CORRELATING SURFACE TEMPERATURE MEASUREMENTS WITH LIQUID LEVELS IN NITROUS OXIDE E CYLINDERS

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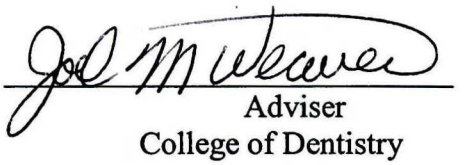

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ABSTRACT

There are several methods described in the literature that may be used to approximate the amount of liquid nitrous oxide that remains within an E cylinder. Currently no one method is both reliable and practical. Weighing the cylinder requires the tedious task of repeatedly removing the tank from its suspension mechanism. The pressure gas gauge, although accurate, does not correspond to the change in weight or volume of nitrous oxide until there is only gas remaining in the tank. This investigation attempted to determine whether the thermal topography of an E cylinder during times of gas flow could be correlated with the location of the liquid gas interface. Initially, the temperature pattern along the entire length of the cylinder during use was studied. Using those results, we subsequently focused on thermal patterns associated adjacent to the region of the meniscus. The height of the meniscus was independently identified using the net weight of the nitrous oxide and a commercially available liquid propane indicator strip. The area located directly beneath this level was then studied while the tank was in use.

We were able to identify repeatable thermal patterns that correlated with the level of the liquid gas interface. The results of this study indicate that using surface temperature measurements of an E cylinder while in use appears to be a practical and reliable method for determining the height of the liquid within the tank.

Dedicated this to my husband, Kevin, for his support, understanding and selflessness throughout this endeavor.

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CHAPTER 1

INTRODUCTION

Throughout history, mankind has sought various ways to alleviate pain, but it was not until the late eighteenth century that modern anesthesia had its beginnings. This was initiated by the development of inhalation agents, and this class of anesthetics remain, to date, a mainstay of many anesthetic regimens. Of all the inhalation agents, nitrous oxide is possibly the oldest anesthetic, and has certainly enjoyed the longest period of frequent use. The development of nitrous oxide is credited to an English scientist, Joseph Priestly, and the recognition of its anesthetic potential was noted by Sir Humphry Davy.[12, 14]

Even today nitrous oxide continues to be one of the most widely used inhalation agents in modern balanced anesthesia techniques used principally in combination with other anesthetic agents. It is also used as a single agent in combination with oxygen to provide anxiolysis and analgesia for patients undergoing minor surgical procedures with or without local anesthesia.

Nitrous oxide is a colorless, non-irritating gas with a slightly sweet odor and taste. It is manufactured by heating ammonium nitrate in a controlled process. It is non-

flammable, however, at 565 degrees Fahrenheit the nitrogen-oxygen bond is broken and oxygen is made available for the support of combustion.

Nitrous oxide exists as a gas at room temperature. Its critical temperature, the temperature above which a gas cannot be liquefied regardless of the amount of pressure applied is 36.5 degrees Celsius. Thus, under normal atmospheric conditions, it can be kept as a liquid without an elaborate refrigeration system.[13]

As a result of these properties, nitrous oxide is stored in metal cylinders under pressure where, under standard temperature, it exists as a liquid and vapor. During clinical use, the pressure above the liquid contents of the cylinder remains constant at 745 pounds per square inch (psi) until the liquid is exhausted.[3, 13] After the last remaining liquid has evaporated, the pressure gauge then reflects the gaseous quantity of the remaining nitrous oxide in a typical linear fashion as described by Boyle's Law. It is only during this latter phase that the volume of nitrous oxide remaining in the cylinder is proportional to the pressure.

An ideal method for identifying the amount of liquid nitrous oxide remaining in the cylinder should be reliable, practical and preferably inexpensive. To date, such a method does not exist. A practitioner using typical in-office E cylinders for the delivery of nitrous oxide has no practical method of determining how much nitrous oxide is remaining until the pressure gauge begins to descend from its standard reading of 745 psi. At this point such a cylinder, originally containing 1590 liters, now has approximately 400 liters of gas remaining.[13] To compensate for the inability to estimate the amount of nitrous oxide remaining in the tank, it is commonplace to maintain a spare supply of nitrous oxide for those occasions when the tank becomes empty.[3]

In order to account for the total amount of nitrous oxide used, one could calculate the total number of liters used based on the liter per minute flow rate multiplied by the number of minutes of use during the procedure. Due to the many alterations of concentration and flow that a practitioner encounters during a usual procedure, it is impractical to manually document the total amount used. One could possibly employ a cumulative flow-meter to quantify the total output of gas by placing this in series with the usual anesthetic circuit. Such a flow meter would need to be positioned prior to the nitrous oxide/oxygen mixing manifold of the standard anesthetic machine to ensure it only accounts for the nitrous oxide dispensed. It would also be necessary to manually reset this each time the tank is replaced. One drawback would be that these flow-meters could only be reliably used for known full tanks. If a partially used tank were connected then the tank would have to be weighed and the remaining liquid nitrous oxide accurately calculated before connecting to the anesthetic circuit.

As suggested, the weight of the cylinder can also be used to calculate the liquid height of remaining nitrous oxide. One would have to obtain the manufacturer specified tank dimensions in addition to some of the physical constants of nitrous oxide to perform the calculation. Repeated weighing of the cylinder would require frequent dismounting from the tank-specific-yoke system from which they are suspended. Unfortunately, repeatedly removing the cylinders from anesthesia-machine yokes is not only tedious, but exposes the connection system (gaskets, pin-index etc.) to increased wear and the possibility of damage. This would also require the scaled blue prints of each tank manufacturer and for each type of cylinder to ensure accurate calculations for each tank weighed.

A more practical approach would be the detection of the liquid level. There are various means by which a level or interface between phases can be detected, both direct and indirect. Methods of direct level measurements utilize physical properties of a substance including but not limited to electrical, optical and thermal properties.[9, 17] A gauge or sight glass may also be used to continuously monitor the position of an interface. In the context of the nitrous oxide cylinder, with its contents maintained under pressure, placing a sight glass in the wall of the cylinder may weaken the integrity of the stainless steel tank. Additionally, it would require the current tanks be either altered or remade entirely causing this method to be potentially dangerous as well as cost prohibitive. On the other hand, employing indirect methods to detect an interface involves converting measurements of some other quantity; a common example is pressure.[9, 17, 20] Another possible method involves using magnetic floats that could be placed in the tank to detect and identify a level. This method would exploit the attraction between two magnets to locate the level.

Other plausible methods of determining the amount of nitrous oxide rely on identifying patterns along the surface of the cylinder. For example, along the surface of the cylinder there are a number of characteristic changes that occur near the liquid gas interface. One such method is the use of sound. Sound waves produce a distinct pattern when passed through a particular medium. A coupled ultrasound transmitter and detector can detect the disparity in oscillations between media.[2, 11] For instance, the propagation of a sound wave through a fluid within a metal container is different when compared to the propagation through an empty metal container. Numerous scientific fields have dedicated research to detecting fluid levels for various purposes using this technology.

