# The effective power output of the Taurus 301 blood warmer when warming small volume units of red cell concentrate described using simulated blood products

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## Declaration

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## Format and Acknowledgements

Professor Ian Mason is acknowledged for his role in the development of a remarkable medical device, and moreover, for supporting this effort to fully understand the same.

This manuscript has been made to comply with the University of Cape Town guidelines of 2017 for MMed minor dissertations and will adopt the monograph format.

Referencing is as per the Vancouver style.

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# Abstract


**Background and Literature review**
At Groote Schuur Hospital, the lead anaesthesiologist in the cardiothoracic team, J. Ozinsky, identified the need for a device capable of warming blood rapidly prior to transfusion. Such a device was subsequently developed as a collaborative effort between the Department of Anaesthetics and Department of Electrical Engineering at the University of Cape Town. The device became known as the "Taurus" blood warmer, namesake of the Head of Department at the time, and clinical leader of the project, Prof. A.B. Bull. A subsequent version of the Taurus, which warms blood within the bag in which it is packaged, remains in active clinical service at Groote Schuur Hospital.

Literature search reveals that devices which employed electromagnetic radiation for warming of blood and blood products were met with resistance following many case reports of haemolysis induced by warming. A common theme identified was that of elevated risk of haemolysis, due to local overheating, in blood products of high haematocrit (HCT) and small volume. The Taurus 301 performance has been evaluated extensively and the device used for over 30 years. Without any literature available to suggest that the device is overtly harmful it may be concluded that the device design is one that may be drawn upon with confidence especially for these blood products at elevated risk of haemolysis. The Taurus range of blood warmers represent the only examples of a radio-frequency blood warmers that were made available commercially for clinical use.

In 1996 fire swept through the factory responsible for manufacture of Taurus blood warmers. Taurus manufacturing capability was not restored and more than a quarter century has now passed since the last Taurus 301 was commissioned. Taurus devices may still be found in active service within some South African hospitals.(1) The author has also observed the scrapping of at least 3 units from the Groote Schuur Hospital Complex over the past 5 years and, if the situation parallels that of other hospitals, the Taurus may soon be lost to clinical practice.

**Research questions**
The mean effective power output of the Taurus 301, when used for the warming of small volume units of red cell concentrate, in the setting of massive transfusion, prior to this study, was unknown. The primary aim of this study was to describe the mean effective power output of the Taurus 301 in this context.

To realise this aim, four identical bags of simulated, small volume, red cell concentrate were prepared and cooled to 4 $^{o}$C before being warmed sequentially using a Taurus 301 which remains in active service. For each warming instance calorimetry was used to determine effective power output of the device. The bags were thereafter again cooled to 4 $^{o}$C and 24 such warming instances undertaken.

It was also unknown whether or not the increase in effective power output observed for bags warmed serially, in the Taurus 301, is significant. The secondary aim of this study was to determine the extent and significance of this increase. This secondary aim was achieved by means of subgroup analysis in which comparison was made between effective power output

observed for bags warmed as a function of sequence within a batch of serial warming instances.

**Methods**

For the purposes of evaluating the warming performance of an electromagnetic blood warming device, concentrations of saline may be used to simulate the electrical properties of specific blood products. The interaction between blood and electromagnetic radiation has been exhaustively studied and these data made available. Perusal of these data will reveal, among other properties, the conductivity of blood for a range of haematocrit values, temperatures and electromagnetic field frequencies. Using these data, and that of saline solutions, a saline-based blood product simulation is possible.

The experiment was conducted within a laboratory adjacent to the main theatre complex at 2 Military Hospital, a tertiary-level hospital in Cape Town, South Africa, where there remains a functional Taurus 301 blood warmer. This particular Taurus 301 is functional and used regularly for the warming of red cell concentrates.

Four simulated bags of red cell concentrate of small volume served as subjects for the experiment. These four bags underwent cycles of cooling and then warming, using the Taurus 301.

**Results**

The Taurus 301 mean effective power output, when considering all warming instances, was 172.04 W (n = 96; 95% CI 169.61 – 174.47). A mean effective power output of 153.11 W (n=24; 95% CI 151.37 – 154.85) and 181.61 W (n=24; 95% CI 179.95 – 183.26) was observed when warming the first bag and last bag in each batch respectively. Taurus maximum power output was thus seen to be observed during warming of the last bag in a batch.

When considering the difference in effective power output between bags warmed first and those warmed subsequently, a statistically significant increase in mean power of 25.25W ($p < 0.001$; 95% CI 23.00 to 27.49) was observed.

**Conclusion**

This research has determined the mean maximum effective power output of Taurus 301, when used to warm the most vulnerable of blood product units, to be 181.61 W (n=24; 95% CI 179.95 – 183.26), and makes this value known in the interests of providing insight into what is likely a safe power output target for a prototype modernised Taurus.

# 1. BACKGROUND & SIGNIFICANCE

Devices designed specifically for the warming of banked blood, prior to transfusion, have been described as early as 1941.(2) Warming blood did not become commonplace until much later. As recently as the year 1965 the Western Province Blood Transfusion Service strictly prohibited the practice.(3) This was, however, a time in which there was much research underway in the field of heart transplantation, a procedure that often called for massive blood transfusions. Marked reductions in subject temperature following such massive transfusions of cold blood were observed and identified as an important factor in the development of cardiovascular complications.(4, 5)

At Groote Schuur Hospital, the lead anaesthesiologist in the cardiothoracic team, J. Ozinsky, who would later go on to provide anaesthesia for the first successful human heart transplantation, identified the need for a device capable of warming blood rapidly prior to transfusion.(6) Such a device was subsequently developed as a collaborative effort between the Department of Anaesthetics and Department of Electrical Engineering at the University of Cape Town.(7) The device become known as the "Taurus" blood warmer, namesake of the Head of Department at the time, and clinical leader of the project, Prof. A.B. Bull. Taurus employed the use of a valve triode, the predecessor of the transistor, configured as an oscillator, to generate radio frequency (RF) electromagnetic radiation capable of warming blood inductively within the glass bottles in which it was packaged at the time.(8, 9) A subsequent version of the Taurus, which warms blood within the bag in which it is packaged, remains in active clinical service at Groote Schuur Hospital.(1)

### Prototype development

Bull sought assistance, from Prof. J.L.N. Besseling of the Department of Electrical Engineering, for the development of a blood warming capability for massive transfusions. The request for assistance was well received and Besseling presented the problem as a potential undergraduate electrical engineering research project. Prof. I.M. Mason of Oxford University, an undergraduate of the University of Cape Town at the time, took interest in project.(10)

The pre-prototype was developed over two months and demonstrated the ability to warm whole blood, within glass Baxter bottles, safely and aseptically, from 4 to 34 $^{o}$C in approximately three minutes. Remarkably, the functional prototype (Taurus) rolled into the theatre complex at Groote Schuur just 10 weeks later.(10)

### Red cell survival testing

In-vivo evaluation of red cell survivability was also undertaken with a pair of investigators serving themselves as volunteers. A single unit of blood was crossmatched against both participants and red cells $Cr^{51}$ radio-labelled. One participant was transfused, from this radio-labelled crossmatched unit, a quantum of un-warmed blood, whilst the other participant received a quantum of blood warmed using the Taurus under evaluation. There was no significant difference observed between the half-life of the warmed vs un-warmed cells. This experiment suggested that blood warming using the Taurus prototype, with oscillator set to operate at around 33 MHz, resulted in no significant decrease in survivability of transfused red blood cells. Despite its simplicity, this experiment paved the way for acceptance of the novel device into clinical practice.(7)

A commemorative wall near the entrance of Groote Schuur Hospital lists the development of the Taurus blood warmer among other "Hospital Firsts": 1965 - The development of a rapid warming device for massive blood transfusions (Fig. 1).

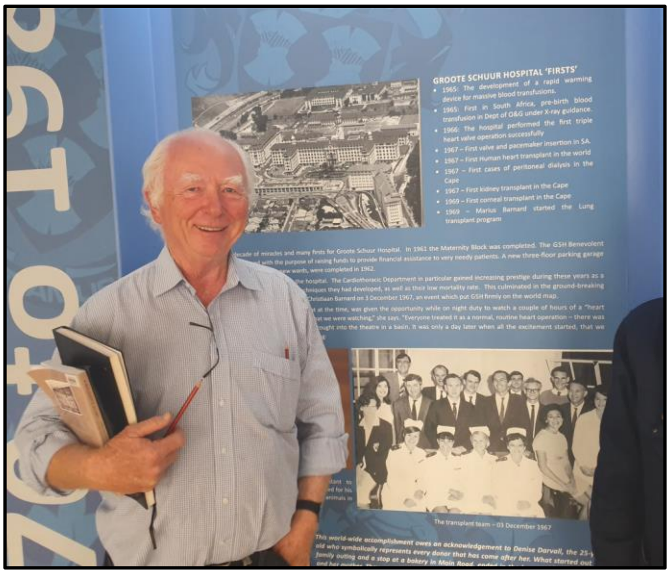

Figure 1 - Prof. I.M. Mason at the commemorative wall near the entrance of Groote Schuur Hospital

## Early versions of the device

### *Taurus Mk1*

The first Taurus to carry a corresponding nameplate was the version Mk1. The Instrument Manufacturing Corporation in Cape Town was responsible for commercialisation. Whether or not the Taurus MK1 was used during the operation which saw Louis Washkansky receive a donor heart is unknown. The device was available for use by the cardiothoracic team at the time but the account of the anaesthetic published by Ozinsky made no mention of it specifically.(11)

### *Taurus Mk2*

By 1970 the Plessy group had acquired Cape Town's Instrument Manufacturing Corporation along with the Taurus Mk1. Plessy revised the design and dubbed it Mk2. A Taurus Mk2, manufactured by Plessy South African circa 1970, is part of The Nagin Parbhoo History of Anaesthesia Museum collection which is housed within Department of Anaesthesiology and Perioperative Medicine at Groote Schuur Hospital.(12) This model, on display (Fig. 2), demonstrates the 600mL, thick walled, glass, Baxter bottles that were used, at the time, to package whole blood for transfusion.(1)


Figure 2 - Taurus Mk2 on display in the Nagin Parbhoo History of Anaesthesia Museum

***Taurus 300***

Substantive mechanical redesign of the Mk2 was called for in the late 1970's when the Western Province Blood Transfusion Service began packaging blood in polyvinyl chloride (PVC) bags. Blood packaged in bags assumed a rectangular rather than cylindrical shape as was the case with blood in Baxter bottles. The coiled inductor, which formed part of the radio frequency circuit used to warm the blood, relied upon by the Mk1 and Mk2, would no longer be appropriate for the new, roughly rectangular shaped packaging. The Taurus 300 thus adopted a capacitive, rather than inductive, warming approach in which the rectangular "slab" of blood was sandwiched between two metal plates over which a radio frequency (RF) waveform was applied. The blood, in this configuration, behaves like a lossy dielectric substance of a capacitor. Heating results owing to the blood interacting with the alternating electric field within the capacitor and converting a portion of this to heat in a process known as dielectric loss.(13)

Taurus's electrical mechanism will be discussed in detail under a specific heading; however, the historical account of the Taurus 300 is not complete without noting that the design for the pre-prototype, centred around a valve triode configured as a Colpitts oscillator. This oscillator type calls for a tank element which consists of two capacitors and an inductor. The Mk1 and Mk2 were able to warm blood by placing it within the inductor, whilst the Taurus 300 was able to achieve the same by simply configuring the blood bag to fit between the electrodes of one of the tank circuit capacitors. Remarkably, despite dramatic changes to the shape and packaging of the blood presented to the device, the oscillator mechanism remained thus largely unchanged.(7, 14)

***Taurus 301***

Plessy South Africa would manufacture the Taurus 300 until circa 1989 when the parent company merged with the General Electric Company. A further merger with Siemens in the following year resulted in fragmentation of the Plessy group of companies. The designs for the Taurus were transferred to Cape Medical Engineering Incorporated (C.M.E.I.) and revised with the Taurus 301 as the result.(10)

Whilst the RF oscillator remained largely unchanged, the Taurus 301 (Fig. 3) sported newer, more reliable control circuitry that made use of integrated circuits rather than discrete electrical components.(15)

The author has acquired a Taurus 301 that was scrapped and has added this to the Nagin Parbhoo History of Anaesthesia Museum collection.

Figure 3 - A Taurus 301 in active service at Groote Schuur Hospital in 2022

## Subsequent safety testing

The results of the initial safety testing for electromagnetic radio frequency warming of blood in a Taurus prototype, and an early Taurus design, were published in 1965 and 1967 respectively.(7, 8) By 1990 many things had changed about the design of the device as well as the packaging and processing of blood that it was designed to warm.

From a hardware perspective, most notably, the device’s RF oscillation frequency had been shifted from 33 MHz to 27.12 MHz. This was in order to be compliant with the Industrial Scientific Medical (ISM) frequency band requirements.(16) This lower frequency had greater potential to polarize red blood cell membranes and result in lesion of warming, influencing their longevity. The shape of the warming cavity and the mechanism of electromagnetic field formation had also changed significantly.(10)

From a blood product perspective, transfusion practices had also changed. No longer was whole blood the product of choice for massive transfusion. The use of red cell concentrate had, by 1960, become common practice. Red cell concentrate has a greater haematocrit (HCT), smaller volume and different preservatives relative to whole blood.(17) Taurus would need to be evaluated anew in order to demonstrate safety when warming this new blood product.

The safety tests were repeated using the latest Taurus, a model 301, and published in 1992. In vitro, the investigators found a small increase in free plasma haemoglobin following warming. This was however without any accompanying increase in potassium, lactate dehydrogenase or red cell membrane fragility.(14) Lack of congruence observed in these aforementioned markers of haemolysis make conclusion about whether or not the device induced haemolysis difficult.(18) Further, it must be noted that, in this experiment, the mean temperature achieved following warming of whole blood and red cell concentrate was 31.5 $^{o}$C and 30.5 $^{o}$C respectively.(14) These temperatures are lower than those observed in other studies.(2, 19-22) These low end point temperatures suggest that the safety tests may not have exposed the blood products under investigation to the same amount of radio frequency energy was the case in other studies. The extent of haemolysis observed may thus underestimate that which would occur if end point temperatures were higher.

In vivo red cell survivability tests, where autologous banked blood was stored for 33 days and then infused as red cell concentrate, were also performed. Each volunteer acted as their own control and pre-transfusion warming of blood in a Taurus 301 was shown to have no deleterious influence on in vivo red cell survivability at 24 hours and 21 days when compared to un-warmed blood. It was concluded that the Taurus 301 could be recommended as safe for the warming of both whole blood and red cell concentrates.(14)

**Taurus in modern times**

Despite access to a multitude of other blood technologies the author has observed, at Groote Schuur Hospital, a busy, tertiary-level, academic hospital, that the majority of anaesthetists opt to use the Taurus 301 for the warming of blood in most instances. Despite a design rooted in the 1970's the author believes there are characteristics innate to the Taurus 301 that make the device extremely well suited to modern practice in the developing world, and perhaps modern practice in general:

From an environmental perspective, the Taurus is distinctly different from other technologies in that it requires no physical consumables.(15) This lack of consumables negates the need for transport, storage and packaging of consumables, the consumables themselves and disposal of biohazardous consumables following a warming instance. The machine itself is also made largely from recyclable metal parts. A life-cycle analysis of the technology would likely reveal a markedly greener approach to blood warming than a consumables dependent approach.

From a logistical support perspective, the Taurus, once placed and plugged in, requires little beyond calibration and maintenance of the mechanical parts.(15) The majority of devices in operation appear to have done so without any attention to maintenance for the past decade.

From a simplicity perspective, the Taurus may be operated simply reading the instructions printed on the door of the device. Without any significant training any member of a clinical team would be able to safely operate the device. This simplicity stands in stark contrast to many other devices which use consumables that need to be connected to a patient's intravenous (IV) giving set. (23-25)

From a cost perspective the Taurus is appealing in that the variable overheads incurred in operating the machine are limited to the electricity it consumes. Costs associated with special training, procurement and disposal of consumables do not apply to the Taurus. Further, a single Taurus machine, placed strategically within a theatre complex, can serve many theatres simultaneously. This is not possible for in-line type warmers which must stand alongside an individual patient.(26-30)

From clinical utility perspective, the transition from the routine use of whole blood to packed red cells highlighted, for many clinicians, the importance of the relationship between blood viscosity and temperature. This as high-viscosity cold blood requires more pressure to achieve a given rate of flow through the standard blood-giving IV filter, than does warmer, low-viscosity blood. (2, 31) Warm blood may be given faster, and with a lower incidence of haemolysis, than cold blood in the same setting.(31) In-line blood warmers typically warm blood only after the filter has been traversed.

From a practicality perspective, the author suggests that, in some instances, in a large, busy, theatre complex a heavy, easily identifiable, and relatively immovable device may be preferrable. Such a device, often called upon in the emergency setting, is less likely to be stolen, knocked over, misplaced or difficult to find when needed. Similar cannot be said for smaller devices with wheels and trailing power cords.(2)

### Inappropriate use of Taurus for the warming of "Packed Red Cells"

Set into the fiberglass door of the Taurus 301 is a notice which reads: "DO NOT USE FOR PACKED RED CELLS" (Fig. 4). The author has observed clinicians opting to administer blood without warming on account of this notice. Other clinicians will likely have felt uncomfortable using the device or would have opted to use alternative blood warming technologies.

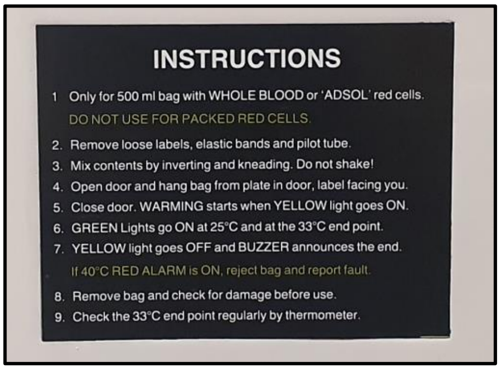


Figure 4 - Notice on the door of Taurus 301 which reads: "DO NOT USE FOR PACKED RED CELLS"

Harrison concluded that the new Taurus 301 was safe for warming blood other than whole blood of volume 500mL as was the case for the preceding model, the Taurus 300.(14) Assumption by many users of the Taurus 301 has been that the manufacturer did not accept the conclusion arrived at by Harrison following his evaluation, and simply wished to pass on the risk, no matter how small, to the clinicians who would continue using the device "off label".

