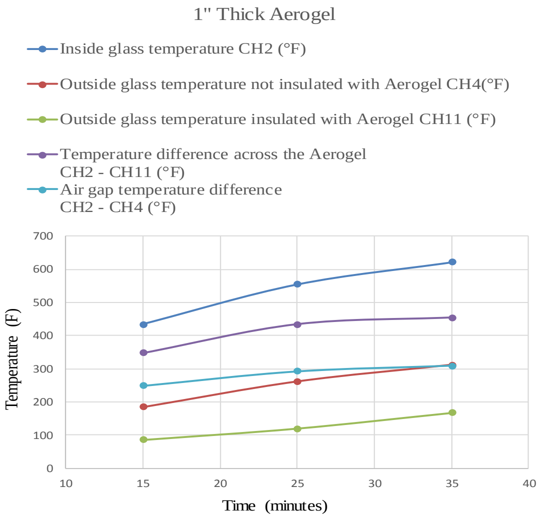

Fig. 8: Temperature variation with time for five significant location of the aerogel sandwich. The case of 1" thick aerogel.

When comparing the outside glass temperature's trend of the 1" thick aerogel with that of 0.5", as shown in Figures 7 and 8, it is clear that the 1" aerogel provides better performance even though its density is more than 50% larger than the 0.5" thick aerogel.

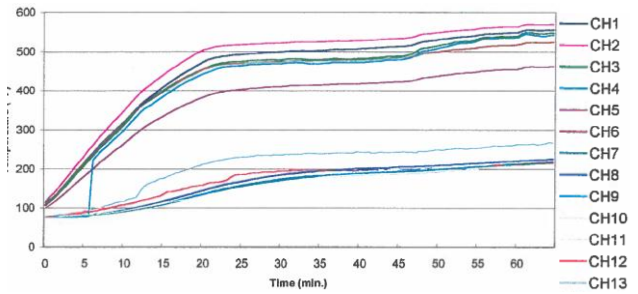

Fig. 9: Temperature variation with time for 13 significant location of the aerogel sandwich. The case of 0.5" thick aerogel.

The next Figures 9 and 10 are sample plots of continuous data acquisition of surface temperature at all locations described before. Temperature variation with time at 13 significant locations is observed. Plots shown in Figure 9 and 10 are showing results for the 0.5" and the 1" thick aerogel respectively.

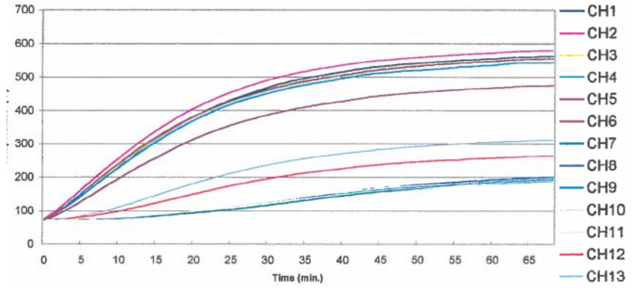

Fig. 10: Temperature variation with time for 13 significant location of the aerogel sandwich. The case of 1" thick aerogel.

It is significant to notice that outsides temperatures of the insulated glass door approached the 200F levels after 60 minutes of operation beyond the first hour. This is indicated in Channel 11 temperature variation with time as shown in both Figure 9 and Figure 10. It is also observed that the rate of temperature increase of the insulated glass is significantly lower than that of the inner glass door temperatures during the first 25 minutes of measurements.

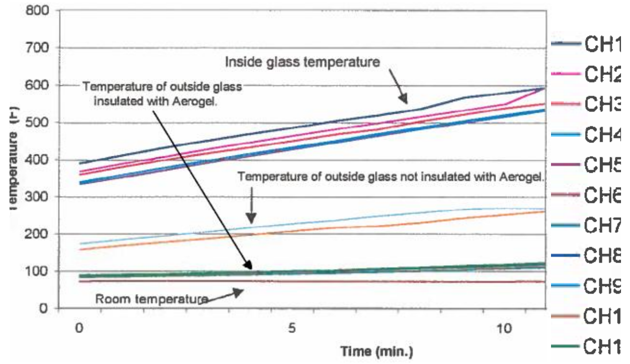

Fig. 11: Temperature variation with time for 12 significant location of the aerogel sandwich during the first 10 minutes of operation. The case of 1" thick aerogel.

For the case of 0.5" thick aerogel, the slope of temperature variation with time for inner surface of the glass door was observed to be 22 F /min, compared to the slope of 7F/min for aerogel-insulated glass as shown in Figure 9.