Aerospace engineers at NASA have applied ultrasound technology in this manner to detect the hydraulic fluid level in the metal aircraft struts.[2] The United States Bureau of Customs and Border Protection is testing an acoustic inspection device which measures acoustic velocity and attenuation of ultrasonic wave pulses as a way to analyze the liquid contents of sealed contains.[5]

In an unrelated field, agricultural engineers have employed infrared technology to detect differences in heat in order to identify the height of substances being stored in silos.[18] Various substances typically have differing rates of thermal capacitance, as does the same substance in different phases. Thermal capacitance of a certain amount of matter is the quantity of heat, measured in Joules, required to raise its temperature by one degree Kelvin. In general, material in the gas phase will change temperature much more readily than the same substance in the liquid phase. When the silos were analyzed at steady state or thermal equilibrium, no differences were seen. However, when subjected to a thermal transition, such as occurs following sunrise in the case of agricultural silos, the materials or different phases within the tank regions behaved differently.[18]

A fluid-gas interface is also known to have an interesting and characteristic pattern during evaporation. According to the classical kinetic theory, there are sharp changes in temperature near the interface of an evaporating liquid; the liquid being warmer than the gas. When studying steady state evaporation in the past, the thermocouples used could only measure within 27mean free paths or 0.5mm of the interface. Recent research by Fang and Ward were able to measure temperature within one mean free path of the interface of an evaporating liquid. Contrary to the classic theory, their results indicated that it was in fact the higher energy molecules that escaped

the liquid during evaporation, and the temperature of the evaporated molecules at the interface was greater than those still in the liquid phase.[7] Hence, they demonstrated a discontinuity in temperature across the interface that is much larger in magnitude and in the opposite direction to that predicted by the classical kinetic theory.[7] This temperature gradient at the liquid-gas interface was found to be as large as 7.8 degrees Celsius depending on the rate of evaporation. These findings suggest that the temperature gradient generated by the neighboring gas and liquid phase may be unique enough and apparent enough, that even through metal cylinders, it can be detected and used as an aid in the determination of the location of the meniscus.

Our investigation set out to analyze the temperature changes along the surface of a commonly used E cylinder (Figure 6) to ascertain whether or not features of this surface profile could be used to determine the height of the remaining liquid. Guided by the principles of liquid evaporation and fluid-gas interface temperature gradients, we undertook an investigation to establish the changes in surface temperature patterns along a nitrous oxide cylinder during constant use. Our aim with this research project was to determine the usefulness of cylinder surface temperature characteristics, during use, as a method of determining the fluid / gas interface (level of the meniscus) and therefore the remaining volume of liquid nitrous oxide.

We proposed dividing the research into two phases. A preliminary investigation was undertaken to analyze the surface temperature changes of a nitrous oxide cylinder during constant use. Secondly we set out to analyze the cylinder surface temperature in the vicinity of the calculated meniscus during constant use.

CHAPTER 2

MATERIALS AND METHODS

Preliminary Investigation:

Each tank, labeled A, B and C, was individually weighed on a balance (Detecto-Medic, Detecto Inc. Brooklyn, NY). For each cylinder, the weight of nitrous oxide was obtained by subtracting the tare weight specific for that tank, engraved into the surface of each tank, from the measured gross weight. The density of nitrous oxide under standard atmospheric conditions is 1222.8 kg/m^3.[4] Using this information the volume (V) of nitrous oxide was calculated.

The technical specifications used for the manufacturing of the nitrous oxide E cylinders are displayed in Figure 6. From this diagram, the internal diameter of these tanks is stated to be 102.01 millimeters (mm), making the radius (r) 51.005mm. Substituting 3.141592 for pi (π) in the standard equation for calculating volume in a cylinder, ($V = \pi r^2 h$), the liquid column height (h) of nitrous oxide in each cylinder was obtained. This was marked on the external surface of each tank.

The tanks were then mounted to the yoke system specific for nitrous oxide on the anesthesia delivery unit and left in that environment for eight to twelve hours to

equilibrate to the room temperature. Successful equilibration was confirmed by placing the sensor (Omega Handheld Microprocessor Digital Thermometer) along the cylinder surface and demonstrating that the surface temperature variance along the cylinder was within 0.6°C. According to the manufacturer unit specifications, the thermosensor is accurate to within 0.6°C.

Beginning at the base of each tank, nine markings were made along the length of the tank spaced ten centimeters apart. Each marking was designated by a letter, 'A' at the most superior point, through the letter 'I' at the most inferior aspect.

The single point temperature sensor was mounted in an insulating block of Styrofoam so that only the recording surface was exposed and could be placed in firm contact with the cylinder surface. A small amount of silicone based heat sink compound was placed at each of the designated temperature recording sites. The gas cylinder was opened and a flow rate of four liters per minute was established. The temperature readings were measured and documented every 15 minutes for 120 minutes. The single sensor was moved from site A to site I in a sequential manner. At each site the sensor was held in place until no further change in recorded temperature was observed over a period of thirty seconds. This process was repeated for two additional nitrous oxide cylinders.

Secondary Investigation:

The second component of this investigation began similarly. Each tank, labeled Y and Z, was individually weighed on a balance (Detecto-Medic, Detecto Inc. Brooklyn, NY) and the net fluid weight was obtained by subtracting the tare weight from the total weight. Again using the technical description for an E cylinder construction provided by the

manufacturer (Figure 6), the fluid level within the cylinder was calculated. Each corresponding height was measured and marked on the appropriate tank. In addition a common propane tank indicator (Dynaview patented LP Level Indicator, Buffalo, New York) was attached lengthwise to the side of the tank such that the calculated meniscus was midway along the length of the indicator strip. Boiling water was poured over the tank generating a detectable temperature differential between the liquid and gas phases allowing the location of the meniscus to become evident on the indicating strip. The level of the meniscus indicated by the propane strip was then marked on each tank. Any discrepancy between the calculated height and the one obtained by using the propane-indicating strip, was compensated for by placing the uppermost sensor 2cm below the lesser of the two heights to ensure that the position of the meniscus would detected by the probes during its descent.

The tanks were then mounted to the yoke system specific for nitrous oxide on the anesthesia delivery unit and allowed to re-equilibrate to room temperature overnight.

For this portion of the investigation, a multi-sensor logging unit was acquired (HOBO U12 Temperature Data Logger, Onset). Each of the four probes (T1, T2, T3, T4) was connected to the data logger, with probe T1 located superiorly and T4 inferiorly. The temperature probes were mounted in a Styrofoam block and spaced 1.5cm apart. The sensors were placed vertically with T1 located superiorly. The data logger was programmed to record the temperature of each probe simultaneously at thirty second intervals. Silicone based heat sink compound was applied to each of the four temperature sensors. A uniform tank temperature was confirmed by the readings of the individual sensor temperatures after positioning on the tank surface. Prior to commencing gas flow,

each probe had to demonstrate a cylinder surface temperature variance of less than or equal to 0.5˚C. According to the manufacturer, the accuracy of the data logger is 0.35˚C between temperature readings of 0-50˚C.

The nitrous oxide cylinder was then opened and the flow-meters were set to a flow of four liters per minute for nitrous oxide and two liters per minute for oxygen. This ratio of two-thirds nitrous oxide is a common concentration used in clinical practice. In order not to allow the nitrous oxide/oxygen mixture to disperse into the laboratory, the mixture exiting the delivery unit was evacuated immediately to suction. At the conclusion of the investigation, each cylinder was reweighed and the liquid height recalculated to ensure that the meniscus had passed all four temperature sensors and was at least 1cm below the lowest sensor.

CHAPTER 3

RESULTS

Preliminary Investigation

The gross weight of the studied tanks ranged from 19.2lbs (8.64kg) to 20.2lbs (9.09kg) with a mean of 19.53lbs (8.87kg). The stamped tare weight of the cylinders averaged 13.2lbs (6.0kg) so that each tank was filled with a mean of 6.3lbs or 2.84kg with a range of 5.8 to 7.0lbs (2.34-3.15kg) of nitrous oxide. The manufacturer's product information gave this value as 6.41lbs (2.91) kg.