This literature review has revealed, however, that the notice on the door of Taurus is leading clinicians to incorrect conclusions about which products are suitable for warming in the device. "Packed red cells", in blood bank parlance, refer to a specific type of red cell preparation that is not commonly issued for transfusion, but is rather an intermediate in the blood banking process. Following centrifuge, and removal of both plasma and buffy coat, the product which results is referred to as "packed red cells". This product typically has an HCT in excess of 0.8 and thus demonstrates much greater viscosity than would be expected for other blood products. Following addition of preservative, additional anticoagulant and a volume of plasma, the resultant preparation has an HCT of approximately 0.6 and a volume of 250-350 mL – this product is called "red cell concentrate", or alternatively, "haemoconcentrate". "ADSOL®", a registered trademark, describes a specific preservative additive that is used in the preparation of red cell concentrates as described above.(14)

In more modern general medical- and anaesthetic literature, the term "*packed red cells*" has come to refer to a product which is technically red cell concentrate. The Taurus 301, we can thus infer, is therefore being used appropriately when used to warm "*packed red cells*".

Literature review also reveals a trend in which localised “hot-spot” formation, due to high viscosity and resultant poor mixing, is likely the main contributing factor resulting in haemolysis of blood warmed using electromagnetic means.(19, 21, 22, 32, 33) It is thus likely that the very high HCT typical of packed red cells was justification enough for specifically prohibiting the warming of packed red cells in the Taurus 301.(15)

## The future for Taurus 301

More than a quarter century has passed since the last Taurus 301 was commissioned, yet the devices may still be found in active service within some South African hospitals. The author is aware of 2 such units which remain functional within the Groote Schuur Hospital Complex, and an additional 2 in other Cape Town based hospitals. How broadly and in what numbers the Taurus 301 was deployed by C.M.E.I. / Plessey is unknown. The author has also observed the scrapping of at least 3 units from the Groote Schuur Hospital Complex over the past 5 years and, if the situation parallels that of other hospitals, the Taurus may soon be lost to clinical practice.

## Taurus RF generation mechanism

Both ultrasonic and microwave warming mechanisms were considered potentially useful in the Taurus pre-prototype. These were, however, rejected in favour of RF on account of cost and poor penetration into blood respectively.(7)

### *Frequency selection*

An oscillator frequency, in the RF range, of 33 MHz was chosen for two important reasons. First, data available revealed that between 25 MHz and 100 MHz the electrical interaction between red cells and alternating electric fields was at minimum, and thus also the likelihood of specific red cell biological adverse effects.(7) Second, the blood for warming was packaged in glass bottles of radius 4.2cm and an electric field of frequency of 33 MHz would demonstrate a skin effect greater than this radius with resultant uniform field strength all the way through the body of blood.(14) Fortuitously the need to comply with international regulations and operate within the allocated industrial, scientific and medical (ISM) frequency band (26,957 MHz to 27,283 MHz) did not require that the device operating frequency be moved outside of the above specified frequency range.(16)

### *Colpitts oscillator*

The operating frequency of a Colpitts oscillator is set by three components, two capacitors and an inductor. These three components, known as a tank circuit, have a particular resonant frequency. When the tank circuit is paired with a gain device, a valve triode in the case Taurus, in an arrangement as shown in figure 5, a positive feedback relationship is established where RF power is circulated in the system at approximately the resonant frequency of the tank circuit.(14)

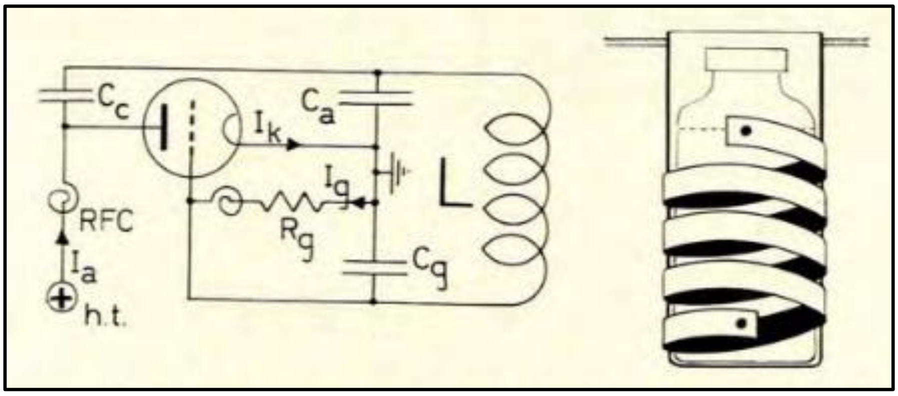

Figure 5 - Schematic diagram of the Colpitts oscillator circuit as implemented in the Taurus Mk1; The blood bottle is illustrated as being situated within the core of the inductor labelled "L"

All versions of the Taurus have warmed blood by placing blood *within* one of these tank circuit elements. In the prototypes, MK1 and MK2 the blood and bottle were housed within the inductor, and for models 300 and 301 the blood was sandwiched between two plates, as illustrated in figure 6, which formed one of the tank circuit capacitors.(15) It is Important to note that blood, itself a biological and highly variable substance, was part of the circuit that attempted to set the operating frequency of the oscillator circuit to within the ISM frequency band.

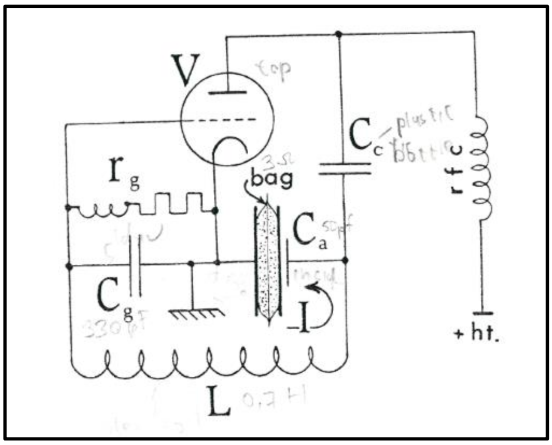

Figure 6 - Schematic diagram of the Colpitts oscillator circuit as implemented in the Taurus 300 and 301; The blood bag may be observed as fulfilling the role as a dielectric substance between two parallel plates of the capacitor labelled "Ca"

***Conditions favouring maximum power delivery***

In RF systems, maximum power delivery is achieved when there is appropriate matching of the source and load impedance.(34) This means that when a load has an impedance either lower, or higher, than that of the source, there will be a resultant wave of reflected power. This wave of reflected power travels back towards the source and will influence components along the way. Depending on the RF generator design, some reflected power may be radiated as electromagnetic energy, some may be converted to heat within components or transmission line elements, and some may prevent further energy from being added to the system by the source. Ultimately some of the reflected power never reaches the blood and this is thus observed as decreased effective power delivery.

In Taurus, impedance mismatch has contributed to the device safety. When a small volume unit of blood is inserted into the device it experiences this as a decrease in load impedance relative to a full volume unit, and subsequently delivers less power into this unit as a result of impedance mismatch resulting in reflected power.

Colour temperature change may be observed in the glow that radiates through the holes in the Faraday cage on the posterior of the Taurus. This change follows fluctuation in the temperature of filament within the valve triode as a result of changing source-load impedance matching, and consequently the amount of reflected power which must be dissipated as heat.

Blood impedance decreases as a function of temperature.(35) So marked is this effect that it was used as the switch-off signal for in the Taurus MK1 and MK2, as opposed to measured temperature, where decrease in blood impedance with warming would create sufficient mismatch to signal that sufficient heating has occurred.(8)

Further, the author has observed that the movable plate within the body of the Taurus, which makes direct contact with the PVC blood bag, warms up considerably during operation of the device. The first bag in a batch would lose heat energy via conduction to the cool plate whilst subsequent bags would suffer heat energy losses of smaller magnitude. Put another way, blood bags warmed subsequent to the first may benefit from a quantum of heat energy added by conduction in addition to RF heating.

## Modern solid-state switching technology

The pre-prototype Taurus was conceived at a time when the silicone transistor was less than 10 years old.(9, 36) The valve triode, a delicate, evacuated, glass envelope housing three electrodes, was instead used in an oscillator to generate the RF that would be used to warm blood. A valve triode, as shown in figure 7, has powered every model of Taurus since. The Taurus 301, last revised circa 1990 employed the use of some silicone semiconductor technology but only for control circuity and not in the RF generator.(15)

Figure 7 - A Philips valve triode model TB 3/750 in circuit within a Taurus 301

Much has changed in semiconductor industry since even the most recent Taurus design. In the time since, entirely new semiconductor technologies have arisen and, simultaneous to this, the valve triode has become obsolete. A newer switching technology in the form of gallium-nitride (GaN) FET (field-effect transistor), largely driven by the 5G cellular industry, is available and capable of handling an order of magnitude more power than both previous generation switching technologies (Fig. 8) as well as the valve triodes implemented in Taurus.(37, 38) GaN semiconductor switching technologies could be implemented in an RF generator suitable for blood warming.

A modern approach to generation of RF will likely be considerably different to that which was implemented in Taurus:

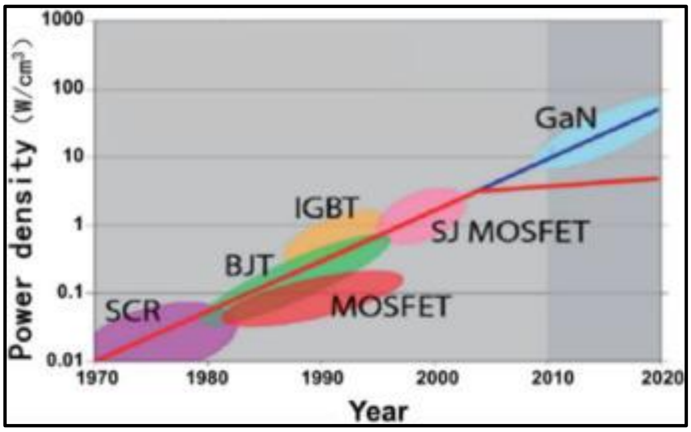


Figure 8 - Graphic illustrating the relationship between types of switching technologies, associated power density and the year of development; Silicon controlled rectifier (SCR), bipolar junction transistor (BJT), insulated gate bipolar transistors (IGBTs), metal oxide semiconductor field effect transistors (MOSFETs), super-junction (SJ) MOSFETs and Gallium nitride (GaN))(38)

***Energy efficiency***

Energy efficiency is important in terms of environmental impact, but in the context of solid-state switching technologies, inefficiency results in heat which must be removed to prevent damage to electrical components. The valve triode implemented in Taurus is large, robust and can glow red-hot (Fig. 9) without sustaining damage. The same cannot be said for silicone-based switching technologies which must be actively cooled to drive their loads without suffering the ill effects of reflected power.

Figure 9 - Taurus 301 valve triode glowing during device operation

The factors that influence the impedance of blood include its volume, temperature, HCT, ion concentration, packaging and orientation within the warming fixture.(10) As a result, an RF energy source using a more modern, mismatch-tolerant class of RF generator will likely be sought. Such RF energy sources will not have the innate ability to decrease power output for small, low impedance units of blood as is the case with the valve triode in a Colpitts oscillator configuration.

***Compliance with regulation***

If a modern RF device is to be compliant in terms of electromagnetic radiation regulations, it will either need to be heavily shielded or operate strictly in the narrow ISM band.(16) A Colpitts oscillator, implemented as has been done in Taurus blood warmers, may not be suitable for such a task, given the variability of the blood that forms an integral part of its tuning mechanism.(7, 14)

## Justification for proposed research

Whilst not the norm, red cell concentrates may be processed and dispatched with an HCT as high as 0.7 and volume as low as 210 mL.(39) Such units are at elevated risk of poor mixing, localised hot-spot formation and disproportionate lesion of warming.(20) Power output limitation may be particularly important when warming such products.

Relative to the TB 3/750 valve triode around which Taurus is bult, modern GaN and LDMOS semiconductors have made the delivery of comparably massive amounts of RF power possible.(15, 37) With great power comes great responsibility and, should the designers of a modernised Taurus seek to use these solid-state switching technologies, whilst striving to match the Taurus 301 safety record, they would do well to limit their device power output to levels typical of the Taurus 301.(40)

The Taurus 301 performance has been evaluated extensively and the device used for over 30 years. Without any literature available to suggest that the device is overtly harmful it may be concluded that the device design is one that may be drawn upon with confidence. Whilst limited effective power output alone is not the panacea allowing for safe RF warming; agitation mechanisms, temperature metrology and fail-safes should not be discounted; it is an important contributor. Without knowledge of what this effective power output is, those who seek to modernise the Taurus 301 may risk selecting a value that represents either over, or under powering. Specifying a design that delivers too much power may not be identified as harmful in subsequent safety testing which may result in irreparable harm to the reputation of an entire technology as has been the case with microwave blood warming.(22, 32) Design specification which is overly conservative, on the other hand, may result in a device of restricted clinical utility.

# 2. LITERATURE REVIEW

### Scope of literature for review

A review of literature relating to all blood warming technologies is beyond the scope of this article. This literature review will instead focus on devices which make use of electromagnetic radiation for the purposes of warming blood. A wide range of electromagnetic radiation frequencies have been used for this purpose and associated technologies will be considered in order of increasing wavelength: Microwave, infrared (IR) and radio-frequency (RF). Other themes identified during review of the literature will follow.

### Search strategy

A search of the electronic database, PubMed, was performed for articles published in English using the following search queries for microwave, infrared and radio frequency blood warming technologies respectively:
((blood[Title]) AND (warm*[Title] OR heat*[Title])) AND (microwave[Title/Abstract]), ((blood[Title]) AND (warm*[Title] OR heat*[Title])) AND (infrared[Title/Abstract] OR infra-red[Title/Abstract]) and ((blood[Title]) AND (warm*[Title] OR heat*[Title])) AND (radio-frequency[Title/Abstract] OR radio-wave[Title/Abstract] OR high-frequency[Title/Abstract] OR RF[Title/Abstract]). These queries yielded 27, 25 and 24 results.

Of the 27 articles related to microwave radiation blood warmers, 12 noted to be irrelevant based on review of the tile. The remaining 15 articles were accessed for review.

Of the 25 articles related to infrared radiation blood warmers, 24 noted to be irrelevant based on review of the tile. The remaining 1 article was accessed for review.

Of the 24 articles related to radio-frequency radiation blood warmers, 19 noted to be irrelevant based on review of the tile. The remaining 5 articles were accessed for review.

Additionally, a PubMed query looking for articles relating to electromagnetic blood warmers known to the author was used: Taurus, Ohio-987, Transfusio-Therm, Infusotherm 407 and Fluido.

Literature found as a result of ad hoc online search, using Google and Google Scholar, will also be included.

### Microwave warming

#### *Early history*

The development of the cavity magnetron in 1940 allowed for a reduction in the size of World War II era practical radar systems by orders of magnitude. During wartime the Allies put this technology to use and enjoyed radar superiority that Axis counterparts would never match. Serendipitous was the finding by Percy Spencer, whilst servicing one such active radar set, that his leg became warm when positioned alongside the device. Such was the heating that the "Mr. Goodbar" chocolate bar in his pocket had liquified. This event, the first documented microwave warming of foodstuffs, was a key moment in the history of the microwave oven, a device which would make the magnetron near globally ubiquitous.(41-43) It is likely that the success of the microwave oven resulted in interest in the use of the same technology for the blood warming.

### *Historical microwave blood warmers*

*Swiss microwave blood warmer*

The development of the first microwave device developed specifically for blood warming took place in Switzerland and was described in 1964. The device warmed blood within glass bottles and did so with "no significant changes". No laboratory evaluation data of the device performance is available.(2, 44)

*Ohio Model 987 microwave blood warmer*

In 1967, taking inspiration from the Swiss microwave blood warmer, a United States team described their own prototype: A magnetron oscillator tuned for 2450 MHz and capable of 1000 watts of power output was selected for the device. Microwave energy was directed into the cavity of the device in which there was a rotating, plastic, cylindrical receptacle into which the user would place the blood to be warmed.(2)

The team described, in both articles related to the prototype, that their microwave device had a tendency towards non-uniform heating of blood. Localised "hot spots" would form and these were blamed for the significant increase in free plasma haemoglobin observed following warming.(2, 45) Despite this concern the resultant Ohio Model 987 (Fig. 10) would be fitted with an even more powerful, 1100 watt magnetron. Aluminium shielding would be added to strategic locations to protect the tapered edges of the bags, the waveguide modified so as to direct microwave energy towards the central part of the blood bag being warmed, and the speed of rotation of the plastic receptacle increased in an attempt to mitigate the "hot spot" problem.(45)

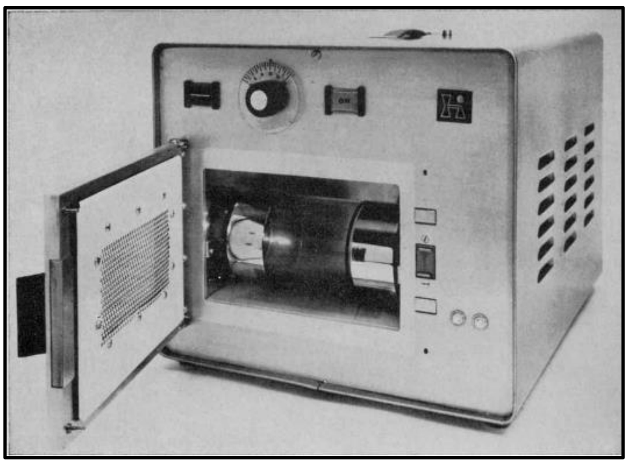

Figure 10 - Ohio Model 987 Blood Warmer

The first case of extensive haemolysis caused by the Ohio Model 987 took place in 1971.(32) Over the course of two years at least 8 clinical case reports of haemolysis of blood for transfusion were reported.(32, 33, 46) Whilst some of these complications could all be attributed to either failure of the proper mechanical mixing function of the device, or use of the machine in a manner contrary to the manufacturer instructions,(32, 33) in at least three cases extensive haemolysis of the blood being warmed resulted despite adherence to the manufacturer's prescribed process.(46)

In the wake of these case reports the lesion to blood caused by the Ohio Model 987 (and also the Taurus 300) during warming was carefully evaluated and compared that of warming using the, more traditional, temperature-controlled water bath. Following observation that 35% of blood warmed using the Ohio device was grossly haemolysed, the authors concluded that the use of microwaves for the warming of blood intended for transfusion in man should be questioned.(22)

*Infusotherm 407*

Researchers who evaluated the Infusiotherm 407 describe a microwave blood warmer with "a swivelling mechanism of the rotating holder which allows continuous mixing and uniform warming of the red-cell suspension."(47)

Published results of device performance from 1985 were favourable with increases in free haemoglobin and lactate of 8% and 7% above those for un-warmed blood respectively.(48)

Comparison was also made between warming lesion with the Isotherm 407 and in-line warming by passing blood through coiled tubing immersed in a temperature-controlled water bath. No significant difference in lesion of warming was observed between the two methods tested.(47)