The data collected from this investigation was also observed at a higher sampling rate in the early minutes after the first hour of operation of the fireplace. This is done to furtherly understand the temperature rise with time during this period. Figure 11 provides a sample plot of such measurements for the case of 1" thick aerogel insulation.

The early minutes temperature measurements establish the fact that low slope of temperature variation with time can be achieved using aerogel insulation. This is important because most child burns from fireplaces are caused during early operation of the fireplace when the fireplace is operated with a flip of a switch and no adult supervision is available. This conclusion is also observed with thinner aerogel insulation in the case of 0.5" thickness.

V. CONCLUSIONS AND RECOMMENDED FUTURE WORK

The pilot work to investigate the feasibility of enhancing child safety from hearth products using aerogel insulation is presented. Preliminary conclusions from the current investigation are as follows:

A. Thermal Performance:

- Rigid and transparent silica aerogel presents a potential insulation material to gas-fired hearth appliances. In specific, insulating the glass doors of gas-fired hearth appliances has shown significant advantages. Greater than 500 F glass door temperatures where lowered to 200 F levels.
- Silica aerogel being transparent enough to preserve to radiative heat transfer to the room, while insulating the conductive heat transfer to the outside glass, is observed.
- Silica aerogel with densities ranging from 0.13 to 0.21 grams per cubic centimeters has shown significant reduction in the rate of change of outside glass temperature compered to uninsulated fireplace glass.
- Early minutes of measurements after the first hour have shown significant flatness of outside temperature. This can provide an early intervention of adults during unintended operation of fireplaces by children.
- Challenges observed in this pilot experiment included slight decay in transparency of silica aerogel posing a risk of lowering radiative heat transfer to the room. It was also observed that silica aerogel high hygroscopy necessitate sealing the aerogel insulation from atmospheric air to prevent moisture from being absorbed by silica aerogel. This fact can increase the cost of utilizing aerogel as an insulation material for the current application.

B. Child Safety Performance:

- Silica aerogel insulation of hearth appliances is a potential material to provide significant opportunity to safeguard children against severe burns from glass doors.
- This investigation provided a pilot procedure to quantify the reduction of outside glass temperature steeply from over 500 F to around 200 F. The required temperature to prevent scalding in children is reported by the American Burn Association as 120 F [21]. Third degree burns in children can occur with 5-second contact with 140 F water [21] to [26].
- It is concluded that aerogel insulation at a feasible 1" thickness can lower the outside glass temperature but not enough to prevent first and second degree burns when contact is extended. The observed outside temperatures of 200 F are not low enough to prevent third degree burns as a preliminary result of this pilot study.
- The current investigation has shown the promise that silica aerogel can lower outside temperature to levels that can prevent severe burns in children if exposure in less than 5 seconds. It is not yet enough to lower outside glass temperature below the 120 F scalding limit set by many safety standards.
- Further investigation of the ability of aerogel insulation of fireplace glass doors to lower temperatures below the 172 F limit set by ANSI and CSA effective Jan 1, 2015.

It is recommended that further studies to be conducted using thicker than 1" silica aerogel to investigate the potential to lower glass temperature below scalding levels. It is also recommended to develop means to seal silica aerogel from moisture in the atmosphere to limit decay in its transparency.

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AUTHOR BRIEF BIOGRAPHY

Dr. Emad Tanbour has more than 24 years combined experience in Mechanical Engineering in both academia and industry. His industry experience spans over 18 years in the areas of product development, energy efficient appliances and sustainability, thermal systems design and engineering management. He is an expert researcher in industry and had been leading industry-academia funded research since 1997. Dr. Tanbour is an innovator with over 13 US pending and issued patents all of which resulted in products sold in North America. Most of his innovations are in the field of sustainable design of domestic and commercial appliances. Dr. Tanbour has advanced knowledge of computer aided engineering, CFD and computational mechanics. He is an expert user and trainer of computer aided design using solid modeling. He has conducted research in the areas of heat transfer, thermal-fluids, and energy systems and led many years of research and development projects in the interdisciplinary areas of Mechanical Engineering. He received his bachelor’s degree in Mechanical Engineering and ranked third over his cohort and received full scholarship to pursue graduate studies towards his Ph.D. in Mechanical Engineering from the University of Iowa. During his studies at Iowa, Dr. Tanbour led the thermal design of all control circuits for NASA Cassini spacecraft that was launched to Saturn. Dr. Tanbour is the recipient of Arch T. Colwell Award from Society of Automotive Engineers and had served for five years as ABET industry consultant. He also received EMBA training courses at the University of Iowa.