The surface temperature along the length of the cylinders, after 12 hours in a constant environment, was for tank A 19.3° C (range 19.0° – 19.5°C), tank C 20.8° (range 20.6° – 20.9°C), and tank B 21.8 C (range 21.5° – 22.0°C). The maximal temperature variation was 0.5° Celsius in any given cylinder. The average tank temperature corresponded within one degree Celsius of the thermostat registered room temperature.

After setting a constant flow of 4 liters per minute (lpm) the surface temperature of the compressed nitrous oxide cylinders decreased in a steady and uniform manner for the first 15 minutes. The decline in temperature continued between 15 and 30 minutes

with the extent of change lessening in the readings of the upper three thermistors (A, B & C), particularly in tanks A and C. The lower markers (D through I) continued to have steep descent during this time. This change in rate of temperature loss in the upper regions of the tank became more evident between 30 and 45 minutes. Between 45 and 60 minutes the readings at point D demonstrated an abrupt change in the rate of temperature loss with continued cylinder use. At this interval the decline at point D was observed to mimic the thermal changes of markers A through C. From this time, until the completion of the investigation, the temperature at point D remained reasonably stable. The remaining temperature registration at points E through I retained their much steeper rate of descent during this period demonstrating a significant and steady decrease in the recordings. The descent at these points (E through I) fell within a range of 1.6-1.8˚C in tank A, 1.5 to 2.3˚C in tank C, 2.1-2.6˚C in tank B for the 45-60 minute period.

Between the 60 and 75 minute interval, the rate of decline at point E displayed an alteration in its rate and began to imitate all points located above it. The temperature recordings for point E from this time onward remained relatively consistent until the conclusion of the investigation. Thermistors G, H and I then descended uniformly from the 75 minute mark until the termination of the study period.

In general the uppermost portion of a tank demonstrated a mild to moderate decline in thermal readings. In this region, tank A displayed the least thermal change descending from 19.5° to 16.7° Celsius, a difference of 1.8° Celsius, whereas tank B demonstrated the most significant drop of 6.3 ° Celsius from 22.0° to 15.7°. The temperature readings of Tank C in this region declined from 20.7° to 17.1°, a difference of 3.6° Celsius.

During the study period the coldest reading, at any given time, migrated steadily toward the base of the cylinder. For the duration of the investigation, the nadir was not located at the base of the cylinder. At all observed times the coldest point was found to be at a variable distance from the cylinder base and all readings inferior to this trended upward. There was, in general, an overall decline in tank temperature and an increasing disparity between the measurements at points A and I. By the completion of the experiment the differential between A and I was 10.5° C, 10.7° C and 12.8° C in tanks A, C, and B, respectively.

Points F and G both located in the lower portion of the tank were noted to have a significant decrease in temperature over the length of the experiment. Tank A showed a decent at point F from 19.1° C to 5.6°, a difference of 13.5°C. Tank B was noted to have the largest differential, an 18.2° difference in temperature measurements at point F over the 120 minute experiment. Tank C illustrated a modest fall in temperature of 15.7°C at point G.

The results of the second phase of our investigation are as follow:-

The gross weight of the studied tanks ranged from 19.7lbs (8.95kg) to 20.3lbs (9.23kg) with a mean of 20.0lbs (9.09kg). The stamped tare weight of the cylinders averaged 13.6lbs (6.2kg) so that each tank was filled with a mean of 6.4lbs or 2.91kg with a range of 6.3 to 6.5lbs (2.86-2.95kg) of nitrous oxide. The manufacturer's product information gave this value as 6.41lbs (2.91) kg.

The liquid height calculated using the weight measurements obtained were 28.6cm, 29.3cm for tanks Y and Z respectively. The height values acquired with the

propane indicating strips were 27.9cm (tank Y) and 28.9cm (tank Z), a discrepancy of 0.7cm and 0.4cm

Both tanks demonstrated a state of uniform surface temperature for the region being recorded. As soon as the tank was opened and the gas allowed to escape at a rate of 4 lpm there was a rapid and almost immediate descent in surface temperature demonstrated in all four probes. The four adjacent recordings also were observed to have a homogeneous negative slope or uniform decline in temperature per unit time.

The probe located most superiorly, T1, was the first to exhibit an abrupt change in its direction reaching its lowest temperature of 13.64 in tank Y and 11.273˚C in tank Z. T1 began to show a steady rise in temperature readings, causing a complete reverse in its slope. This climb continued until the conclusion of the study, resulting in a difference that averaged 1.49˚C from its lowest reading. At this point the three probes located inferior to T1 maintained their uniform descent.

Less than twenty minutes following the change in the slope of T1, there was a noticeable and sudden rise in temperature readings registered in probe T2. The lowest reading reached was 12.98˚C in tank Y and 10.516˚C in tank Z. From this point until the conclusion of the study, the temperature at T2 rose between 1.13˚C and 1.39˚C. The rate of ascent in T2 from that point forward mimicked the rate of rise in T1. At this point and for the next twenty minutes the two lower probes, T3 and T4, continued their consistent pattern of decline.

At this point, a similar event occurred in the readings of probe T3. There seemed to be an immediate shift from the consistent decrease to a steady ascent. The lowest temperature recording for the T3 probe was 9.46˚C in tank Y and 11.88˚C in tank Z, at

which point it then rose by greater than a whole degree Celsius in both tanks by the end of the study period forty minutes later. The probe T4 continued down its original path of decline through this time.

Finally, approximately twenty minutes following the change in probe T3 a similar occurrence appeared in probe T4. After reaching its nadir temperature reading at 11.13˚C in tank Y and 8.717˚C in tank Z, there was a reversal of its original negative slope to a positive one. By the conclusion of the study, the temperature reading at T4 had risen by less than one degree Celsius yet mimicking the ascent of the other three probes.

The net weight of the cylinders at the conclusion of the investigation was 3.3lbs (1.5kg) for tank Y and 3.7lbs (1.68 kg) for tank Z. From these weight measurements, the liquid height calculated for tanks Y and Z were 15cm and 17 CM respectively. This confirmed that the fluid level had traversed all four temperature probe sites.

CHAPTER 4

DISCUSSION

It would be ideal if the method for identifying the amount of liquid nitrous oxide remaining in the cylinder was practical, reliable and preferably inexpensive. So far, a single method meeting all of these criteria does not exist. There are several methods explained in the literature to assess the quantity of nitrous oxide within a cylinder. If the tare weight of all cylinders were dependable, then weighing the cylinders may be reliable. However, the act of repeatedly removing and remounting the cylinders from the suspension mechanism associated with modern anesthetic machines is impractical and potentially damaging to the suspension mechanism. The pressure gauge is also not an effective means by which an operator can estimate the quantity of liquid nitrous oxide left. As has already been observed, the saturated vapor pressure of nitrous oxide under standard conditions remains 745 psi even though both the weight and volume of the cylinder contents are decreasing.[3] The correlation between pressure and volume described by Boyle's Law exists only when all liquid has evaporated. At this point in an E cylinder, common estimates of residual nitrous oxide gas are generally quoted as being approximately 400L.[13]

Results from other studies indicate that characteristic changes in surface temperature could prove to be a practical and reliable method for determining the height of the liquid.[18, 21] If this were the case then anesthesiologists would readily be able to predetermine the volume of remaining nitrous oxide at which he/she would wish to be alerted and place a temperature-sensitive marker at this point.