*Haemotherm microwave blood warmer*

The Haemotherm, manufactured in West Germany, was available in two configurations: The Haemotherm Universal, which could warm blood in both bags and bottles, and the Haemotherm B, which was intended for warming blood in bags only. The Haemotherm used magnetrons oscillators of the same frequency as was seen in the Ohio Model 987, but implemented these quite differently – The device had an output power of just 400 watts, made use of two magnetrons, and rotated the blood bag back and forth through 350$^{o}$ rather than through complete rotations in one direction.(21)

Investigators commented specifically on the device mixing mechanism and associated this with lesion of warming of smaller magnitude that had been seen with the Ohio Model 987. There was, however, significant haemolysis observed with units of whole blood warmed using the Haemotherm B despite end temperatures between 36.0$^{o}$C and 36.8$^{o}$C. This finding was highly suggestive of localised overheating by the device. It was also found that marked haemolysis occurred when the blood being warmed had haematocrit exceeding 0.7 or mass less than 300g.(21)

Significant was the conclusion that neither exposure to microwave radiation, nor final temperature of the blood per se, but rather local overheating due to poor mixing of blood during warming and poor penetration of microwaves into the blood were the critical factors leading to haemolysis.(21)

***Contemporary microwave blood warmers***

*<u>Transfusio-therm 2000</u>*

The only commercially available microwave warmer suitable for blood, revealed by this literature review, is the Transfusio-therm 2000/3000 (Fig. 11). The device is capable of warming both fresh frozen plasma, whole blood and red cell concentrates. Further, the manufacturers claim compatibility with blood product volumes 100-600 mL. Warming is achieved by means of a 950 watt microwave magnetron, and three bags may be warmed simultaneously.(49)

Figure 11 - Transfusio-therm 2000 microwave blood warmer

Literature search reveals only one article which evaluated the device effect on erythrocyte preparations. Reassuringly, the red cells concentrates warmed using the Transfusio-therm 2000 tested favourably with no markers suggesting increase in haemolysis when compared to the same warmed comparably using a water bath.(50)

An evaluation of the Transfusio-therm 2000 for the warming of fresh frozen plasma was, however, undertaken in 2003. No local overheating was reported although the authors noted that the lower of the three trays resulted in more rapid heating than was seen in the other two trays. The authors recommended that the shape and size of the blood products should be standardized and that fresh frozen plasma units should be frozen in a regular rectangular receptacle such that the frozen product would have flat surfaces and no narrowing at the edges as is seen with bags.(19)

At the time the device was manufactured by Zeipel Medical GmbH, Heilbad Heiligenstadt, Germany. The device is now owned by EICMED GmbH, Heilbad Heiligenstadt, Germany and it is unclear whether the device has undergone any changes since 2003.(49, 51)

***Problems associated with microwave blood warming***

The underlying theme which emerges for microwave warming is that of poor penetration of electromagnetic energy into blood with resultant localised hot-spot formation and subsequently damage. Microwave energy, typically generated by a magnetron at 2450 MHz, has been shown to penetrate less than 8mm into biological tissue.(52) Adequate mixing of the blood during microwave warming appears to be both especially critical in prevention of hot-spot formation, and simultaneously a vulnerability responsible for many of the past failures of the technology.(22, 32, 33, 50)

### Infrared warming

The PubMed search terms described reveal one experimental IR warmer which is potentially suitable for warming of blood in the context of massive transfusion. This device employs the use of IR light-emitting diodes (LEDs) to warm the bag both pre-infusion and in-line during infusion. Using this technique, the authors claim to be able to deliver fluid at 38.5 $^{o}$C at flow rates in the range 100-1500 mL/min. Whilst the fluid is delivered to the patient at physiological temperatures, the time taken to warm the bag pre-infusion (0.7 $^{o}$C/min) limits clinical utility in the massive transfusion context.(53)

Ad hoc online searching reveals also the Fluido AirGaurd System (The Surgical Company, Amersfoort, The Netherlands), a commercially available device that uses IR to heat blood, or other IV fluids, to physiological temperatures at flow rates up to 750 mL/min. The IR warming takes place within a disposable, single use, proprietary giving set.(28) No publications evaluating the Fluido AirGuard System could be found.

More generally, as for microwave warming, the use of IR for warming of blood pre-transfusion, would need careful consideration regarding its power and depth of penetration into the blood bag. IR radiation is characterised by wavelengths 780 nm - 1000 um and frequencies of 300 GHz to 215 THz.(54, 55) Given that the most important parameter which determines the penetration of electromagnetic radiation into tissue, is its wavelength, absorption of IR energy within millimetres is not unexpected.(56)

### Radio frequency warming

This literature search reveals that the Taurus range of blood warmers represent the only examples of a radio-frequency blood warmers that were made available commercially for clinical use. Four important studies have evaluated the performance of Taurus, the most recent of which was published in 1992.(7, 8, 14, 20). Taurus was also mentioned in two articles, published 1974 and 1991 respectively, which reviewed blood warming techniques prevalent at the time.(23, 24)

# 3. RESEARCH QUESTION, AIMS AND OBJECTIVES

**Research Question**

The effective power output of the Taurus 301, when used for the warming of small volume bags of red cell concentrate, was unknown, and was described by collecting data around a number of instances of warming simulated small volume bags of red cell concentrate.

The Taurus 301 is also known to exhibit increased effective power output when used to warm bags of blood products in rapid succession(14). It was believed that this effective power increase is significant. The factors which likely contribute to this increase in power delivery have been discussed above. Our main hypothesis was that there would be a significant increase in the mean effective power output of the device for simulated small volume bags of red cell concentrate warmed serially.

**Primary Aim**

The mean effective power output of the Taurus 301, when used for the warming of small volume bags of red cell concentrate, in the setting of massive transfusion, prior to this study, was unknown. This study set out to describe the mean effective power output of the Taurus 301 in this context.

**Secondary Aim**

It was unknown whether or not the increase in effective power output observed, for bags warmed serially was significant.

This study set out to determine the extent and significance of the effective power output increase that has been observed in this context.

**Objectives of the Study**

Objectives included (i) sourcing appropriate bags for simulation of blood products, (ii) design of the simulated blood product, (iii) preparation of the simulated blood products, (iv) warming of simulated blood products and (v) data collection, (vi) capture and (vii) analysis.

Each of the above points is expanded upon in the methodology discussion below.

# 4. METHODOLOGY

## Study Design

This is an observational analytic study in that four bags of simulated, small volume red cell concentrate were warmed serially in batches using a Taurus 301, and measurements made. The resultant data were used for the realisation of both the study primary and secondary aims.

## Setting & Subjects

The experiment was conducted within the main theatre complex at 2 Military Hospital, a tertiary-level hospital in Cape Town, South Africa, where there remains a functional Taurus 301 blood warmer. This particular Taurus 301 is functional and used regularly for the warming of bags red cell concentrate as supplied by the Western Cape Blood Service (WCBS), the regional blood bank. Following setup and workflow testing, the data collection was completed over the course of 15 days.

Four simulated bags of red cell concentrate of small volume served as subjects for the experiment. These four bags underwent cycles of cooling and then warming, using the Taurus 301.

## Design and manufacture of simulated blood bags

### *Sourcing of blood bag*

Blood bag material, nominal volume, presence of ports, labels and tubes all influence the electrical properties of the final product. High fidelity simulation of red cell concentrate bags, as delivered by the blood bank, required that the same bags were used for simulation. The WCBS agreed to support this research by making the necessary bags available following Human Research Ethics Committee (HREC) approval (UCT HREC 156/2023).

### *Design of the simulated blood products*

For the purposes of characterising warming using the Taurus 301, a simulated blood product must have certain characteristics that closely match those of the target blood product being simulated. Such characteristics include the design of packaging, volume of fluid and electrical conductivity of the fluid.

Simulation of packaging was not necessary owing to the same packaging being made available by the WCBS.

A laboratory scale (Model No. PE 360, Mettler Toledo) (Fig. 12) was used to measure the tare weight of the PVC bags and to allow for the addition of the correct mass of saline solution required to simulate the smallest volume (210 mL) specified by the WCBS for red cell concentrate products.(39) Whilst 210 g of saline was added to each empty PVC bag, the volume of saline added to each bag was considered to be 210 mL given the negligible difference in density, at 20 $^{o}$C, between pure water and the saline being used for simulation of red cell concentrate (998.22 g/L and 1001.9 g/L respectively).(57)

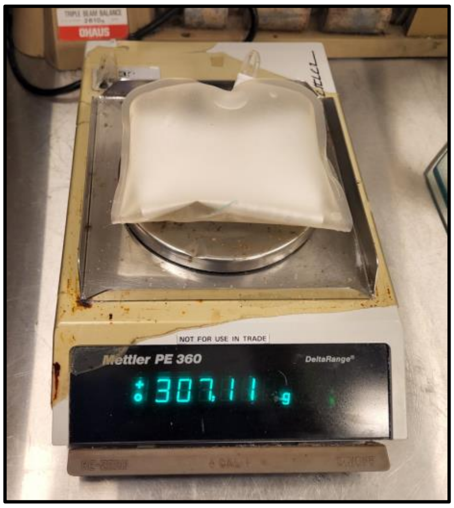


*Figure 12 - Mettler Toledo laboratory scale used to measure the tare weight of the blood bags and that of saline added*

The interaction between blood and electromagnetic radiation has been exhaustively studied and the data made available. Perusal of these data revealed, among other properties, the conductivity of blood for a range of haematocrit values, temperatures and electromagnetic field frequencies. At 27 MHz, the operating frequency of the RF oscillator within the Taurus 301, and at a temperature of 295 K, blood conductivity is 8.270 mS/cm and 8.839 mS/cm for haematocrit values of 57% and 39% respectively.(35)

The small difference in conductivity observed, despite a large variation in haematocrit, is by design. The operating frequency of Taurus was chosen to be well above the so-called Maxwell-Wagner beta relaxation frequency range, this the frequency range in which conductivity appears to be haematocrit dependant. Above this frequency the red cell membranes themselves do not appear to interact meaningfully with the electric fields and do not thus become polarised in response to the alternating electric field applied to them.(10)

The National Institute of Science and Technology (NIST) describes that pure deionised water is non-conductive. When there are ions present in water, however, the solution demonstrates electrolytic conductivity directly proportional to concentrations of these ions. The electrolytic conductivity is a result of ionic movement, and all ions contribute to the electrolytic conductivity of the solution. The conductivity. of the solution is directly proportional to the ion concentration such that 0.9% NaCl in water has a conductivity of 14.5 mS/cm at 20 $^{o}$C.(58) Using the above data, fluid of electrical conductivity resembling red cell concentrate, at 27 MHz, was prepared by adding NaCl to achieve a concentration of 0.51% (5.1 g/L).

Adding credibility to the simulation blood bag design, is the close correlation between the calculated NaCl concentration for simulation, and that which is described, by the manufacturer, in the Taurus 301 User Manual, for device testing (0.5%).(15) Further, in the original article describing the Taurus, prototype, testing using 0.5% saline resulted in warming times closely correlating with that of whole blood.(14)

***Manufacture of the simulated blood products***

Bags provided by the WCBS contained anticoagulant and preservative solutions. These bags were washed out thoroughly using the same saline solution that was used for the simulated blood product. A port on each bag was then modified (Fig. 13A) to allow the insertion of a thermocouple probe into the geometric centre (Fig. 13B) of the bag. This is the location where temperature measurements were taken before and after each warming instance.

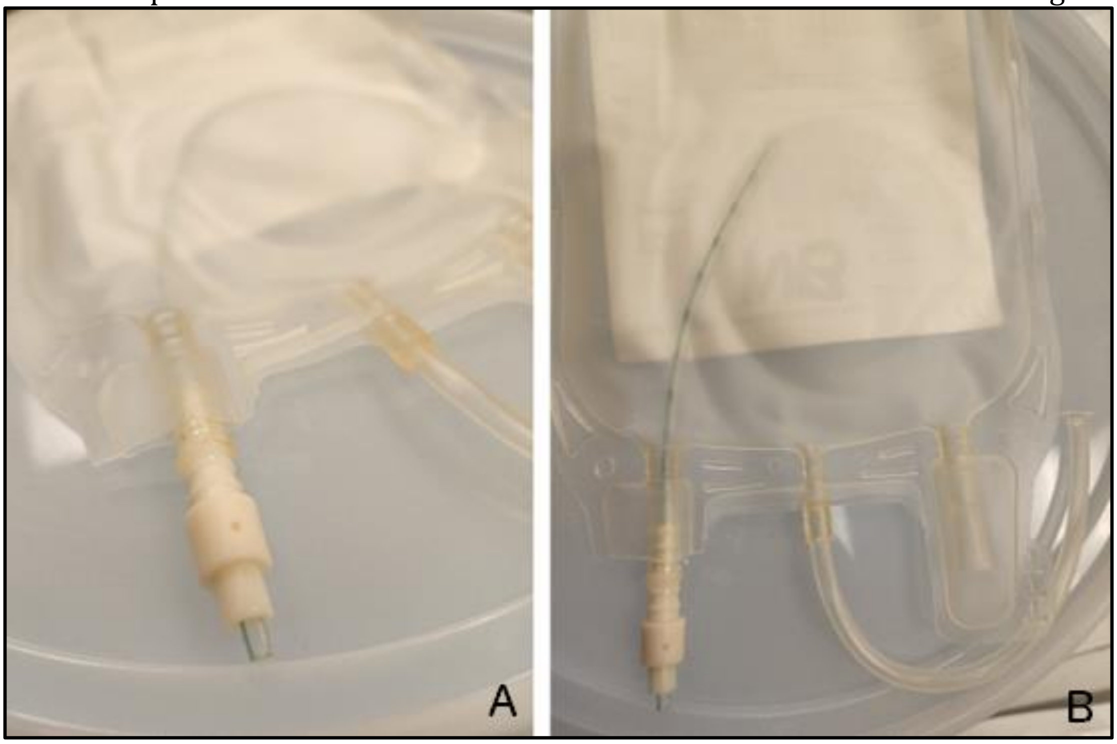


Figure 13 - Modification to the port on the PVC bag which creates a channel into which a thermocouple probe was inserted for the temperature at the geometric centre of the bag to be measured

For each of the four simulated small volume red cell concentrate bags, 210 g of 0.51% NaCl solution was added to complete the simulated blood product bag.

## Data Collection & Measurements

The experiment, measurements and data collection were performed by the author.

Quantitative and qualitative data for each instance of warming were recorded on a data collection form (Appendix A). Data collected included:

- Date and time
- Ambient temperature
- Temperature measurements for both the bag and Taurus circular take-up plate made prior to warming
- Temperature measurements for both the bag and Taurus circular take-up plate made following warming

- Duration of the complete warming cycle as indicated by sounding of the Taurus buzzer
- Notes relating to any other observations made, deviations from defined workflow or abnormal occurrences that occurred during the particular warming instance

**Measurement method**

For a batch of fluid warming instances, the following process was followed:

- A new data collection form was prepared. (Appendix A)
- Bag removed from fridge and placed on towel
- Thermocouple probe inserted into the modified outlet port of bag and temperature measured 10 seconds after insertion of the probe considered
    - If temperature of bag was > 5 $^{o}$C, bag was returned to fridge and further time allowed for cooling to take place
    - If temperature of bag was <= 5 $^{o}$C, temperature was noted and experiment was to proceed
- Thermocouple probe used to measure Taurus 301 circular take-up plate temperature
    - If temperature of the Taurus circular take-up plate was < 25 $^{o}$C then the experiment was allowed to proceed
    - If temperature of the Taurus circular take-up plate was >= 25 $^{o}$C then the bag was returned to fridge in order to allow more time for the Taurus to cool
- Bag under test was then loaded into the Taurus 301
- Stopwatch started and the warming cycle in Taurus 301 started
- Note made to indicate whether the current warming instance was the first, second or third warming instance in the batch
- Stopwatch stopped when the alarm buzzer indicating that the Taurus 301 warming cycle is complete sounded
- The duration of the warming instance noted
- Bag under test then removed from the Taurus 301 and place on towel
- Thermocouple probe then used to measure Taurus 301 plate temperature
- Thermocouple probe then inserted into the modified outlet port of the bag
- Maximum temperature measured in the 10 seconds after insertion of the probe noted
- Any noteworthy events, observations or deviations from the methods described above were then recorded on the data collection form
- Bag temperature measurements were made using a UNI-T thermometer (Model No. UT320D, UNI-Trend) connected to a UNI-T K-type thermocouple probe (Model No. UT-T12, UNI-Trend), inserted into the modified outlet port in order to make measure the temperature of the fluid within the bag
- Taurus plate temperature measurements were made using a UNI-T thermometer (Model No. UT320D, UNI-Trend) connected to a UNI-T surface contact K-type thermocouple probe (Model No. UT-T06, UNI-Trend)

The data collected during an entire batch of warming instances were to be rejected should the collection process be disturbed for any reason including:

- Clinical need for the Taurus device arises
- Clinical need for the researcher arises
- Electrical supply failure

- Failure of the Taurus device

**Data Management**

Data capture forms were printed, and a form completed for each batch of warming instances. Once completed, forms were collected and collated. The information was captured into a Microsoft Excel spreadsheet for statistical analysis later. Regular backups of the spreadsheet were saved onto a secure cloud storage system and a USB data storage device. The data collected are available in Appendix C.

**Pilot data**

During initial experiments, data were collected using a Taurus 301 device that has been scrapped and subsequently returned to working order. PVC bags resembling blood bags (Fig. 14) were purchased from a party supplies shop and used during these initial experiments.

Figure 14 - PVC bags resembling blood bags used during path-finding experiments

In the first pilot experiment series a bag of 0.5% saline 330mL was warmed, and then cooled a total of 25 times. The resultant data suggests that the effective power output follows, as determined by Jarque-Bera and Shapiro-Wilk tests, a normal distribution. Mean effective power output was 204.32 W (95% CI 195.31 – 213.33; SD 4.51). We were thus able to expect normally distributed data when a single bag is warmed in the same way repeatedly.

In the second test series, two bags of saline, 0.51% 300 mL and 0.55% 480 mL respectively were prepared, cooled and then warmed one after the other, in alternating order, a total of 12 times. This revealed that there is a marked effective power increase when a bag is warmed subsequently as opposed to first. For the smaller volume bag, the mean effective power output when warmed first compared to when warmed subsequently was 202.48 W (SD 6.93) and 219.30 W (SD 9.30) respectively. For the larger volume bag, the mean effective power output when warmed first compared to when warmed subsequently was 265.97 W (SD 3.93) and 276.66 W (SD 2.15) respectively. Interestingly the difference in effective power output observed between first and subsequent warming instances was larger for the smaller volume bag (16.82 W) than was evident in larger volume bag (10.69 W).

## Sample Size Calculation

The aim of the study is to describe the mean effective power output for the Taurus 301 when used in the setting of massive transfusion. It was hypothesised that the device' mean effective power output would be greatest for the fourth bag warmed in a given batch. This aim required that the mean effective power output of the fourth bag in the batch, be adequately described.