Individually, the net weight disparity of the cylinder contents, in this study, was within 0.6lbs of the manufacturer's stated guidelines for filling E cylinders. However, the average net weight determined for the cylinders used in the preliminary investigation was 6.3lbs, less than a two percent difference from the 6.4lb manufacturer guidelines. For those tanks used in the second part of the study, the average net weight of the cylinders was in fact 6.4lbs.

The temperatures taken at rest along the surface of each tank corresponded to the room temperature in which they were kept in the several hours leading up to the investigation. According to the manufacturer, the inherent accuracy of the Omega thermal sensors is 0.6˚C. The readings registered at time zero for the initial study displayed minimal variations in thermal readings of 0.5˚C and could have be attributed to probe discrepancy.

The controlled escape of nitrous oxide vapors from the tank was initially accompanied by a uniform cooling observed along the entire surface of the cylinder. This suggests that static equilibrium between the liquid and gas phases within the tank is altered immediately upon opening of the cylinder. As the vapors escape, evaporation is occurring at the liquid gas interface with the liquid being used as a reservoir. This response is one classically expected and has been demonstrated in more general

investigations such as is summarized in the following chart (Figure 7) and reported by the School of Aerospace at Tsinghua Space Center, China.[21] This figure describes the temperature change reported in their study during the removal of liquefied gas from a storage tank and shows a sharp cooling experienced during the liquid vaporization. This cooling was also responsible for an associated sharp pressure drop within the container after which the evaporation slowed down.

The energy required to overcome the attractive forces between the molecules in the liquid state in order to enter the gaseous phase is known as the latent heat of vaporization.[16] It varies for every substance and is dependent on intra and intermolecular forces and surrounding atmospheric pressure. For nitrous oxide, at standard atmospheric pressure, it is 376.1 kJ/kg.[1,4] The energy needed for the continued phase change begins with the surroundings intimate with the interface, utilizing the potential energy stored in this environment. It is during this period of evaporation that there is a shift in energy of the neighboring molecules and thus an alteration in the adjacent temperatures. If the energy required for vaporization were acquired evenly from the environment surrounding the liquid gas interface, then a decrease in the temperature of both phases would be expected.

It appears from our observation that upon opening the pressurized cylinder, the energy for this process is preferentially acquired from the liquid phase. It is in the liquid phase that we recorded the largest change in temperature. This change in the previous static equilibrium is most likely driven by the active evaporation that is occurring at the liquid gas interface as lost gas is replenished with fresh gas from the surface of the liquid. This would seem a logical process since the saturated vapor pressure of nitrous oxide is

5070kPa at 21.1 °C and would drive the evaporation of the liquid as long as the pressure surrounding the open tank were less than the vapor pressure of nitrous oxide.

After the initial temperature drop there was a decrease in the rate of decline of the sensors positioned in the upper third of the tank, suggesting their location to be in the gaseous phase. At the 45 minute marker, the top three sensors A, B, C demonstrated a steady leveling and little variation in their readings was noted for the remainder of the study. As the study progressed, it was noticed that there evolved a widening differential between adjacent markers situated in the middle of the tank. This disparity of the centrally located markers could be explained by the research of Fang and Ward which suggests a relatively large difference in temperature between liquid and gaseous molecules bordering the interface during evaporation.[7] Those sensors located in the lower portion continued with the original pattern of descent. This would suggest, that for the entire duration of the study, sensors F through I were positioned solely in the liquid phase and was confirmed by the calculation of the height of the meniscus at the end of the investigation.

The fact that in this preliminary part of the investigation, the lowest temperature was recorded at a point above the base of the cylinder is probably also best explained as a result of the balance between two paths of energy transfer. First, the constant extraction of energy in the form of heat from the neighboring fluid leads to a continued temperature decline commencing at the evaporation surface that extends linearly with time to more distant areas of the fluid body. Secondly, the delivery of heat energy is also acquired from the surrounding room atmosphere and conducted through the metal container and its liquid contents. It appears that an equilibrium is reached at a point within the liquid

above the base of the cylinder and below the fluid meniscus. The transfer of energy from the surrounding atmosphere is evidenced by condensation which regularly forms during use. This would also explain the migration of the coldest temperature toward the base of the cylinder as the liquid source evaporates and the level of the meniscus falls. If the length of the experiment were extended, the coldest temperature would eventually register at the most inferior point on the tank.

One could speculate that if the nitrous oxide had been set to flow at a rate higher than that done during the study, the time required to produce the thermal patterns detected in this investigation may have been shortened. In fact higher flows accompanied by an increased rate of evaporation could potentially widen the temperature differential observed at meniscus. Fang and Ward in their highly controlled observations demonstrated that increasing the rate of evaporation amplified the separation in temperature measurements between the molecules in the liquid phase and those in the adjacent vapor layer.[7]

For the second component of our investigation, the level of the liquid gas interface was determined using two different methods. In both cases the calculated level was larger than the level achieved through utilizing the commercial propane indicating strip. The calculated height was 0.4-0.7cm more, a difference of 1.3-2.4%. This error may be a result of nuances in temperature changes that are designed into the propane tank indicator strip and unique to the thermal characteristics of propane. Another source of error is the quantity of hot water used to activate the thermal indicator strips. We did not accurately determine the temperature or quantify of hot water used to change the

temperature strips. This could have theoretically contributed to variations in indicated fluid level.

The temperature readings gathered in the second investigation, prior to commencing the gas flow, not only correlated with room temperature, but were all within 0.2˚C of each other. According to Onset, the manufacturer of the Data Logger and temperature probes used in this study, the thermistors have a guaranteed accuracy of 0.35˚C when measuring temperatures between 0˚C and 50˚C.

In the second phase of the investigation, all four probes were placed in the liquid phase according to the height values obtained from both the weight calculations and the one acquired by using the commercial indicator. Initially, the temperature recordings coincided with the registered room temperature. There was some concern that the conductivity of the stainless steel, the major component of the cylinder, could have skewed the results and masked the actual underlying temperature changes. Interestingly, wide ranges in temperature measurements, up to 3 or 4 degrees Celsius, were observed over a very limited distance despite the high heat conductivity of metal compounds.

Once the tank was opened and the gas released at a flow of 4 lpm, there was a uniform and almost immediate descent noted in all four probes. This demonstration can probably be attributed to the extraction of heat from the liquid phase to supply the energy needed to vaporize the nitrous oxide fluid to gas. The abrupt change that was later noted in each of the four probes occurred in succession and is most probably to be attributed to the fall in the level of the fluid meniscus below the corresponding sensor. It was also noted that these changes were reproducible and occurred over similar time frames in both

tanks tested. Although the actual temperature values in each tank were different, the level of descent observed in each probe was comparable.

With continued evaporation, and after the liquid level descended below the recording sensor, there was a gradual but steady rise in the temperature readings in the sensors adjacent to the gas phase. This steady rise in temperature is difficult to explain and cannot be explicated by a simple difference in potential energy reserve in the differing phases. These findings are nevertheless supported by observations made by Tsinghua Space Center, China and Fang and Ward and during the initial component of our study.[7,21]

Having demonstrated that unique changes in temperature occur on the surface of a nitrous oxide cylinder during use, it now needs to be incorporated into the development taking place in thermally active materials. Methods for potentially identifying this differential already exist. Temperature-sensitive paint could possibly be formulated for the required temperature range and generated to identify two adjacent areas when a temperature differential of greater than two degrees in exists. Liquid crystal thermography contains chemical compounds and mixtures which exhibit the mechanical properties of liquids and the optical properties of solids.[6] Thermochromic liquid crystals change color with respect to changes in temperature and may be formulated to respond to various ranges in temperature. Linearly arranged and adjacent crystal strips could possibly be successfully created for use with nitrous oxide cylinders. Those available commercially, for use with methane tanks, were however disappointing and showed no correlation to the nitrous oxide liquid gas interface during our experiments. Initial findings reported by Global Security concerning the use of biologic heat seeking systems

are also very promising. The United States military is focusing on the physiologic and the molecular dynamics of snake proteins as extremely sensitive heat sensors. Such an array of proteins with the ability to detect very fine temperature changes, as small as two thousandths of a degree, are exciting and will theoretically provide the ability to produce a sensor that can detect a range of thermal patterns possibly within a single and flexible sensor.[8] Most useful in our field of study will be the development of a sensor that can detect changes in temperature or temperature differences rather than absolute temperature measurements.