### *Sample size calculation*

Given the normal distribution of data observed in pilot experiments, making use of the observed standard deviation for a single unit warmed repeatedly in the same fashion (SD 4.51), and setting a margin of error to slightly less than 1% of the mean (2 W), a sample size of 23 was calculated to be sufficient to describe the mean effective power output as per the primary aim with a 95% level confidence.(59) We aimed to collect data from 24 batches of warming instances such that at the time of sub-group analysis of the dataset according to each of the four bags prepared, there would be equal numbers in each sub-group.

## Data Analysis

For every warming instance the effective power output was calculated as described in equation 1 below:

$$P_e = \frac{\Delta T(m_p c_p + m_s c_s)}{t}$$

Equation 1: Where $P_e$ is the effective power output in watts (W); $\Delta T$ is the difference between bag temperatures measured before and after a warming instance in degrees Kelvin (K); $m_p$ is the mass of the empty PVC bag in grams (g); $c_p$ is the specific heat of PVC(60) (J/g.K); $m_s$ is the mass of saline added to the bag (g); $c_s$ is the specific heat of saline(61) (J/g.K); t is the time taken for the warming cycle in seconds (s)

The statistical tools available in the IBM SPSS Statistics (Version 28.0.1.1) package were used to analyse the data.

Data collected during pilot experiment demonstrated a normal distribution of effective power output by the Taurus 301. Similarly, data collected during this experiment were predicted to exhibit normal distribution. Normality testing was, however, repeated to inform further statistical analysis.

The study primary aim was realised by analysing data collected during the warming of all the bags of simulated blood, and grouping these according to warming sequence number in order to describe the mean effective power output for each position within a batch. With reference to the study secondary aim, a two-tail t-test was used to make comparison between the effective power output observed for units warmed first and those warmed subsequently. Additionally, repeat measures ANOVA was used to determine between which levels the increase in effective power output was statistically significant.

Further analysis of the dataset was also be undertaken to explore the contribution of conductive heat transfer, from the Taurus take-up plate, to total energy delivery to the simulated bags of blood. The take-up plate makes direct contact with the 0.4mm thick PVC blood bag throughout the warming cycle. A roughly rectangular area of contact is formed between the side of the PVC bag and the take-up plate. A surface area of approximately 104 $cm^2$ is available where conductive heat energy exchange may take place, over the PVC bag, during warming (Fig. 15).

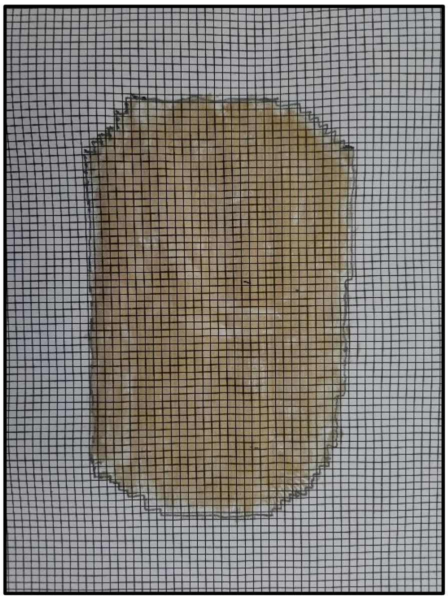

Figure 15 - A roughly rectangular impression, measuring 8x13cm, made by a simulated blood bag used in this study

To allow for this, two linear equations were described which estimate the temperature, during the warming cycle, of the take-up plate (equation 2), and the temperature of the simulated blood (equation 3), as a function of time.

$$T_p(t) = \left( {T_{pe}}/{T_{ps}} \right)(t) + T_{ps}$$

Equation 2: Where $T_p(t)$ is the temperature of the take-up plate at a given time following commencement of a warming instance in degrees Kelvin (K); $T_{pe}$ is the take-up plate end-temperature in degrees Kelvin (K); $T_{ps}$ is the take-up plate start temperature in degrees Kelvin (K); t is the specified 1s time interval

$$T_b(t) = \left( {T_{be}}/{T_{bs}} \right)(t) + T_{ps}$$

Equation 3: Where $T_p(t)$ is the temperature of the take-up plate at a given time following commencement of a warming instance in degrees Kelvin (K); $T_{pe}$ is the take-up plate end-temperature in degrees Kelvin (K); $T_{ps}$ is the take-up plate start temperature in degrees Kelvin (K); t is the specified 1s time interval

Using the formula for conductive heat transfer, as shown in equation 4, the amount of energy exchanged between the take-up plate and bag of simulated blood being warmed was calculated for every second of the warming cycle. The total amount of energy added to each bag, by the take-up plate, by means of conduction, was considered the sum of all the intervals calculated for the duration of the warming cycle.

$$Q_i = k_p\, A\; {}^{\Delta T}\!/_{l_p}$$

Equation 4: Where $Q_i$ is the amount of energy transferred during a particular 1 second interval in joules (J); $k_p$ is the thermal conduction coefficient for PVC (W/m.K); A is the area of contact between the take-up plate and the PVC bag ($m^2$); ΔT is the temperature gradient between the take-up plate and the bag (considered to have homogenous temperature) in degrees Kelvin (K); $l_p$ is the thickness of the PVC bag in meters (m)

This was performed for the mean values associated with the first and fourth warming instances in order to calculate the theoretical contribution of conductive warming when bags are warmed both individually and serially.

The graphing tools within Microsoft® Excel® 2019 MSO (Version 2202 Build 16.0.14931.20652) were used to perform the above calculations with respect to the contributions made by conductive warming.

## 5. RESULTS

As per the sample size calculated above, each batch of 4 bags of simulated small volume red cell concentrate was exposed to 24 warming cycles. Data were thus collected relating to 96 individual warming instances. Data collected during one batch were discarded as the warming process was interrupted on account of clinical need for the Taurus 301 being used in the experiment. The warming of this batch was then repeated after the bags had again been cooled as per the protocol described above.

Normal distribution of effective power output observed was confirmed using the Shapiro-Wilk test (Appendix E: Table 1).

One-way analysis of variance (ANOVA) showed no significant difference between the effective power observed for each of the four bags of simulated small volume red cell concentrate which were prepared (Appendix E: Table 2). This analysis suggests that the four bags behaved similarly within the Taurus 301 and during temperature measurement.

The Taurus 301 mean effective power output, when considering all warming instances, was 172.04 W (n = 96; 95% CI 169.61 – 174.47) (Appendix E: Table 3). A mean effective power output of 153.11 W (n=24; 95% CI 151.37 – 154.85) and 181.61 W (n=24; 95% CI 179.95 – 183.26) was observed when warming the first bag and last bag in each batch respectively (Fig. 16) (Appendix E: Table 4). Taurus maximum power output was thus seen to be observed during warming of the last bag in a batch.

A statistically significant upward trend in the mean effective power output, as a function of position within the batch of warming instances, was observed between the first and second ($p<0.001$), as well as between the second and third ($p<0.001$) bags warmed (Appendix E: Table 5). First, second, third and fourth bags demonstrated powers of 153.11 W (n=24; 95% CI 151.37 – 154.85), 174.29 W (n=24; 95% CI 172.24 – 176.46), 179.17W (n=24; 95% CI 177.62 – 180.71), and 181.61 W (n=24; 95% CI 179.95 – 183.26) respectively (Fig. 16) (Appendix E: Table 4).

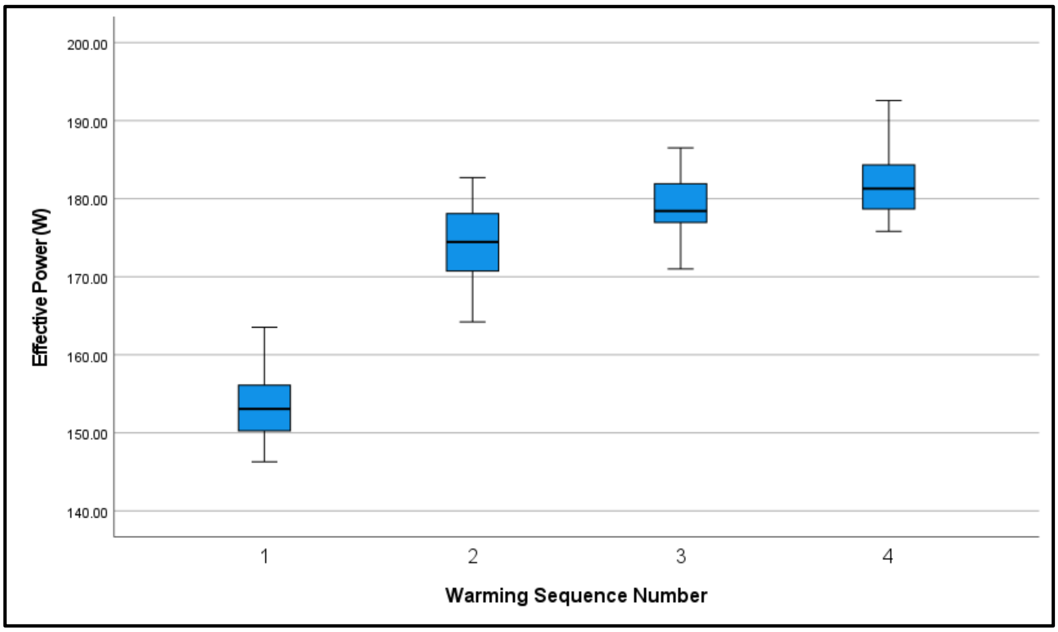


Figure 16 - Graph of effective power output for each position within the batches of warming instances

Increase in mean effective power output by 28.5 W ($p<0.0001$, 95% CI 26.16 – 30.84) was observed when comparing the first and fourth bags warmed in a batch of warming instances (Table 1).

**Comparing means for Effective Power Output between first and fourth bag warmed in a batch**
**(t-test for Equality of Means)**

| | t | df | | Mean | Std. Error | 95% Confidence Interval of the | |
|---|---|---|---|---|---|---|---|
| | | | Two-Sided p | Difference | Difference | Lower | Upper |
| Effective Power (W) | 24.536 | 46 | <0.0001 | 28.49875 | 1.16149 | 26.16079 | 30.83671 |

*Table 1 - Results of a two-tail t-test comparing means for effective power output observed for the first and fourth bags in a batch of warming instances*

An increase in the mean starting temperature of the take-up plate within the Taurus 301, by 7.97 °C ($p<0.001$; 95% CI 7.44 to 8.49), was observed between the first and second warming instance. Mean temperature increases of less magnitude, 1.10 °C and 0.30 °C respectively, were observed between subsequent warming instances (Fig. 17) (Appendix E: Table 6).

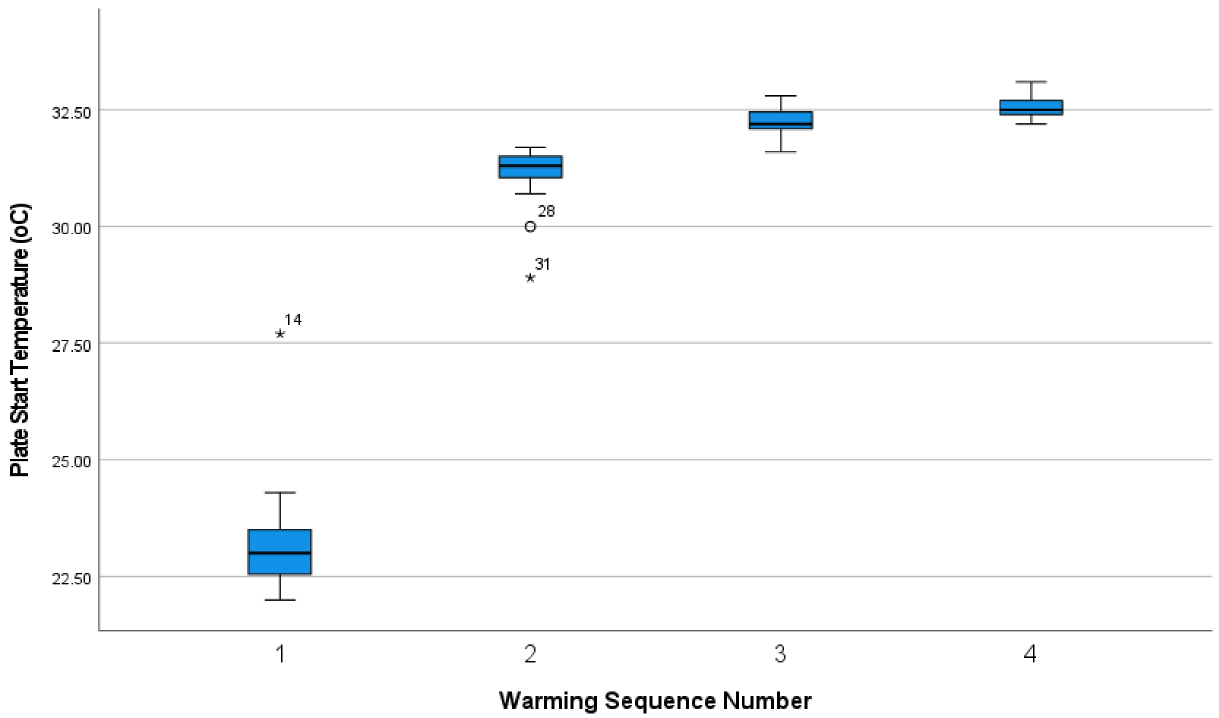


Figure 17 - Graph demonstrating increase in Taurus 301 take-up plate starting temperature following each warming instance in a batch

The mean temperature of each of the bags measured at the end of a warming cycle demonstrated a downward trend (Fig. 18). The decrease in mean bag end-temperature was, however, only statistically significant between the first and second warming cycles (0.4 °C; $p=0.011$; 95% CI 0.0625 to 0.7292) (Appendix E: Table 7). A similar observation was made during the initial evaluation of the Taurus model 300.(14)

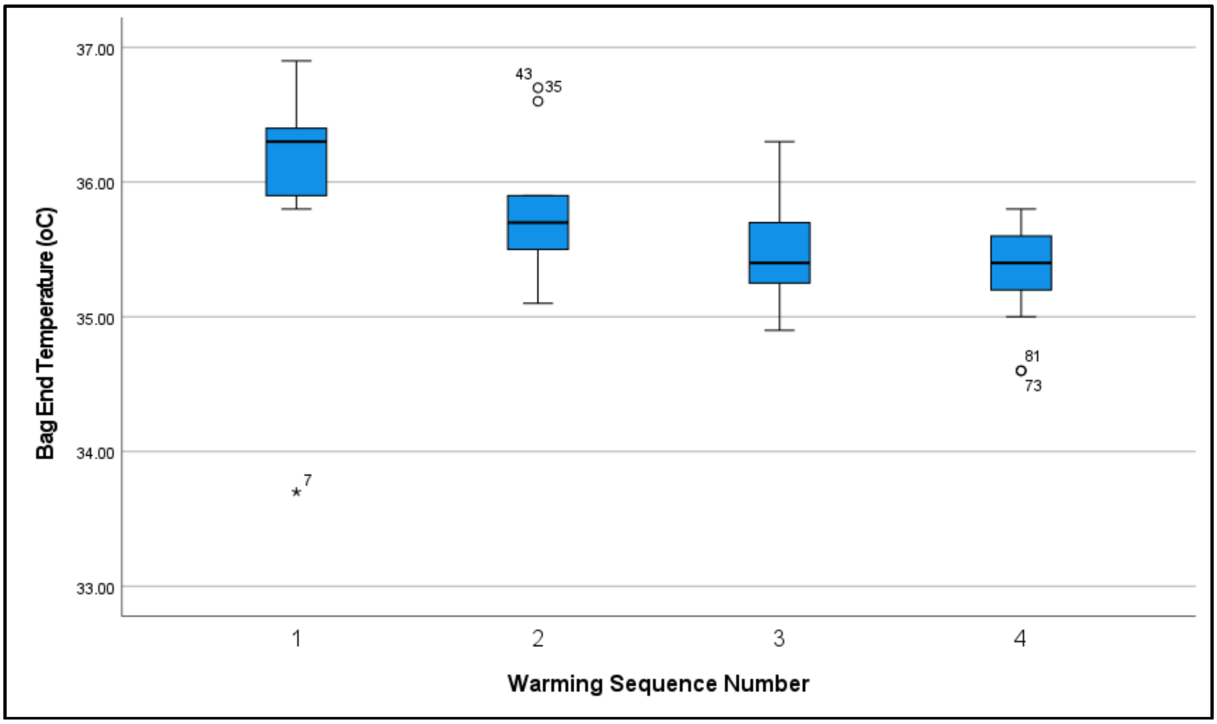

Figure 18 - Graph demonstrating decrease in bag temperature following each warming instance in a batch

The mean duration of each warming instance within a batch demonstrated a decreasing trend where durations were 185 s, 160 s, 155 s and 152 s respectively (Fig. 19). Statistically significant decrease in warming cycle duration was observed between the first and second ($p<0.001$), as well as second and third ($p<0.05$), but not the third and fourth ($p=0.479$), warming instance) (Appendix E: Table 8).

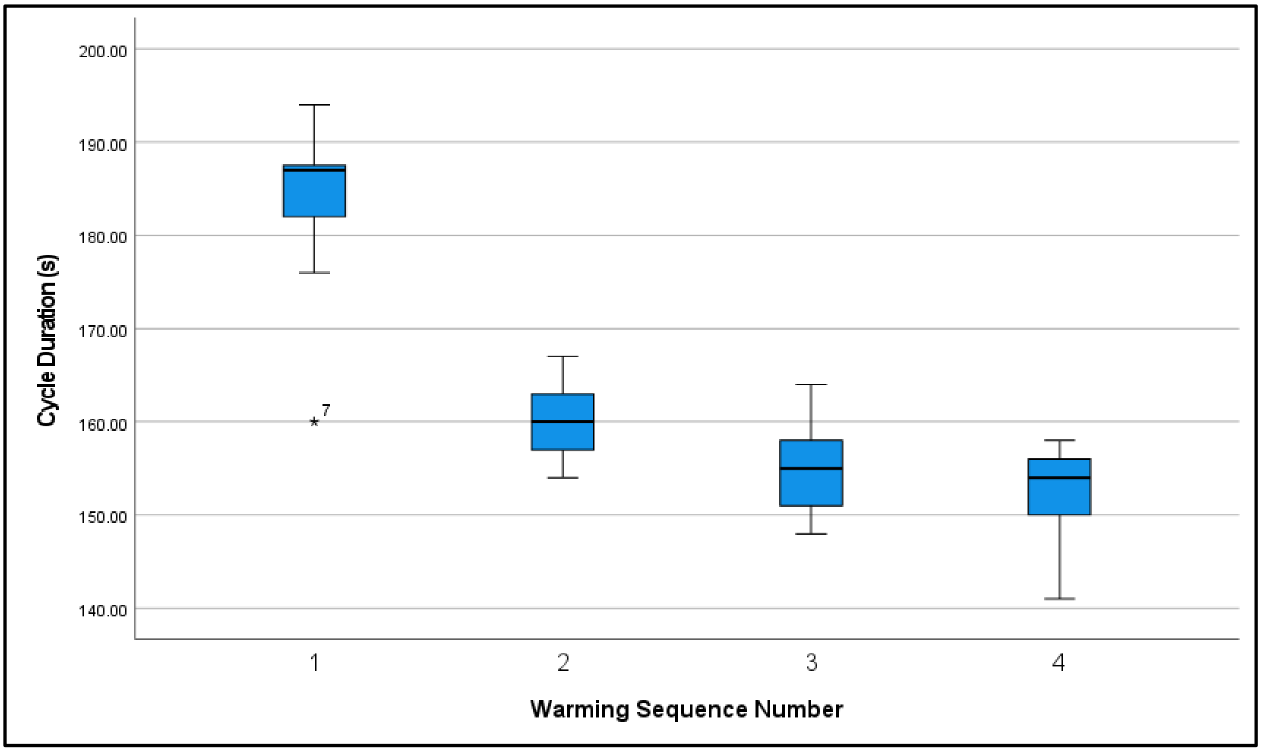

*Figure 1915 - Graph demonstrating decrease in warming cycle duration following each warming instance in a batch*

When considering the total amount of energy added to each bag, as a function of the batch warming sequence number, no significant differences were observable (Fig. 20) (Appendix E: Table 9).

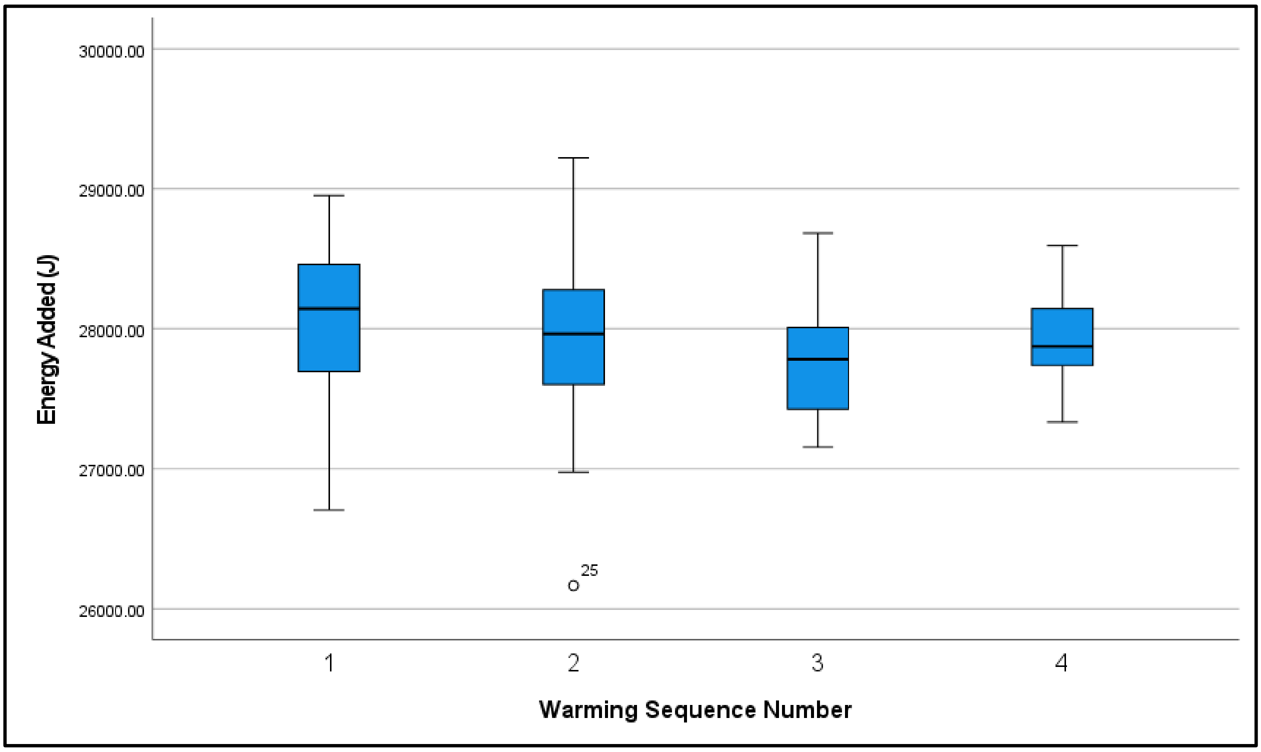


*Figure 20 - Graph demonstrating quantity of energy added following each warming instance in a batch*

During the first, and fourth warming instance of a batch the mean energy transferred into the bag, by means of conduction, was estimated to be 37.5 W and 97.0 W respectively (Fig. 21, 22). Estimate is thus that conductive heating may contribute as much as 59.5 W more towards warming in the fourth, compared to the first warming instance in a batch.

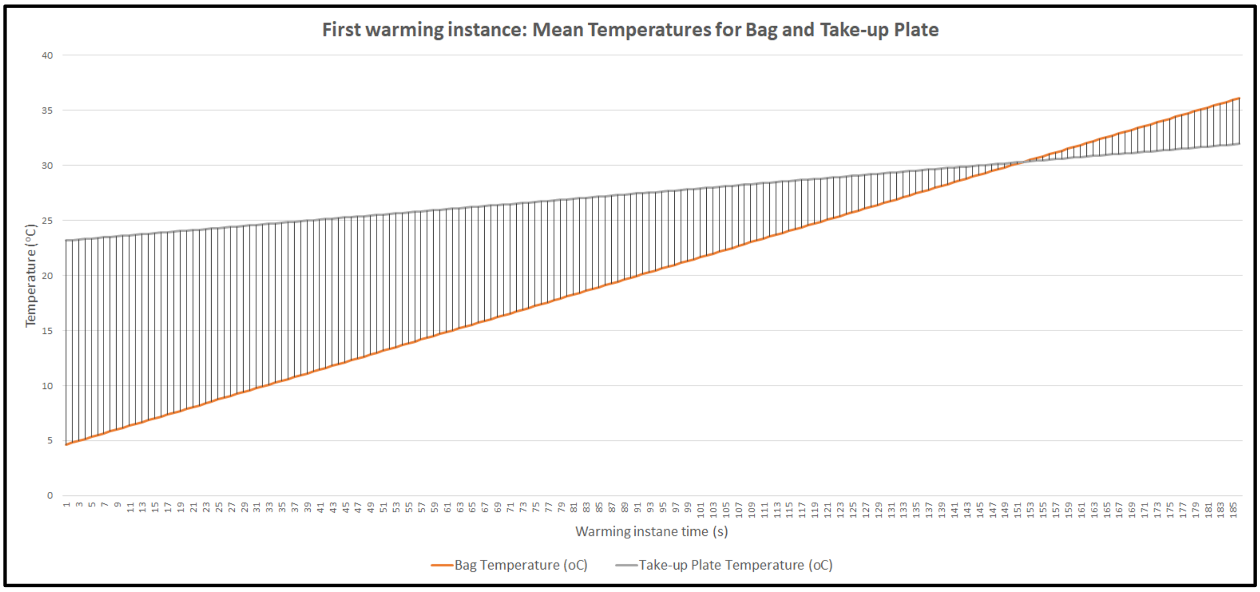


*Figure 161 - Graph depicting conductive energy transfer (vertical lines), for the first warming cycle in a batch, over time*

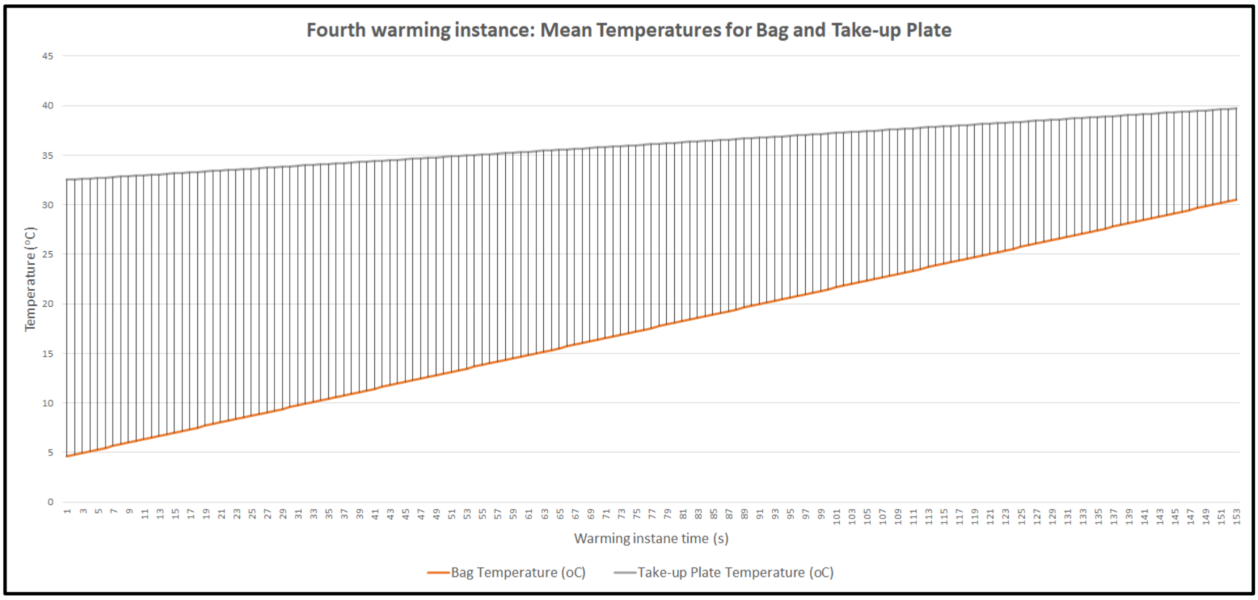


*Figure 22- Graph depicting conductive energy transfer (vertical lines), for the fourth warming cycle in a batch, over time*

# 6. DISCUSSION

**With reference to the study aims**

This aims of this study have both been successfully realised. With reference to the main aim, the mean effective power output of the Taurus 301, in the setting of massive transfusion is 172.04 W (95% CI 169.61 – 174.47); and with reference to the secondary aim, it is now known that there is a statistically significant increase in effective power output when the device is used to warm bags serially. A mean effective power output of 153.11 W (SD 4.12) and 181.61 W (SD 3.92) was observed when warming the first bag and last bag in each batch respectively.

**Increase in effective power output**

The most striking feature revealed by analysis of the data collected is that of significant increase in effective power delivered by the Taurus 301 following completion of the first warming cycle. This represents an increase in power by more than 16%. Two possible explanations for this phenomenon have been proposed:

*Valve triode warm up time*

First, valve triodes are known to require an amount of time to "warm up". Prior to this the valve will not have attained its nominal operating characteristics and power delivery may thus remain sub-maximal for some time.(62) The datasheet for the Phillips TB 3/750 valve triode does not specify a range of typical operating temperatures, nor any typical "warm up" times, likely as these are dependent on both how the valve is implemented within a circuit, as well as the load under which it functions.(63)

An attempt to quantify the contribution of valve triode "warm up" time to the observed increase in effective power output as described is beyond the scope of this study.

*Conductive warming*

Second, those who thought the Taurus 301 to be a "hot plate" warmer may have been at least partially correct in their assumption. Data in this study have revealed a marked increase in the starting temperate of the circular, movable metal plate (take-up plate) within the Taurus 301 following the warming of the first bag (Fig. 17).

This study has collected insufficient data to allow for the determination, beyond rough estimate, of the extent to which conduction of heat energy contributes to the function of the Taurus 301. There is, however, sufficient data to show, as demonstrated in Appendix D, that heat energy added by means of conduction could be entirely responsible for the 28.5 W of observed difference in effective power output between bags warmed first (153.11 W, 95% CI 151.37 - 154.85) and those warmed fourth (181.61 W, 95% CI 179.95 – 183.26) in a batch (Fig. 16) (Appendix E: Table 5).

**Decrease in bag end point temperature**

The downward trend in observed bag temperature achieved in this study (Fig. 18) is of smaller magnitude than was described during the initial evaluation of the Taurus 300.(14) Design changes were likely implemented which mitigated this problem. It is thought that as the chassis of the device warms during operation, the thermistor in the door is similarly warmed and contributes to earlier than intended termination of the warming cycle.

**Decrease in cycle duration**

The marked decrease in cycle duration observed (Fig. 19) did not result in a corresponding decrease in total amount of energy added (Fig. 20). Rather, there was no statistically significant difference in mean energy added to bags when grouped according to warming sequence number (Appendix E: Table 9). This phenomenon is explained by the fact that the warming cycle for each bag is terminated when the bag reaches a certain temperature, and given the increase in effective power output of the Taurus 301, as a function of warming sequence number, the warming cycle is completed in less time.

**Taurus 301 maximum output power observed**

Whilst the data collected clearly reveal an increase in the Taurus 301 effective power output as a function of temporal position within the batch of warming instances, it is not clear to what extent an increase in RF electromagnetic energy is responsible. The primary aim of this study has been realised and the Taurus maximum power output shown to take place during warming of the last bag in a batch of four.

Targeting this maximum value in a modernised protype Taurus should, however, be cautioned against given that data analysis points to an increase in conductive heat transfer being more likely responsible for the increase in effective power. Alternatively, those who seek to modernise the Taurus may consider taking advantage of heat energy transfer by conduction and actively warm the surfaces which come into direct contact with the PVC blood bags. Such practice may result in a decrease reliance on RF energy for warming.

# 7. LIMITATIONS

The Taurus 301 is a complex device that has demonstrated the ability to safely warm blood. This study has, however, not examined many aspects of the device which contribute towards this ability to perform its function safely. Other researchers may wish to explore in more detail the Taurus mixing mechanism and device component temperatures during operation.

***Taurus mixing mechanism***

On the inside of the door of the Taurus 301 is a rectangular faceplate on which the bag of blood to be warmed is hung. Within the door of the Taurus 301 is a motor which actively drives the faceplate. When the door of the device is closed the bag is squeezed between the rectangular faceplate and the circular take-up plate. The bag and take-up plate move in sympathy with the faceplate. When activated the motor rotates the bag slowly in one direction and then rapidly back in the other before coming to an abrupt stop against a rubber stopper (Fig. 23). This asymmetrical movement may play an important role in the mixing of the fluid within the PVC bag during the warming process, thus preventing localised over heating.

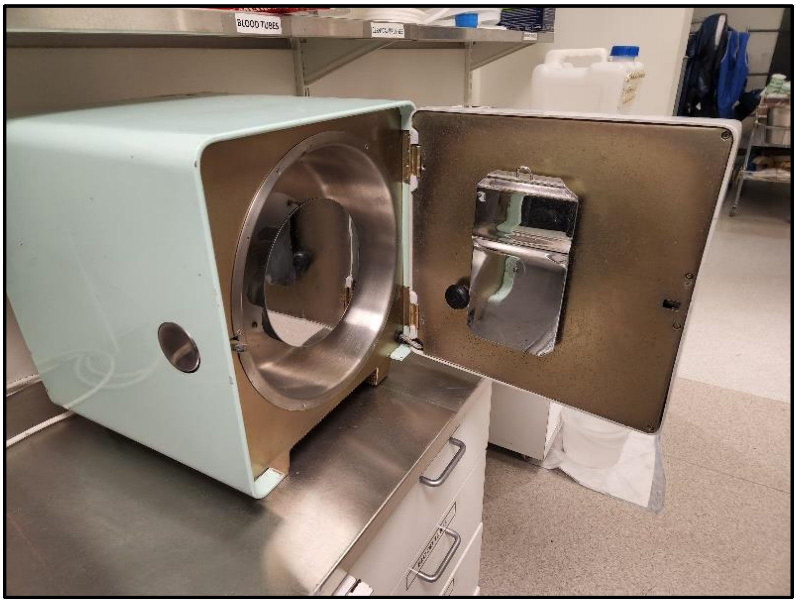

Figure 2317 - A Taurus 301 with door open revealing the rectangular faceplate on the door and the circular take-up plate within the body of the device

***Taurus component temperatures***

During this study we investigated only the temperature of one plate within the warming cavity. To properly understand the movement of energy in and out of the bag, temperatures of both plates, the surrounding chassis, and the air temperature within the device should be measured. With these additional values it may be possible to accurately characterise the Taurus 301 function in terms of conduction, convection and radiation.

***Study design limitations***

Other factors identified which further limit the value of the study include:

i) Only one Taurus 301 device was studied

ii) The study made use of saline as a blood analogue

iii) Temperatures were recorded at the beginning and the end of each warming cycle rather than continuously during the warming process

# 8. CONCLUSION

The aims of this study have been realised in that the maximum effective power output of the Taurus 301, for simulated small volume bags of red cell concentrate, in the setting of massive transfusion, has been determined. It has also been demonstrated that the device exhibits a significant increase in effective power output following the warming of the first bag in a batch. This research has provided an objective effective power output value which is likely a safe target for a prototype modernised Taurus.

Further insight has also been gained regarding the important contribution that conductive heating makes towards the Taurus 301 functionality. An increase in transfer of heat energy by conduction is proposed as the most likely mechanism responsible for the increase in effective power output following the warming of the first bag in a batch as described above. Recommendation to those who seek to modernise the Taurus is thus to target not the maximum power demonstrated in this study, but rather the effective power output characterising the warming of the first unit in a batch of warming instances.

Those clinicians who continue to make use of the Taurus 301 may also continue to do so with confidence given that, despite increase in effective power output observed when used to warm blood serially, the device did not over heat any bags, and added similar quantities of energy to each bag warmed regardless of position within a batch of bags being warmed.

During the process of literature review, pilot and data collection, the author has also gained a deeper appreciation for the complexity of the Taurus 301 and the need for further research into the performance of the device' mixing mechanism. Further, efforts at Taurus modernisation will benefit from being able to use, whilst developing a prototype, the same, easily reproducible and freely available simulated blood bag as has been described in this study.