This study supports the idea that such a sensor would then have a useful role in the detection of fluid levels within a metal cylinder and would be of practical value for use in nitrous oxide cylinders.

CHAPTER 5

CONCLUSION

The surface temperature measurements of a metal nitrous oxide cylinder recorded during use suggest a unique thermal pattern by which the height of the liquid contents could be discerned. There was a marked difference in surface-temperature changes that developed at points immediately above and below the calculated liquid-gas interface of nitrous oxide in a standard E cylinder during use. Further study, however, is needed to determine the influence of evaporation time and evaporation rate on the temperatures found in the vicinity of the liquid gas interface and to investigate the design of a probe that would efficiently register this difference in a clinical environment.

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APPENDIX

CHARTS AND GRAPHS

TABLE 1 – Temperature degrees Celsuis for Tanks A, B, C

POINTS ON TANK	TIME IN MINUTES 0	15	30	45	60	75	90	105	120
TANK A									
A	19.5	17.4	17.1	16.8	16.7	17	16.7	16.9	17.2
B	19.3	17	16.6	16.2	15.9	16	19.5	16.2	16.2
C	19.2	16.2	15.6	15.1	14.6	14.6	14.5	15	15
D	19.2	16	14.3	13.4	12.7	12.9	12.5	13.5	13.1
E	19.2	16.3	14.7	12.8	11	9.9	9.1	10.3	9.8
F	19.1	16.5	14.8	12.9	11.3	10.2	8.4	7.8	5.6
G	19.1	16.8	14.8	13	11.3	10.2	8.6	7.6	6.1
H	19	16.8	15	13.2	11.6	10.5	8.8	8	6.2
I	19	17	15.1	13.4	11.8	10.7	9.1	8	6.7
TANK B									
A	22	19.4	17.8	16.9	16.6	16	15.7	15.7	16.1
B	21.9	19.1	17.5	16.3	15.7	15.2	14.8	15.2	15.3
C	22	18.7	17	15.4	14.7	13.9	13.4	13.5	13.7
D	21.9	19.1	16.7	13.8	12.7	11.9	11.6	11.3	11.7
E	21.9	19.2	16.8	14.4	11.8	9.3	7.9	8	7.8
F	21.9	19.3	17	14.3	12.2	9.5	6.4	4.9	3.5
G	21.8	19.4	17.1	14.5	12.2	9.7	6.7	5	2.8
H	21.7	19.6	17.3	14.8	12.4	9.7	7.1	5.2	3
I	21.5	19.7	17.2	15.1	12.6	10	7.5	5.5	3.3
TANK C									
A	20.7	18.4	17.6	17.1	17	17.1	17.1	17.1	17.2
B	20.8	18.2	17.2	16.6	16.4	16.7	16.5	16.9	16.6
C	20.8	18	16.8	16	15.6	15.6	15.7	15.5	15.7
D	20.9	17.6	16	15	14.3	14	13.9	14.1	14.2
E	20.8	17.7	15.6	13.7	12.1	11.5	11.5	11.7	11.6
F	20.8	17.9	15.7	13.9	11.6	10.2	7.5	8	7.9
G	20.9	18	16.1	14.1	12	10.5	7.7	6.2	5.2
H	20.8	18.2	16	14.2	12.3	10.8	8.1	7	5.7
I	20.6	18.4	16.3	14.6	13.1	11.8	8.4	7.2	6.5