## REFERENCES


1. Gordon PCH, N.D.; Marais, J. Pioneers in South African Anaesthesia: Professor Arthur Bull and the Taurus Radiofrequency Blood Warmer. South Afr J Anaesth Analg. 2013;19:2.
2. Restall CJ, Leonard PF, Taswell HF, Holaday RE. A microwave blood warmer: preliminary report. Anesth Analg. 1967;46(5):625-8.
3. Ozinsky J. The Need for Warming Stored Blood. SAMJ. 1965.
4. Boyan CP, Howland WS. Cardiac Arrest and Temperature of Bank Blood. JAMA. 1963;183(1):58-60.
5. Boyan CP, Howland WS, editors. Blood temperature: a critical factor in massive transfusion. The Journal of the American Society of Anesthesiologists; 1961: The American Society of Anesthesiologists.
6. Gordon P. Joseph (Ozzie) Ozinsky. SAMJ: South African Medical Journal. 2017;107:1052-.
7. Besseling JLNBABdPJME, Mason IM. The rapid warming of blood for massive transfusion by radio frequency induction. African Journal of Health Professions Education. 1965;39(7):137-40.
8. du PLESSIS JME, BULL AB, BESSELING JLN. an assessment of RADIO FREQUENCY INDUCTION HEATING OF BLOOD for massive transfusion. Anesthesia & Analgesia. 1967;46(1):96-100.
9. Sarkar TK, Mailloux R, Oliner AA, Salazar-Palma M, Sengupta DL. History of Wireless: Wiley; 2006.
10. Mason IM. Notes on Taurus 2023-01-01. In: Eave DD, editor. Helderberg2023.
11. Buchanan E. Cardiac transplantation – the anaesthetist's view: A case report. Author: J Ozinsky2017.
12. Gordon PC, James MF. The Nagin Parbhoo History of Anaesthesia Museum – Part 1. Southern African Journal of Anaesthesia and Analgesia. 2019;25:5-13.
13. Britannica TEoE. Dielectric Loss. In: Britannica TEoE, editor. Encyclopaedia Britannica2016.
14. Harrison GG, Bird AR, Jacobs P, Coghlan P, Byrne MJ, Ozinsky J, et al. Method for the safe and rapid pretransfusion warming of stored blood: an in vitro and in vivo evaluation of a radiofrequency (RF) instrument. J Clin Apher. 1992;7(1):12-7.
15. Ltd CMEIP. Taurus 301 Blood Warmer Maintenance Manual. 1990.
16. Van Lonek W. European Regulations of the Radio Spectrum, Ism Use and Safety. Journal of Microwave Power and Electromagnetic Energy. 2001;36(4):199-215.
17. Das P, Smit-Sibinga CT, Halie MR. Supportive therapy in haematology: Springer Science & Business Media; 2012.
18. McCaughey EJ, Vecellio E, Lake R, Li L, Burnett L, Chesher D, et al. Current Methods of Haemolysis Detection and Reporting as a Source of Risk to Patient Safety: a Narrative Review. Clin Biochem Rev. 2016;37(4):143-51.
19. Hirsch J, Bach R, Menzebach A, Welters ID, Dietrich GV, Hempelmann G. Temperature course and distribution during plasma heating with a microwave device. Anaesthesia. 2003;58(5):444-7.
20. Linko K, Hekali R. Influence of the Taurus radiowave blood warmer on human red cells. Hemolysis and erythrocyte ATP and 2,3 DPG concentrations following warming by radiowaves, microwaves and water bath. Acta Anaesthesiol Scand. 1980;24(1):46-52.
21. Linko K, Hynynen K. Erythrocyte damage caused by the Haemotherm microwave blood warmer. Acta Anaesthesiol Scand. 1979;23(4):320-8.

22. Dalili H, Adriani J, Wu WT, Samuels MS. Radiowave and microwave blood warmers: comparison with water bath blood warming units. South Med J. 1973;66(11):1254-9.
23. Iserson KV, Huestis DW. Blood warming: current applications and techniques. Transfusion. 1991;31(6):558-71.
24. Russell WJ. A review of blood warmers for massive transfusion. Anaesth Intensive Care. 1974;2(2):109-30.
25. Indrani G, Rudrashish H. Blood warming in trauma related transfusions-Precepts and practices. Journal of Cardiovascular Medicine and Cardiology. 2019;6(4):094-7.
26. Stihler-Electronic. Stihler-Electronic Astoflo-Plus-eco [Available from: https://www.stihlerelectronic.de/media/stihler_electronic_astoflo_english.pdf.
27. Medical S. Smith-Medical Level-1 Hotine Fluid Warmer [Available from: https://www.smiths-medical.com/-/media/M/Smiths-medical_com/Files/Import-Files/TM194800EN_LR.pdf.
28. Company TS. Fluido Blood and Fluid Warming. In: Company TS, editor. 2020.
29. Barkey. Barkey S-Line fluid warmer [Available from: https://www.hct.group/wp-content/uploads/2018/05/Barkey-S-line.pdf.
30. 3M. 3M Ranger product line [Brochure detailing the 3M Ranger range of products]. Available from: https://multimedia.3m.com/mws/media/1099581O/ranger-fluid-warming-systems-brochure.pdf.
31. Du Plessis JM, Bull AB. Haemolysis occurring during pressure transfusion of stored blood. S Afr Med J. 1966;40(21):479-83.
32. Staples PJ, Griner PF. Extracorporeal hemolysis of blood in a microwave blood warmer. N Engl J Med. 1971;285(6):317-9.
33. McCullough J, Polesky HF, Nelson C, Hoff T. Iatrogenic hemolysis: a complication of blood warmed by a microwave device. Anesth Analg. 1972;51(1):102-6.
34. Davis WA, Agarwal KK. Radio Frequency Circuit Design. 2nd ed: Wiley India Pvt. Limited; 2009.
35. Wolf M, Gulich R, Lunkenheimer P, Loidl A. Broadband dielectric spectroscopy on human blood. Biochimica et Biophysica Acta (BBA) - General Subjects. 2011;1810(8):727-40.
36. Morris PR, Engineers IoE. A History of the World Semiconductor Industry: P. Peregrinus; 1990.
37. Sáez R, Medrano-Marqués N. LDMOS versus GaN RF Power Amplifier Comparison Based on the Computing Complexity Needed to Linearize the Output. Electronics. 2019;8:1260.
38. Zhong Y, Zhang J, Wu S, Jia L, Yang X, Liu Y, et al. A review on the GaN-on-Si power electronic devices. Fundamental Research. 2022;2(3):462-75.
39. Service WCBT. Blood Products and Services Information: Western Cape Blood Transfusion Service; 2022 [Available from: https://www.wcbs.org.za/clinical-information/blood-productsservices/.
40. Lieber SM. Amazing Fantasy #15 1962. 11 p.
41. Conover E. October 8, 1945: First Patent for the Microwave: American Physical Society; 2015 [Available from: https://www.aps.org/publications/apsnews/201510/physicshistory.cfm.
42. Invent.org. Percy L. Spencer: High Efficiency Magnetron: Invent.org; 2023 [Available from: https://www.invent.org/inductees/percy-l-spencer.
43. Ltd MSC. The History & Inventor Of The Microwave Oven: Microwave Service Company Ltd; 2012 [Available from: https://microwaveexpert.wordpress.com/2012/03/26/the-history-inventor-of-the-microwave-oven/.

44. Freysz T, Schwarz H, Hossli G. [A new type of apparatus for rapid warming of fresh preserved blood]. Anaesthesist. 1964;13:174-5.
45. Leonard PF, Restall CJ, Taswell HF, Fairbanks VF. Microwave warming of bank blood. Anesth Analg. 1971;50(2):302-5.
46. Arens JF, Leonard GL. Danger of overwarming blood by microwave. Jama. 1971;218(7):1045-6.
47. Roth-Henschker H, Holzberg E, Oppitz KH, Lehmann C. [Warming resuspended erythrocyte concentrates with a new microwave device. In vitro results and clinical experiences in comparison with continuous flow warming]. Anaesthesist. 1988;37(5):321-30.
48. Stephan H, Larsen R, Sonntag H. [The effect of rewarming of stored blood on plasma value and erythrocytes]. Anaesthesist. 1985;34(7):352-4.
49. EICMED. Operation Manual --- transfusio-therm 3000. In: EICMED, editor. 2022.
50. Hirsch J, Menzebach A, Welters ID, Dietrich GV, Katz N, Hempelmann G. Indicators of erythrocyte damage after microwave warming of packed red blood cells. Clin Chem. 2003;49(5):792-9.
51. Zeipel K, inventorMicrowave appliance used for warming blood or blood derivatives stored in a bag. Germany1987.
52. Fuchs J, Herrling T, Groth N. Detection of free radicals in skin: a review of the literature and new developments. Curr Probl Dermatol. 2001;29:1-17.
53. Nair SS, Sreedevi V, Nagesh DS. Warming of blood and intravenous fluids using low-power infra-red light-emitting diodes. Journal of Medical Engineering & Technology. 2021;45(8):614-26.
54. Illumination) CICo. 17-5802023/01/29. Available from: https://cie.co.at/eilv/580.
55. Giancoli DC. Physics: Principles with Applications: Prentice House; 2004.
56. Hashmi JT, Huang YY, Sharma SK, Kurup DB, De Taboada L, Carroll JD, et al. Effect of pulsing in low-level light therapy. Lasers Surg Med. 2010;42(6):450-66.
57. Drefahl A. DENS1: AQUEOUS SOLUTION DENSITIES 2019 [Available from: https://www.axeleratio.com/calc/solution_density/form/dens1.htm.
58. Shreiner RH, Pratt KW. Primary Standards and Standard Reference Materials for Electrolytic Conductivity. In: Technology NIoSa, editor. 2004.
59. Dhand NK. Statulator: An online statistical calculator 2014 [Available from: http://statulator.com/SampleSize/ss1M.html.
60. Properties M. Polyvinyl Chloride – Density – Strength – Melting Point – Thermal Conductivity 2023 [Available from: https://material-properties.org/polyvinyl-chloride-density-strength-melting-point-thermal-conductivity/.
61. Engineering-Handbook T. Saline Water Property Calculator 2013 [Available from: https://enghandbook.com/thermodynamic-calculators/seawater/?temperature=20.0&pressure=1.01325&salinity=0.005.
62. Blencowe M. Designing Tube Preamps for Guitar and Bass. Second ed2012.
63. Inc. P. Philips TB 3/750. In: Inc. P, editor. 1950.
64. The University of Tennessee DoPaA. Regulating heat flow [Available from: http://labman.phys.utk.edu/phys221core/modules/m9/regulation.html.

## Appendix A: Data Collection Form

(The data collection form used during the experiment may be found following this page)

**Appendix A --- Data Collection Form**

**Effective power output of the Taurus 301 blood warmer when warming small volume units of red cell concentrate described using simulated blood products**

Version 20230227A

Data collection form number:

| Record No. | Date | Time | Operator | Fluid_ID | Warming sequence Number | Start Temperature (degC) | | End Temperature (degC) | | Taurus cycle duration (s) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Bag | Plate | Bag | Plate | |
| | | | | | | | | | | |
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Supplementary notes:

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## Appendix B: Pilot Data

(Spreadsheets containing data collected during pilot experiments may be found following this page)

**Data Collection Form --- Taurus 301 (Pilot) Performance Test**

| Date | Time | Operator | Fluid_ID | Warming instance | Start Temperature (degC) | End Temperature (degC) | Taurus cycle duration (s) |
|---|---|---|---|---|---|---|---|
| | | | | | Thermocouple | Thermocouple | |
| 2022/12/05 | 15:28 | Eave | 1 | 1 | 4.9 | 35.2 | 198 |
| 2022/12/06 | 7:20 | Eave | 1 | 2 | 4.0 | 35.7 | 220 |
| 2022/12/06 | 14:23 | Eave | 1 | 3 | 4.4 | 35.9 | 215 |
| 2022/12/07 | 8:10 | Eave | 1 | 5 | 4.3 | 35.8 | 218 |
| 2022/12/07 | 13:08 | Eave | 1 | 6 | 5.0 | 35.0 | 206 |
| 2022/12/08 | 9:05 | Eave | 1 | 7 | 3.5 | 35.5 | 210 |
| 2022/12/08 | 16:23 | Eave | 1 | 8 | 4.4 | 36.0 | 220 |
| 2022/12/09 | 7:26 | Eave | 1 | 9 | 4.6 | 36.0 | 214 |
| 2022/12/09 | 12:30 | Eave | 1 | 10 | 4.5 | 35.3 | 210 |
| 2022/12/09 | 16:18 | Eave | 1 | 11 | 4.6 | 35.2 | 208 |
| 2022/12/12 | 12:06 | Eave | 1 | 12 | 4.1 | 35.9 | 215 |
| 2022/12/12 | 15:37 | Eave | 1 | 13 | 4.1 | 35.7 | 211 |
| 2022/12/13 | 10:18 | Eave | 1 | 14 | 4.5 | 36.2 | 222 |
| 2022/12/13 | 16:20 | Eave | 1 | 15 | 4.8 | 36.3 | 216 |
| 2022/12/14 | 8:53 | Eave | 1 | 16 | 4.6 | 36.3 | 217 |
| 2022/12/14 | 16:05 | Eave | 1 | 17 | 4.3 | 35.8 | 220 |
| 2022/12/17 | 7:18 | Eave | 1 | 18 | 4.4 | 36.2 | 221 |
| 2022/12/17 | 12:23 | Eave | 1 | 19 | 4.3 | 36.3 | 210 |
| 2022/12/17 | 4:25 | Eave | 1 | 20 | 4.1 | 35.2 | 210 |
| 2022/12/18 | 7:50 | Eave | 1 | 21 | 4.5 | 35.6 | 217 |
| 2022/12/18 | 13:01 | Eave | 1 | 22 | 4.1 | 36.3 | 217 |
| 2022/12/18 | 17:10 | Eave | 1 | 23 | 3.5 | 35.5 | 210 |
| 2022/12/19 | 7:20 | Eave | 1 | 24 | 4.1 | 35.7 | 211 |
| 2022/12/19 | 12:50 | Eave | 1 | 25 | 4.1 | 35.8 | 209 |
| | | | | | | | |
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| | | | | | | | |

**Results --- Taurus 301 (Pilot) Performance Test**

| Effective Power (W) |
|---|
| 212.1 |
| 199.71 |
| 203.0651163 |
| 200.2706422 |
| 201.8446602 |
| 211.2 |
| 199.08 |
| 203.3663551 |
| 203.28 |
| 203.9019231 |
| 204.9990698 |
| 207.571564 |
| 197.9108108 |
| 202.125 |
| 202.4709677 |
| 198.45 |
| 199.4334842 |
| 211.2 |
| 205.26 |
| 198.6387097 |
| 205.6645161 |
| 211.2 |
| 207.571564 |
| 210.2210526 |
| |
| |
| |

**Data Collection Form --- Taurus 301 (Pilot) Performance Test**

| Record No. | Date | Time | Operator | Fluid_ID | First / Subsequent | Start Temperature (degC) | End Temperature (degC) | Plate Start Temp (degC) | Plate End Temp (degC) | Taurus cycle duration (s) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Thermocouple | Thermocouple | Thermopile | Thermopile | |
| 1 | 2023/01/02 | 10:39 | Eave | 300mL 0.51% | First | 4.3 | 36.4 | | | 205.0 |
| 3 | 2023/01/09 | 9:04 | Eave | 300mL 0.51% | First | 4.4 | 35.8 | | | 196.0 |
| 5 | 2023/01/10 | 7:23 | Eave | 300mL 0.51% | First | 4.3 | 36.7 | | | 196.0 |
| 7 | 2023/01/11 | 8:16 | Eave | 300mL 0.51% | First | 4.4 | 35.6 | | | 200.0 |
| 9 | 2023/01/12 | 8:36 | Eave | 300mL 0.51% | First | 3.8 | 36.0 | 23.4 | 36.3 | 190.0 |
| 11 | 2023/01/16 | 14:28 | Eave | 300mL 0.51% | First | 4.3 | 35.7 | 23.0 | 35.9 | 200.0 |
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| | | | | | | | | | | |
| 2 | 2023/01/05 | 14:43 | Eave | 300mL 0.51% | Subsequent | 4.0 | 35.9 | | | 178.0 |
| 4 | 2023/01/09 | 15:08 | Eave | 300mL 0.51% | Subsequent | 3.9 | 35.9 | | | 176.0 |
| 6 | 2023/01/10 | 15:55 | Eave | 300mL 0.51% | Subsequent | 4.3 | 36.2 | | | 198.0 |
| 8 | 2023/01/11 | 15:04 | Eave | 300mL 0.51% | Subsequent | 4.0 | 35.3 | | 39.6 | 177.0 |
| 10 | 2023/01/13 | 7:35 | Eave | 300mL 0.51% | Subsequent | 4.1 | 34.8 | | 38.4 | 173.0 |
| 12 | 2023/01/17 | 8:43 | Eave | 300mL 0.51% | Subsequent | 4.2 | 35.7 | | 39.6 | 177.0 |
| | | | | | | | | | | |
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**Data Collection Form --- Taurus 301 (Pilot) Performance Test**

| Record No. | Date | Time | Operator | Fluid_ID | First / Subsequent | Start Temperature (degC) | End Temperature (degC) | Plate Start Temp (degC) | Plate End Temp (degC) | Taurus cycle duration (s) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Thermocouple | Thermocouple | Thermopile | Thermopile | |
| 1 | 2023/01/02 | 10:44 | Eave | 480mL 0.55% | Subsequent | 4.3 | 32.2 | | | 202.0 |
| 3 | 2023/01/09 | 9:07 | Eave | 480mL 0.55% | Subsequent | 4.4 | 33.4 | | | 212.0 |
| 5 | 2023/01/10 | 7:27 | Eave | 480mL 0.55% | Subsequent | 4.2 | 33.2 | | | 212.0 |
| 7 | 2023/01/11 | 8:21 | Eave | 480mL 0.55% | Subsequent | 4.2 | 33.1 | | | 213.0 |
| 9 | 2023/01/12 | 8:42 | Eave | 480mL 0.55% | Subsequent | 4.2 | 33.6 | | 42.8 | 217.0 |
| 11 | 2023/01/16 | 14:33 | Eave | 480mL 0.55% | Subsequent | 4.3 | 34.2 | | 42.0 | 217.0 |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| 2 | 2023/01/05 | 14:37 | Eave | 480mL 0.55% | First | 4.1 | 33.6 | | | 225.0 |
| 4 | 2023/01/09 | 15:02 | Eave | 480mL 0.55% | First | 3.9 | 33.5 | | | 220.0 |
| 6 | 2023/01/10 | 15:50 | Eave | 480mL 0.55% | First | 4.4 | 34.2 | | | 229.0 |
| 8 | 2023/01/11 | 14:57 | Eave | 480mL 0.55% | First | 4.4 | 33.6 | 23.3 | 38.8 | 227.0 |
| 10 | 2023/01/13 | 7:29 | Eave | 480mL 0.55% | First | 4.1 | 33.0 | 23.2 | 36.2 | 220.0 |
| 12 | 2023/01/17 | 8:35 | Eave | 480mL 0.55% | First | 4.0 | 35.8 | 23.2 | 39.9 | 242.0 |
| | | | | | | | | | | |
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## Appendix C: Raw Data