Figure 1 - TANK A

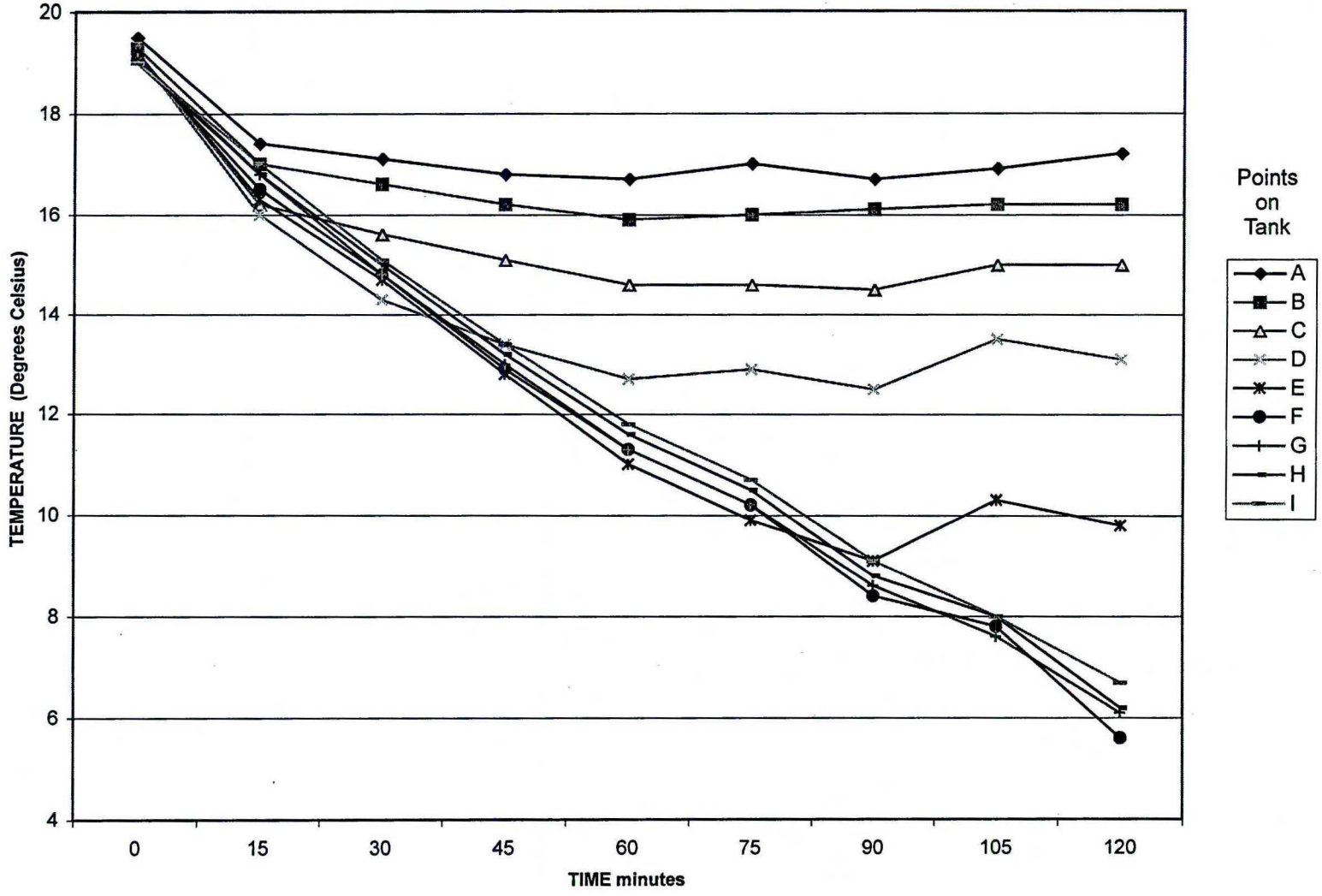

Figure 2 - TANK B

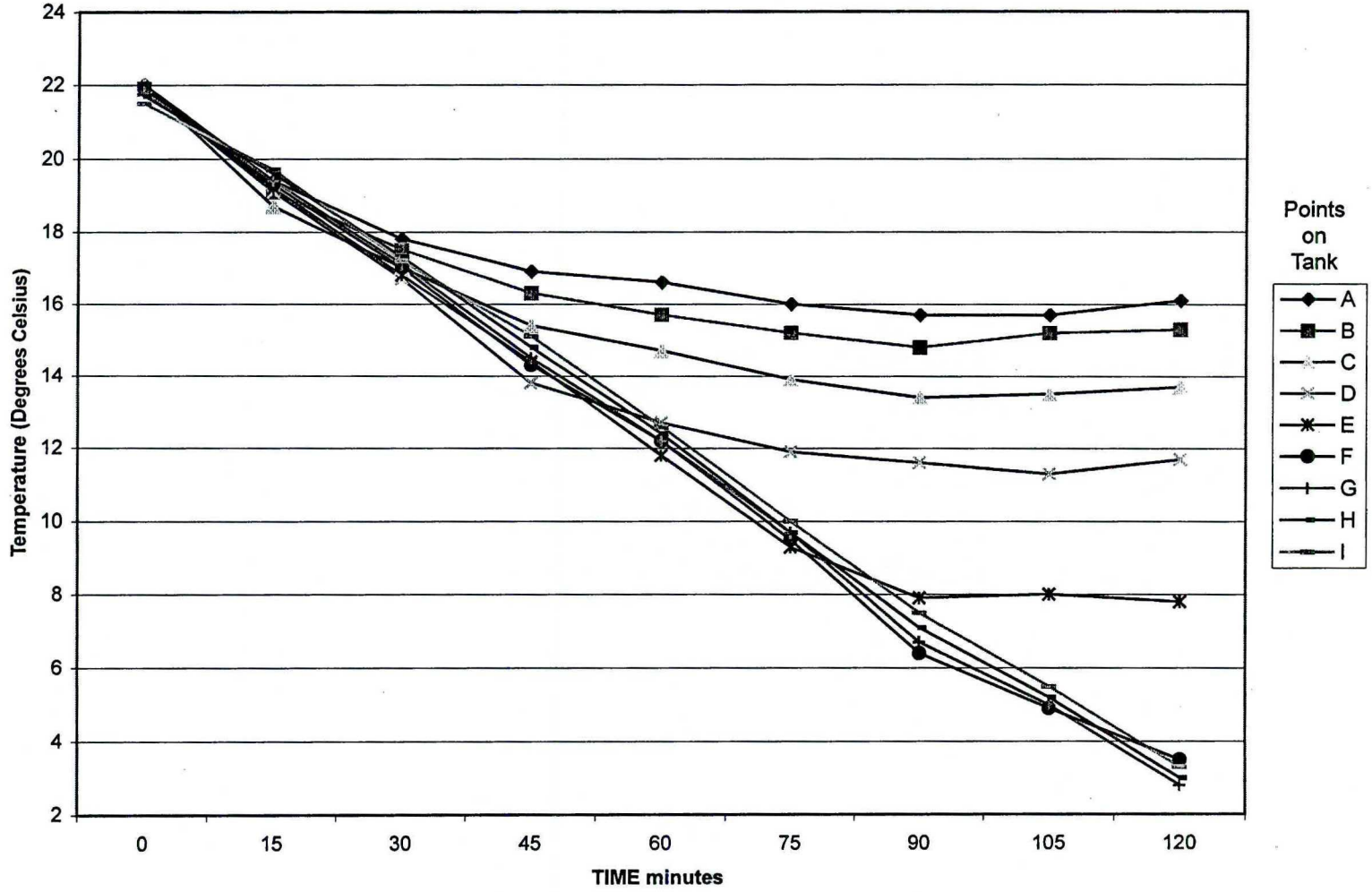

Figure 3 - TANK C

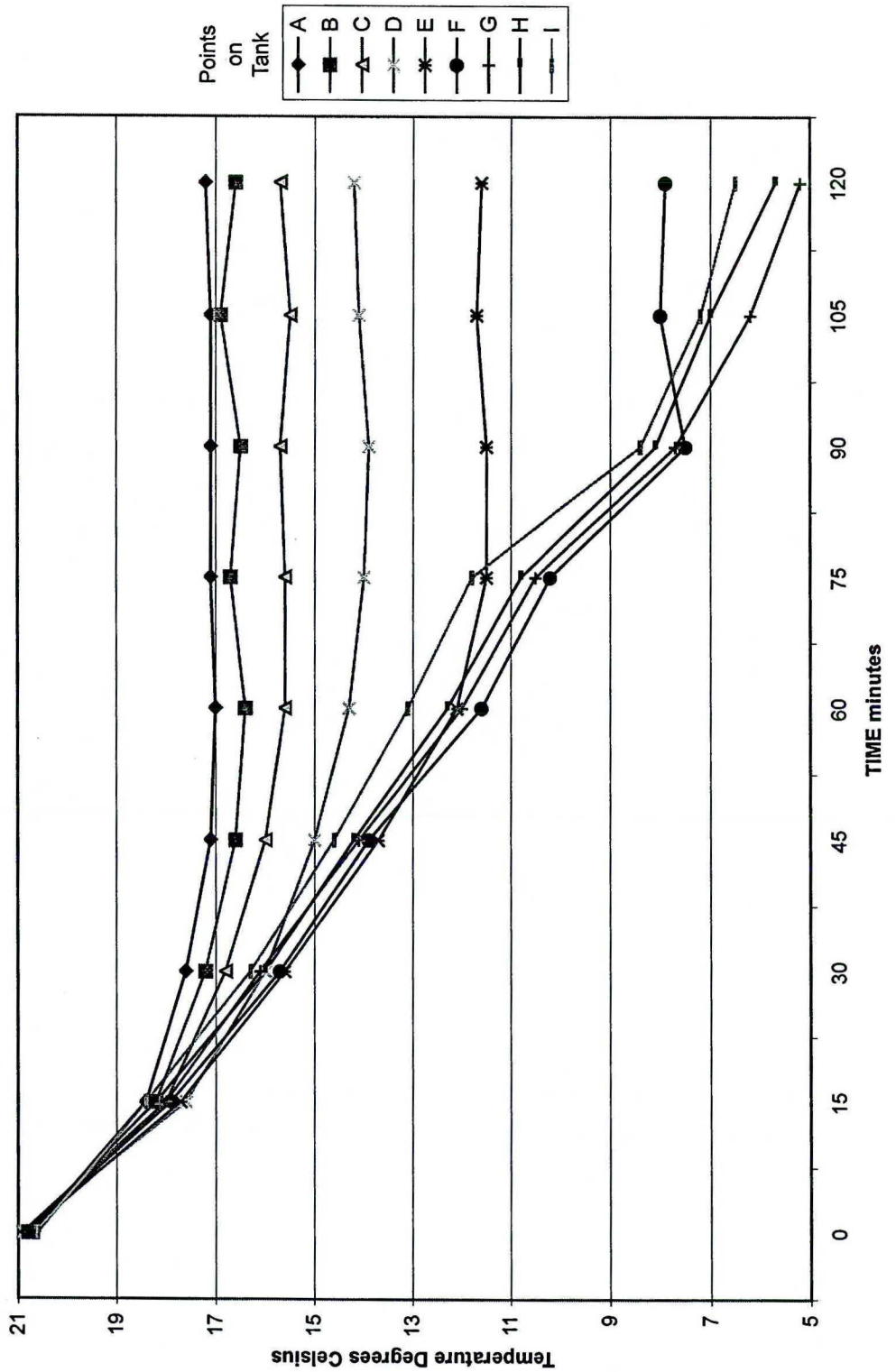