(Spreadsheet containing raw data collected during the study may be found following this page)

| Record_No | Data_ID | Date | Batch_Start_Time | Operator | Bag_ID | Warming_Sequence_No | First_or_Subsequent | First_or_Last | Temperature_Ambient_Start |
|---|---|---|---|---|---|---|---|---|---|
| 1.1 | 1 | 20/03/2023 | 7:53 | Eave | 1 | 1 | 1 | 1 | 22.2 |
| 1.2 | 2 | 20/03/2023 | 7:53 | Eave | 2 | 2 | 2 | 0 | 22.2 |
| 1.3 | 3 | 20/03/2023 | 7:53 | Eave | 3 | 3 | 2 | 0 | 22.2 |
| 1.4 | 4 | 20/03/2023 | 7:53 | Eave | 4 | 4 | 2 | 2 | 22.2 |
| 1.5 | 5 | 20/03/2023 | 14:04 | Eave | 2 | 1 | 1 | 1 | 22.4 |
| 1.6 | 6 | 20/03/2023 | 14:04 | Eave | 3 | 2 | 2 | 0 | 22.4 |
| 1.7 | 7 | 20/03/2023 | 14:04 | Eave | 4 | 3 | 2 | 0 | 22.4 |
| 1.8 | 8 | 20/03/2023 | 14:04 | Eave | 1 | 4 | 2 | 2 | 22.4 |
| 2.1 | 9 | 22/03/2023 | 8:03 | Eave | 3 | 1 | 1 | 1 | 21.3 |
| 2.2 | 10 | 22/03/2023 | 8:03 | Eave | 4 | 2 | 2 | 0 | 21.3 |
| 2.3 | 11 | 22/03/2023 | 8:03 | Eave | 1 | 3 | 2 | 0 | 21.3 |
| 2.4 | 12 | 22/03/2023 | 8:03 | Eave | 2 | 4 | 2 | 2 | 21.3 |
| 2.5 | 13 | 22/03/2023 | 15:02 | Eave | 4 | 1 | 1 | 1 | 21.6 |
| 2.6 | 14 | 22/03/2023 | 15:02 | Eave | 1 | 2 | 2 | 0 | 21.6 |
| 2.7 | 15 | 22/03/2023 | 15:02 | Eave | 2 | 3 | 2 | 0 | 21.6 |
| 2.8 | 16 | 22/03/2023 | 15:02 | Eave | 3 | 4 | 2 | 2 | 21.6 |
| 3.1 | 17 | 23/03/2023 | 9:10 | Eave | 1 | 1 | 1 | 1 | 22.1 |
| 3.2 | 18 | 23/03/2023 | 9:10 | Eave | 2 | 2 | 2 | 0 | 22.1 |
| 3.3 | 19 | 23/03/2023 | 9:10 | Eave | 3 | 3 | 2 | 0 | 22.1 |
| 3.4 | 20 | 23/03/2023 | 9:10 | Eave | 4 | 4 | 2 | 2 | 22.1 |
| 4.1 | 21 | 24/03/2023 | 7:38 | Eave | 2 | 1 | 1 | 1 | 22.4 |
| 4.2 | 22 | 24/03/2023 | 7:38 | Eave | 3 | 2 | 2 | 0 | 22.4 |
| 4.3 | 23 | 24/03/2023 | 7:38 | Eave | 4 | 3 | 2 | 0 | 22.4 |
| 4.4 | 24 | 24/03/2023 | 7:38 | Eave | 1 | 4 | 2 | 2 | 22.4 |
| 4.5 | 25 | 24/03/2023 | 15:00 | Eave | 3 | 1 | 1 | 1 | 21.9 |
| 4.6 | 26 | 24/03/2023 | 15:00 | Eave | 4 | 2 | 2 | 0 | 21.9 |
| 4.7 | 27 | 24/03/2023 | 15:00 | Eave | 1 | 3 | 2 | 0 | 21.9 |
| 4.8 | 28 | 24/03/2023 | 15:00 | Eave | 2 | 4 | 2 | 2 | 21.9 |
| 5.1 | 29 | 27/03/2023 | 8:20 | Eave | 4 | 1 | 1 | 1 | 22.3 |
| 5.2 | 30 | 27/03/2023 | 8:20 | Eave | 1 | 2 | 2 | 0 | 22.3 |
| 5.3 | 31 | 27/03/2023 | 8:20 | Eave | 2 | 3 | 2 | 0 | 22.3 |
| 5.4 | 32 | 27/03/2023 | 8:20 | Eave | 3 | 4 | 2 | 2 | 22.3 |
| 5.5 | 33 | 27/03/2023 | 14:46 | Eave | 1 | 1 | 1 | 1 | 21.7 |
| 5.6 | 34 | 27/03/2023 | 14:46 | Eave | 2 | 2 | 2 | 0 | 21.7 |
| 5.7 | 35 | 27/03/2023 | 14:46 | Eave | 3 | 3 | 2 | 0 | 21.7 |
| 5.8 | 36 | 27/03/2023 | 14:46 | Eave | 4 | 4 | 2 | 2 | 21.7 |
| 6.1 | 37 | 28/03/2023 | 8:10 | Eave | 2 | 1 | 1 | 1 | 21.7 |
| 6.2 | 38 | 28/03/2023 | 8:10 | Eave | 3 | 2 | 2 | 0 | 21.7 |
| 6.3 | 39 | 28/03/2023 | 8:10 | Eave | 4 | 3 | 2 | 0 | 21.7 |
| 6.4 | 40 | 28/03/2023 | 8:10 | Eave | 1 | 4 | 2 | 2 | 21.7 |
| 6.5 | 41 | 28/03/2023 | 14:46 | Eave | 3 | 1 | 1 | 1 | 21.8 |
| 6.6 | 42 | 28/03/2023 | 14:46 | Eave | 4 | 2 | 2 | 0 | 21.8 |
| 6.7 | 43 | 28/03/2023 | 14:46 | Eave | 1 | 3 | 2 | 0 | 21.8 |
| 6.8 | 44 | 28/03/2023 | 14:46 | Eave | 2 | 4 | 2 | 2 | 21.8 |
| 7.1 | 45 | 29/03/2023 | 11:00 | Eave | 4 | 1 | 1 | 1 | 21.6 |
| 7.2 | 46 | 29/03/2023 | 11:00 | Eave | 1 | 2 | 2 | 0 | 21.6 |
| 7.3 | 47 | 29/03/2023 | 11:00 | Eave | 2 | 3 | 2 | 0 | 21.6 |
| 7.4 | 48 | 29/03/2023 | 11:00 | Eave | 3 | 4 | 2 | 2 | 21.6 |
| 7.5 | 49 | 29/03/2023 | 15:05 | Eave | 1 | 1 | 1 | 1 | 21.6 |
| 7.6 | 50 | 29/03/2023 | 15:05 | Eave | 2 | 2 | 2 | 0 | 21.6 |
| 7.7 | 51 | 29/03/2023 | 15:05 | Eave | 3 | 3 | 2 | 0 | 21.6 |
| 7.8 | 52 | 29/03/2023 | 15:05 | Eave | 4 | 4 | 2 | 2 | 21.6 |
| 8.1 | 53 | 30/03/2023 | 7:25 | Eave | 2 | 1 | 1 | 1 | 21.7 |
| 8.2 | 54 | 30/03/2023 | 7:25 | Eave | 3 | 2 | 2 | 0 | 21.7 |
| 8.3 | 55 | 30/03/2023 | 7:25 | Eave | 4 | 3 | 2 | 0 | 21.7 |
| 8.4 | 56 | 30/03/2023 | 7:25 | Eave | 1 | 4 | 2 | 2 | 21.7 |
| 8.5 | 57 | 30/03/2023 | 14:00 | Eave | 3 | 1 | 1 | 1 | 21.5 |
| 8.6 | 58 | 30/03/2023 | 14:00 | Eave | 4 | 2 | 2 | 0 | 21.5 |
| 8.7 | 59 | 30/03/2023 | 14:00 | Eave | 1 | 3 | 2 | 0 | 21.5 |
| 8.8 | 60 | 30/03/2023 | 14:00 | Eave | 2 | 4 | 2 | 2 | 21.5 |
| 9.1 | 61 | 31/03/2023 | 7:20 | Eave | 4 | 1 | 1 | 1 | 21.6 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 9.2 | 62 | 31/03/2023 | 7:20 | Eave | 1 | 2 | 2 | 0 | 21.6 |
| 9.3 | 63 | 31/03/2023 | 7:20 | Eave | 2 | 3 | 2 | 0 | 21.6 |
| 9.4 | 64 | 31/03/2023 | 7:20 | Eave | 3 | 4 | 2 | 2 | 21.6 |
| 9.5 | 65 | 31/03/2023 | 15:00 | Eave | 1 | 1 | 1 | 1 | 21.8 |
| 9.6 | 66 | 31/03/2023 | 15:00 | Eave | 2 | 2 | 2 | 0 | 21.8 |
| 9.7 | 67 | 31/03/2023 | 15:00 | Eave | 3 | 3 | 2 | 0 | 21.8 |
| 9.8 | 68 | 31/03/2023 | 15:00 | Eave | 4 | 4 | 2 | 2 | 21.8 |
| 10.1 | 69 | 03/04/2023 | 11:00 | Eave | 2 | 1 | 1 | 1 | 21.5 |
| 10.2 | 70 | 03/04/2023 | 11:00 | Eave | 3 | 2 | 2 | 0 | 21.5 |
| 10.3 | 71 | 03/04/2023 | 11:00 | Eave | 4 | 3 | 2 | 0 | 21.5 |
| 10.4 | 72 | 03/04/2023 | 11:00 | Eave | 1 | 4 | 2 | 2 | 21.5 |
| 10.5 | 73 | 03/04/2023 | 15:00 | Eave | 3 | 1 | 1 | 1 | 21.7 |
| 10.6 | 74 | 03/04/2023 | 15:00 | Eave | 4 | 2 | 2 | 0 | 21.7 |
| 10.7 | 75 | 03/04/2023 | 15:00 | Eave | 1 | 3 | 2 | 0 | 21.7 |
| 10.8 | 76 | 03/04/2023 | 15:00 | Eave | 2 | 4 | 2 | 2 | 21.7 |
| 11.1 | 77 | 04/04/2023 | 7:30 | Eave | 4 | 1 | 1 | 1 | 21.8 |
| 11.2 | 78 | 04/04/2023 | 7:30 | Eave | 1 | 2 | 2 | 0 | 21.8 |
| 11.3 | 79 | 04/04/2023 | 7:30 | Eave | 2 | 3 | 2 | 0 | 21.8 |
| 11.4 | 80 | 04/04/2023 | 7:30 | Eave | 3 | 4 | 2 | 2 | 21.8 |
| 12.1 | 81 | 05/04/2023 | 7:40 | Eave | 2 | 1 | 1 | 1 | 21.9 |
| 12.2 | 82 | 05/04/2023 | 7:40 | Eave | 3 | 2 | 2 | 0 | 21.9 |
| 12.3 | 83 | 05/04/2023 | 7:40 | Eave | 4 | 3 | 2 | 0 | 21.9 |
| 12.4 | 84 | 05/04/2023 | 7:40 | Eave | 1 | 4 | 2 | 2 | 21.9 |
| 13.1 | 85 | 06/04/2023 | 10:05 | Eave | 3 | 1 | 1 | 1 | 22.1 |
| 13.2 | 86 | 06/04/2023 | 10:05 | Eave | 4 | 2 | 2 | 0 | 22.1 |
| 13.3 | 87 | 06/04/2023 | 10:05 | Eave | 1 | 3 | 2 | 0 | 22.1 |
| 13.4 | 88 | 06/04/2023 | 10:05 | Eave | 2 | 4 | 2 | 2 | 22.1 |
| 13.5 | 89 | 06/04/2023 | 15:30 | Eave | 4 | 1 | 1 | 1 | 21.3 |
| 13.6 | 90 | 06/04/2023 | 15:30 | Eave | 1 | 2 | 2 | 0 | 21.3 |
| 13.7 | 91 | 06/04/2023 | 15:30 | Eave | 2 | 3 | 2 | 0 | 21.3 |
| 13.8 | 92 | 06/04/2023 | 15:30 | Eave | 3 | 4 | 2 | 2 | 21.3 |
| 14.1 | 93 | 11/04/2023 | 8:25 | Eave | 1 | 1 | 1 | 1 | 21.7 |
| 14.2 | 94 | 11/04/2023 | 8:25 | Eave | 2 | 2 | 2 | 0 | 21.7 |
| 14.3 | 95 | 11/04/2023 | 8:25 | Eave | 3 | 3 | 2 | 0 | 21.7 |
| 14.4 | 96 | 11/04/2023 | 8:25 | Eave | 4 | 4 | 2 | 2 | 21.7 |

| Temperature_Bag_Start | Temperature_Plate_Start | Temperature_Bag_End | Temperature_Plate_End | Time_Cycle_Duration | Effective_Power |
|---|---|---|---|---|---|
| 4.6 | 22.5 | 36.5 | 32.1 | 194 | 147.85 |
| 4.7 | 31.5 | 35.2 | 32.9 | 167 | 164.22 |
| 4.9 | 32.3 | 35.3 | 33.4 | 151 | 181.02 |
| 4.9 | 32.7 | 34.6 | 32.9 | 143 | 186.75 |
| 4.7 | 23.6 | 36.0 | 32.6 | 185 | 152.13 |
| 4.6 | 31.6 | 35.5 | 32.9 | 156 | 178.10 |
| 4.7 | 32.1 | 35.4 | 33.3 | 148 | 186.51 |
| 4.4 | 32.4 | 35.3 | 33.5 | 153 | 181.60 |
| 4.5 | 22.3 | 36.4 | 31.9 | 188 | 152.57 |
| 4.8 | 30.7 | 35.7 | 33.0 | 154 | 180.42 |
| 4.1 | 32.1 | 35.7 | 33.3 | 159 | 178.70 |
| 3.8 | 32.4 | 35.4 | 33.5 | 158 | 179.83 |
| 4.6 | 23.0 | 36.4 | 31.1 | 183 | 156.25 |
| 4.5 | 30.0 | 35.7 | 32.7 | 167 | 167.99 |
| 4.3 | 32.0 | 35.3 | 33.5 | 163 | 171.01 |
| 4.5 | 32.7 | 35.2 | 33.3 | 154 | 179.25 |
| 4.5 | 23.0 | 36.4 | 32.2 | 193 | 148.62 |
| 4.2 | 31.4 | 35.5 | 33.4 | 166 | 169.54 |
| 4.2 | 32.5 | 34.9 | 32.8 | 149 | 185.26 |
| 4.1 | 32.3 | 35.5 | 33.4 | 155 | 182.15 |
| 4.2 | 22.4 | 36.4 | 32.7 | 189 | 153.19 |
| 4.4 | 31.7 | 35.9 | 32.5 | 162 | 174.84 |
| 4.6 | 31.6 | 36.3 | 33.3 | 160 | 178.15 |
| 4.1 | 32.4 | 35.6 | 33.4 | 156 | 181.56 |
| 4.6 | 22.9 | 33.7 | 29.6 | 160 | 163.53 |
| 4.3 | 28.9 | 35.9 | 32.7 | 161 | 176.48 |
| 4.3 | 32.0 | 35.4 | 33.3 | 158 | 176.99 |
| 4.6 | 32.5 | 35.4 | 33.5 | 156 | 177.53 |
| 4.4 | 22.2 | 36.9 | 31.9 | 187 | 156.27 |
| 4.2 | 31.1 | 35.7 | 33.0 | 163 | 173.76 |
| 4.5 | 32.2 | 35.9 | 33.6 | 157 | 179.83 |
| 4.8 | 32.7 | 35.0 | 32.9 | 141 | 192.59 |
| 4.4 | 23.1 | 36.4 | 32.3 | 187 | 153.87 |
| 4.5 | 31.5 | 35.2 | 33.0 | 158 | 174.71 |
| 4.8 | 32.1 | 35.0 | 32.9 | 149 | 182.25 |
| 4.6 | 32.2 | 34.6 | 32.9 | 145 | 186.03 |
| 4.8 | 22.6 | 36.1 | 32.4 | 191 | 147.35 |
| 4.8 | 31.6 | 35.7 | 33.1 | 161 | 172.57 |
| 4.5 | 32.1 | 35.0 | 33.3 | 150 | 182.83 |
| 4.3 | 32.2 | 35.1 | 33.5 | 157 | 176.40 |
| 4.5 | 23.2 | 35.9 | 31.7 | 181 | 155.99 |
| 5.0 | 30.7 | 36.6 | 32.8 | 159 | 178.70 |
| 4.6 | 31.8 | 35.3 | 33.3 | 156 | 176.95 |
| 4.5 | 32.5 | 35.6 | 33.2 | 155 | 180.41 |
| 4.5 | 22.8 | 35.8 | 31.7 | 184 | 152.95 |
| 4.4 | 30.9 | 35.7 | 33.0 | 167 | 168.53 |
| 4.3 | 32.3 | 35.9 | 33.3 | 164 | 173.25 |
| 4.7 | 32.5 | 35.7 | 33.5 | 155 | 179.83 |
| 4.9 | 24.0 | 35.8 | 32.2 | 181 | 153.50 |
| 4.9 | 31.3 | 35.3 | 33.1 | 157 | 174.10 |
| 5.0 | 32.2 | 35.2 | 33.2 | 153 | 177.48 |
| 4.9 | 32.4 | 35.7 | 33.3 | 150 | 184.63 |
| 4.4 | 27.7 | 35.8 | 32.3 | 193 | 146.29 |
| 4.6 | 31.5 | 35.9 | 32.8 | 158 | 178.12 |
| 4.7 | 32.1 | 36.2 | 33.3 | 157 | 180.40 |
| 4.6 | 32.5 | 35.6 | 33.7 | 156 | 178.68 |
| 4.5 | 23.0 | 36.4 | 31.9 | 187 | 153.39 |
| 4.8 | 31.3 | 35.8 | 32.9 | 158 | 176.42 |
| 4.5 | 32.3 | 35.5 | 33.2 | 158 | 176.42 |
| 4.5 | 32.4 | 35.4 | 32.9 | 156 | 178.10 |
| 5.0 | 22.7 | 36.1 | 32.2 | 187 | 149.54 |

| | | | | | |
|---|---|---|---|---|---|
| 4.8 | 31.4 | 35.7 | 33.1 | 163 | 170.45 |
| 4.8 | 32.6 | 35.2 | 33.5 | 155 | 176.35 |
| 4.8 | 32.9 | 35.3 | 33.6 | 154 | 178.08 |
| 4.3 | 23.1 | 35.8 | 32.1 | 187 | 151.46 |
| 4.9 | 31.4 | 35.1 | 33.2 | 160 | 169.72 |
| 4.8 | 32.5 | 35.3 | 33.3 | 154 | 178.08 |
| 4.7 | 32.6 | 35.5 | 33.3 | 150 | 184.63 |
| 4.8 | 22.6 | 36.0 | 32.0 | 187 | 150.02 |
| 4.4 | 31.3 | 35.3 | 33.0 | 156 | 178.10 |
| 4.9 | 32.1 | 35.2 | 33.2 | 151 | 180.43 |
| 4.9 | 32.5 | 35.6 | 33.3 | 157 | 175.82 |
| 5.0 | 24.3 | 36.4 | 31.8 | 176 | 160.42 |
| 5.0 | 31.2 | 36.7 | 33.3 | 156 | 182.71 |
| 4.9 | 32.6 | 35.8 | 33.5 | 153 | 181.60 |
| 4.9 | 32.8 | 35.3 | 33.6 | 151 | 181.02 |
| 5.0 | 23.4 | 36.4 | 32.1 | 187 | 150.98 |
| 4.9 | 31.4 | 35.9 | 33.5 | 163 | 171.01 |
| 5.0 | 32.7 | 35.4 | 32.8 | 155 | 176.35 |
| 5.0 | 33.1 | 35.4 | 33.8 | 150 | 182.23 |
| 4.6 | 23.8 | 35.9 | 32.3 | 187 | 150.50 |
| 4.7 | 31.7 | 35.7 | 33.2 | 160 | 174.21 |
| 4.6 | 32.8 | 35.4 | 33.1 | 151 | 183.40 |
| 4.6 | 32.3 | 35.1 | 33.3 | 151 | 181.62 |
| 4.9 | 24.0 | 36.2 | 31.8 | 180 | 156.35 |
| 5.0 | 31.0 | 35.9 | 32.8 | 156 | 178.10 |
| 4.6 | 32.1 | 35.7 | 33.3 | 158 | 176.99 |
| 4.8 | 32.7 | 35.8 | 33.4 | 156 | 178.68 |
| 5.0 | 22.1 | 36.6 | 31.9 | 185 | 153.59 |
| 5.0 | 31.1 | 35.9 | 33.1 | 157 | 176.97 |
| 4.6 | 32.3 | 35.7 | 33.3 | 153 | 182.77 |
| 4.8 | 32.6 | 35.8 | 33.2 | 149 | 187.07 |
| 4.7 | 22.0 | 36.5 | 31.8 | 181 | 157.97 |
| 4.6 | 31.3 | 35.8 | 33.1 | 162 | 173.17 |
| 4.8 | 32.4 | 35.7 | 33.6 | 157 | 176.97 |
| 4.7 | 32.8 | 35.2 | 33.3 | 149 | 184.06 |