Figure 4 - TANK Y

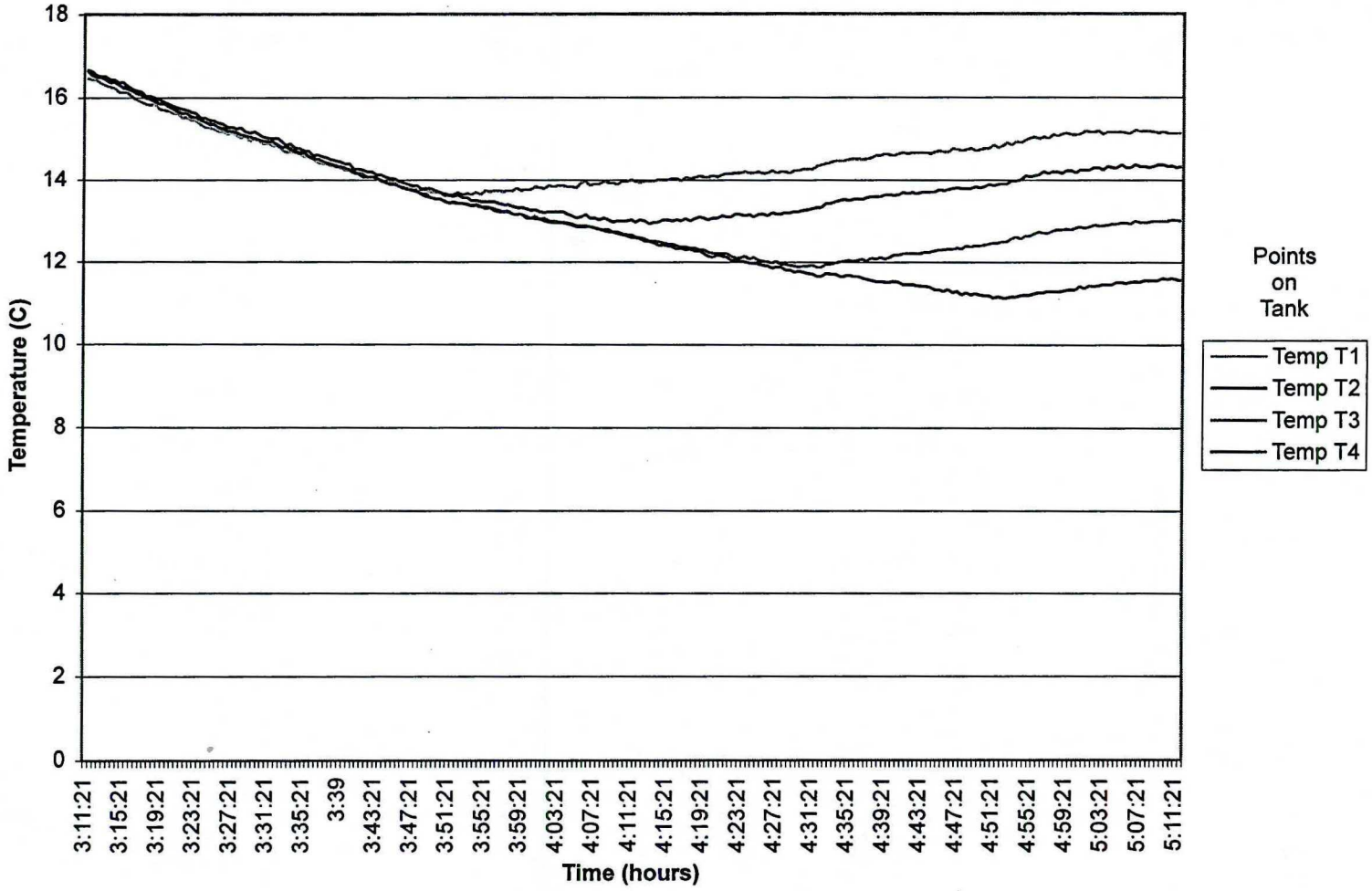

Figure 5 - TANK Z

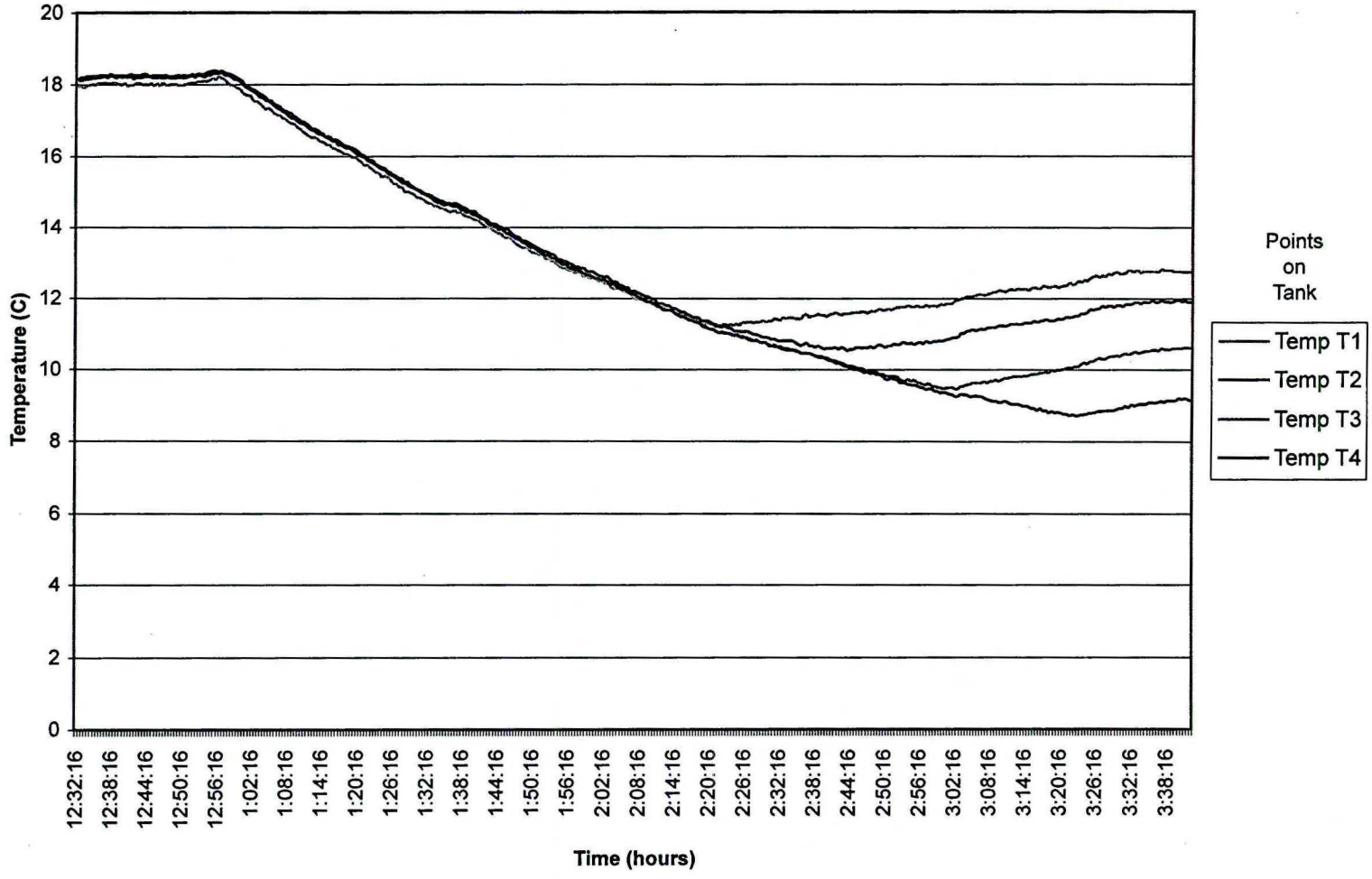

Figure 6 – Manufacturer E cylinder dimensions

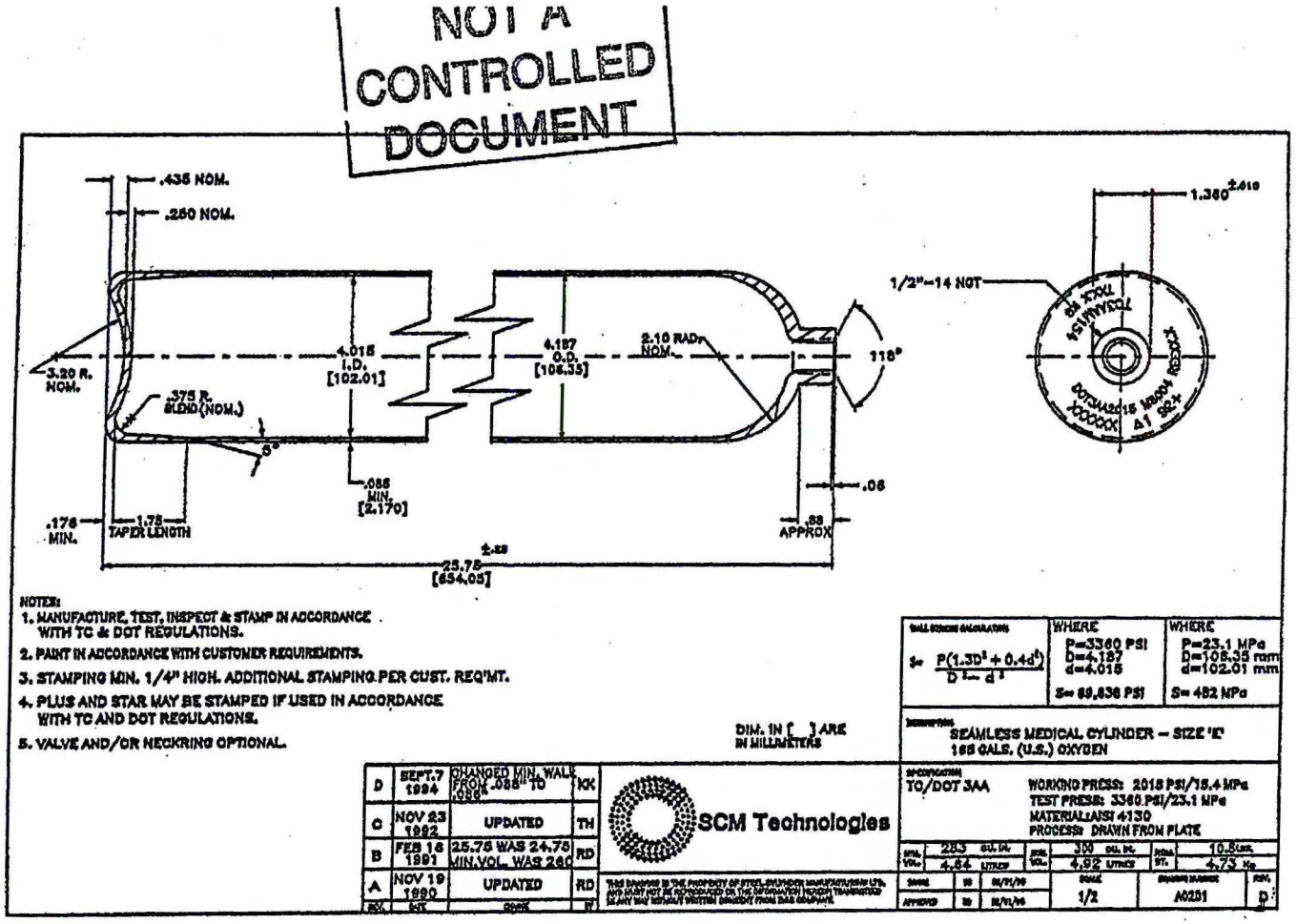

Figure 7

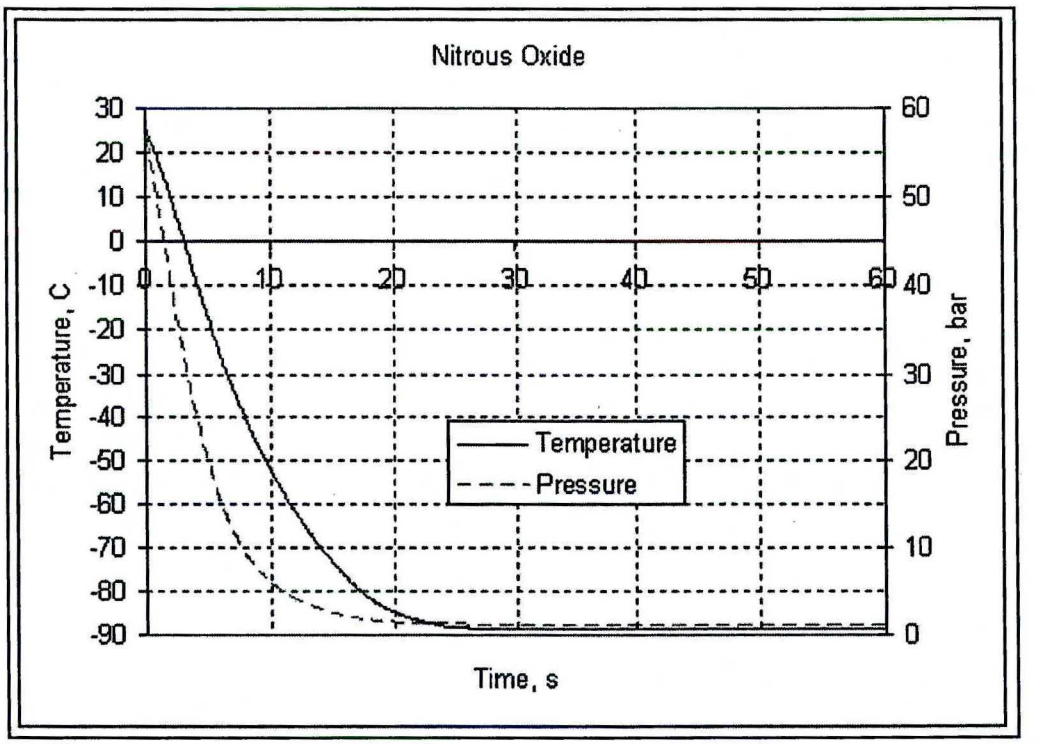

Figure 7: Liquefied gas temperature and pressure during evaporation