## Appendix D: Conductive Heat Energy Calculations

(Spreadsheet demonstrating calculations estimating conductive heat energy transfer)

| | | | |
|---|---|---|---|
| Mass of empty bag (g) | 30 | | |
| Mass of bag filled (g) | 240 | | |
| Mass of fluid (g) | 210 | | |
| | | | |
| Contact area (mm^2) & (m^2) & (cm^2) | 10956 | 0.010956 | 109.56 |
| | | | |
| PVC_thickness (mm) & (m) | 0.3 | | |
| PVC_thermal_conductivity | 0.19 | | |
| | | | |
| PVC_specific_heat (J/g) | 0.88 | | |
| Saline_specific_heat (J/g) | 4.156 | | |

| | First warming instance | Fourth warming instance |
|---|---|---|
| Plate start temperature (mean) | 23.17916667 | 32.54583333 |
| Plate end temperature (mean) | 31.94166667 | 33.34166667 |
| Bag start temperature (mean) | 4.641666667 | 4.604166667 |
| Bag end temperature (mean) | 36.11666667 | 35.3625 |
| Duration of warming cycle (mean) | 185 | 152.375 |
| | | |
| Bag rate of temperature rise (degC/s) | 0.170135135 | 0.201859448 |
| Plate rate of temperature rise (degC/s) | 0.047364865 | 0.00522286 |

| | | |
|---|---|---|
| Contact area (mm^2) & (m^2) & (cm^2) | 10400 | 0.0104 |
| | | |
| PVC_thickness (mm) & (m) | 0.4 | 0.0004 |
| PVC_thermal_conductivity | 0.2 | |
| PVC_specific_heat (J/g) | 0.88 | |
| Saline_specific_heat (J/g) | 4.156 | |

$$\frac{Q}{t} = kA\frac{T_1 - T_2}{l}$$

| | First warming instance | Fourth warming instance |
|---|---|---|
| Conductive Heat Transfer Rate (W) | 37.54435135 | 97.03044743 |

First warming instance

| Time | Bag Temperatu | Take-up Plate Te | Delta_T | Energy_transfer | Cumulative_energy_transfer |
|---|---|---|---|---|---|
| 0 | 4.641666667 | 23.17916667 | 18.5375 | 96.395 | 96.395 |
| 1 | 4.811801802 | 23.22653153 | 18.41473 | 95.75659459 | 192.1515946 |
| 2 | 4.981936937 | 23.2738964 | 18.291959 | 95.11818919 | 287.2697838 |
| 3 | 5.152072072 | 23.32126126 | 18.169189 | 94.47978378 | 381.7495676 |
| 4 | 5.322207207 | 23.36862613 | 18.046419 | 93.84137838 | 475.5909459 |
| 5 | 5.492342342 | 23.41599099 | 17.923649 | 93.20297297 | 568.7939189 |
| 6 | 5.662477477 | 23.46335586 | 17.800878 | 92.56456757 | 661.3584865 |
| 7 | 5.832612613 | 23.51072072 | 17.678108 | 91.92616216 | 753.2846486 |
| 8 | 6.002747748 | 23.55808559 | 17.555338 | 91.28775676 | 844.5724054 |
| 9 | 6.172882883 | 23.60545045 | 17.432568 | 90.64935135 | 935.2217568 |
| 10 | 6.343018018 | 23.65281532 | 17.309797 | 90.01094595 | 1025.232703 |
| 11 | 6.513153153 | 23.70018018 | 17.187027 | 89.37254054 | 1114.605243 |
| 12 | 6.683288288 | 23.74754505 | 17.064257 | 88.73413514 | 1203.339378 |
| 13 | 6.853423423 | 23.79490991 | 16.941486 | 88.09572973 | 1291.435108 |
| 14 | 7.023558559 | 23.84227477 | 16.818716 | 87.45732432 | 1378.892432 |
| 15 | 7.193693694 | 23.88963964 | 16.695946 | 86.81891892 | 1465.711351 |
| 16 | 7.363828829 | 23.9370045 | 16.573176 | 86.18051351 | 1551.891865 |
| 17 | 7.533963964 | 23.98436937 | 16.450405 | 85.54210811 | 1637.433973 |
| 18 | 7.704099099 | 24.03173423 | 16.327635 | 84.9037027 | 1722.337676 |
| 19 | 7.874234234 | 24.0790991 | 16.204865 | 84.2652973 | 1806.602973 |
| 20 | 8.044369369 | 24.12646396 | 16.082095 | 83.62689189 | 1890.229865 |
| 21 | 8.214504505 | 24.17382883 | 15.959324 | 82.98848649 | 1973.218351 |
| 22 | 8.38463964 | 24.22119369 | 15.836554 | 82.35008108 | 2055.568432 |
| 23 | 8.554774775 | 24.26855856 | 15.713784 | 81.71167568 | 2137.280108 |
| 24 | 8.72490991 | 24.31592342 | 15.591014 | 81.07327027 | 2218.353378 |
| 25 | 8.895045045 | 24.36328829 | 15.468243 | 80.43486486 | 2298.788243 |
| 26 | 9.06518018 | 24.41065315 | 15.345473 | 79.79645946 | 2378.584703 |
| 27 | 9.235315315 | 24.45801802 | 15.222703 | 79.15805405 | 2457.742757 |
| 28 | 9.40545045 | 24.50538288 | 15.099932 | 78.51964865 | 2536.262405 |
| 29 | 9.575585586 | 24.55274775 | 14.977162 | 77.88124324 | 2614.143649 |
| 30 | 9.745720721 | 24.60011261 | 14.854392 | 77.24283784 | 2691.386486 |
| 31 | 9.915855856 | 24.64747748 | 14.731622 | 76.60443243 | 2767.990919 |
| 32 | 10.08599099 | 24.69484234 | 14.608851 | 75.96602703 | 2843.956946 |
| 33 | 10.25612613 | 24.74220721 | 14.486081 | 75.32762162 | 2919.284568 |
| 34 | 10.42626126 | 24.78957207 | 14.363311 | 74.68921622 | 2993.973784 |
| 35 | 10.5963964 | 24.83693694 | 14.240541 | 74.05081081 | 3068.024595 |
| 36 | 10.76653153 | 24.8843018 | 14.11777 | 73.41240541 | 3141.437 |
| 37 | 10.93666667 | 24.93166667 | 13.995 | 72.774 | 3214.211 |
| 38 | 11.1068018 | 24.97903153 | 13.87223 | 72.13559459 | 3286.346595 |
| 39 | 11.27693694 | 25.0263964 | 13.749459 | 71.49718919 | 3357.843784 |
| 40 | 11.44707207 | 25.07376126 | 13.626689 | 70.85878378 | 3428.702568 |
| 41 | 11.61720721 | 25.12112613 | 13.503919 | 70.22037838 | 3498.922946 |
| 42 | 11.78734234 | 25.16849099 | 13.381149 | 69.58197297 | 3568.504919 |
| 43 | 11.95747748 | 25.21585586 | 13.258378 | 68.94356757 | 3637.448486 |
| 44 | 12.12761261 | 25.26322072 | 13.135608 | 68.30516216 | 3705.753649 |
| 45 | 12.29774775 | 25.31058559 | 13.012838 | 67.66675676 | 3773.420405 |
| 46 | 12.46788288 | 25.35795045 | 12.890068 | 67.02835135 | 3840.448757 |
| 47 | 12.63801802 | 25.40531532 | 12.767297 | 66.38994595 | 3906.838703 |
| 48 | 12.80815315 | 25.45268018 | 12.644527 | 65.75154054 | 3972.590243 |
| 49 | 12.97828829 | 25.50004505 | 12.521757 | 65.11313514 | 4037.703378 |
| 50 | 13.14842342 | 25.54740991 | 12.398986 | 64.47472973 | 4102.178108 |
| 51 | 13.31855856 | 25.59477477 | 12.276216 | 63.83632432 | 4166.014432 |
| 52 | 13.48869369 | 25.64213964 | 12.153446 | 63.19791892 | 4229.212351 |
| 53 | 13.65882883 | 25.6895045 | 12.030676 | 62.55951351 | 4291.771865 |
| 54 | 13.82896396 | 25.73686937 | 11.907905 | 61.92110811 | 4353.692973 |
| 55 | 13.9990991 | 25.78423423 | 11.785135 | 61.2827027 | 4414.975676 |

| | | | | | |
|---|---|---|---|---|---|
| 56 | 14.16923423 | 25.8315991 | 11.662365 | 60.6442973 | 4475.619973 |
| 57 | 14.33936937 | 25.87896396 | 11.539595 | 60.00589189 | 4535.625865 |
| 58 | 14.5095045 | 25.92632883 | 11.416824 | 59.36748649 | 4594.993351 |
| 59 | 14.67963964 | 25.97369369 | 11.294054 | 58.72908108 | 4653.722432 |
| 60 | 14.84977477 | 26.02105856 | 11.171284 | 58.09067568 | 4711.813108 |
| 61 | 15.01990991 | 26.06842342 | 11.048514 | 57.45227027 | 4769.265378 |
| 62 | 15.19004505 | 26.11578829 | 10.925743 | 56.81386486 | 4826.079243 |
| 63 | 15.36018018 | 26.16315315 | 10.802973 | 56.17545946 | 4882.254703 |
| 64 | 15.53031532 | 26.21051802 | 10.680203 | 55.53705405 | 4937.791757 |
| 65 | 15.70045045 | 26.25788288 | 10.557432 | 54.89864865 | 4992.690405 |
| 66 | 15.87058559 | 26.30524775 | 10.434662 | 54.26024324 | 5046.950649 |
| 67 | 16.04072072 | 26.35261261 | 10.311892 | 53.62183784 | 5100.572486 |
| 68 | 16.21085586 | 26.39997748 | 10.189122 | 52.98343243 | 5153.555919 |
| 69 | 16.38099099 | 26.44734234 | 10.066351 | 52.34502703 | 5205.900946 |
| 70 | 16.55112613 | 26.49470721 | 9.9435811 | 51.70662162 | 5257.607568 |
| 71 | 16.72126126 | 26.54207207 | 9.8208108 | 51.06821622 | 5308.675784 |
| 72 | 16.8913964 | 26.58943694 | 9.6980405 | 50.42981081 | 5359.105595 |
| 73 | 17.06153153 | 26.6368018 | 9.5752703 | 49.79140541 | 5408.897 |
| 74 | 17.23166667 | 26.68416667 | 9.4525 | 49.153 | 5458.05 |
| 75 | 17.4018018 | 26.73153153 | 9.3297297 | 48.51459459 | 5506.564595 |
| 76 | 17.57193694 | 26.7788964 | 9.2069595 | 47.87618919 | 5554.440784 |
| 77 | 17.74207207 | 26.82626126 | 9.0841892 | 47.23778378 | 5601.678568 |
| 78 | 17.91220721 | 26.87362613 | 8.9614189 | 46.59937838 | 5648.277946 |
| 79 | 18.08234234 | 26.92099099 | 8.8386486 | 45.96097297 | 5694.238919 |
| 80 | 18.25247748 | 26.96835586 | 8.7158784 | 45.32256757 | 5739.561486 |
| 81 | 18.42261261 | 27.01572072 | 8.5931081 | 44.68416216 | 5784.245649 |
| 82 | 18.59274775 | 27.06308559 | 8.4703378 | 44.04575676 | 5828.291405 |
| 83 | 18.76288288 | 27.11045045 | 8.3475676 | 43.40735135 | 5871.698757 |
| 84 | 18.93301802 | 27.15781532 | 8.2247973 | 42.76894595 | 5914.467703 |
| 85 | 19.10315315 | 27.20518018 | 8.102027 | 42.13054054 | 5956.598243 |
| 86 | 19.27328829 | 27.25254505 | 7.9792568 | 41.49213514 | 5998.090378 |
| 87 | 19.44342342 | 27.29990991 | 7.8564865 | 40.85372973 | 6038.944108 |
| 88 | 19.61355856 | 27.34727477 | 7.7337162 | 40.21532432 | 6079.159432 |
| 89 | 19.78369369 | 27.39463964 | 7.6109459 | 39.57691892 | 6118.736351 |
| 90 | 19.95382883 | 27.4420045 | 7.4881757 | 38.93851351 | 6157.674865 |
| 91 | 20.12396396 | 27.48936937 | 7.3654054 | 38.30010811 | 6195.974973 |
| 92 | 20.2940991 | 27.53673423 | 7.2426351 | 37.6617027 | 6233.636676 |
| 93 | 20.46423423 | 27.5840991 | 7.1198649 | 37.0232973 | 6270.659973 |
| 94 | 20.63436937 | 27.63146396 | 6.9970946 | 36.38489189 | 6307.044865 |
| 95 | 20.8045045 | 27.67882883 | 6.8743243 | 35.74648649 | 6342.791351 |
| 96 | 20.97463964 | 27.72619369 | 6.7515541 | 35.10808108 | 6377.899432 |
| 97 | 21.14477477 | 27.77355856 | 6.6287838 | 34.46967568 | 6412.369108 |
| 98 | 21.31490991 | 27.82092342 | 6.5060135 | 33.83127027 | 6446.200378 |
| 99 | 21.48504505 | 27.86828829 | 6.3832432 | 33.19286486 | 6479.393243 |
| 100 | 21.65518018 | 27.91565315 | 6.260473 | 32.55445946 | 6511.947703 |
| 101 | 21.82531532 | 27.96301802 | 6.1377027 | 31.91605405 | 6543.863757 |
| 102 | 21.99545045 | 28.01038288 | 6.0149324 | 31.27764865 | 6575.141405 |
| 103 | 22.16558559 | 28.05774775 | 5.8921622 | 30.63924324 | 6605.780649 |
| 104 | 22.33572072 | 28.10511261 | 5.7693919 | 30.00083784 | 6635.781486 |
| 105 | 22.50585586 | 28.15247748 | 5.6466216 | 29.36243243 | 6665.143919 |
| 106 | 22.67599099 | 28.19984234 | 5.5238514 | 28.72402703 | 6693.867946 |
| 107 | 22.84612613 | 28.24720721 | 5.4010811 | 28.08562162 | 6721.953568 |
| 108 | 23.01626126 | 28.29457207 | 5.2783108 | 27.44721622 | 6749.400784 |
| 109 | 23.1863964 | 28.34193694 | 5.1555405 | 26.80881081 | 6776.209595 |
| 110 | 23.35653153 | 28.3893018 | 5.0327703 | 26.17040541 | 6802.38 |
| 111 | 23.52666667 | 28.43666667 | 4.91 | 25.532 | 6827.912 |
| 112 | 23.6968018 | 28.48403153 | 4.7872297 | 24.89359459 | 6852.805595 |
| 113 | 23.86693694 | 28.5313964 | 4.6644595 | 24.25518919 | 6877.060784 |
| 114 | 24.03707207 | 28.57876126 | 4.5416892 | 23.61678378 | 6900.677568 |

| | | | | | |
|---|---|---|---|---|---|
| 115 | 24.20720721 | 28.62612613 | 4.4189189 | 22.97837838 | 6923.655946 |
| 116 | 24.37734234 | 28.67349099 | 4.2961486 | 22.33997297 | 6945.995919 |
| 117 | 24.54747748 | 28.72085586 | 4.1733784 | 21.70156757 | 6967.697486 |
| 118 | 24.71761261 | 28.76822072 | 4.0506081 | 21.06316216 | 6988.760649 |
| 119 | 24.88774775 | 28.81558559 | 3.9278378 | 20.42475676 | 7009.185405 |
| 120 | 25.05788288 | 28.86295045 | 3.8050676 | 19.78635135 | 7028.971757 |
| 121 | 25.22801802 | 28.91031532 | 3.6822973 | 19.14794595 | 7048.119703 |
| 122 | 25.39815315 | 28.95768018 | 3.559527 | 18.50954054 | 7066.629243 |
| 123 | 25.56828829 | 29.00504505 | 3.4367568 | 17.87113514 | 7084.500378 |
| 124 | 25.73842342 | 29.05240991 | 3.3139865 | 17.23272973 | 7101.733108 |
| 125 | 25.90855856 | 29.09977477 | 3.1912162 | 16.59432432 | 7118.327432 |
| 126 | 26.07869369 | 29.14713964 | 3.0684459 | 15.95591892 | 7134.283351 |
| 127 | 26.24882883 | 29.1945045 | 2.9456757 | 15.31751351 | 7149.600865 |
| 128 | 26.41896396 | 29.24186937 | 2.8229054 | 14.67910811 | 7164.279973 |
| 129 | 26.5890991 | 29.28923423 | 2.7001351 | 14.0407027 | 7178.320676 |
| 130 | 26.75923423 | 29.3365991 | 2.5773649 | 13.4022973 | 7191.722973 |
| 131 | 26.92936937 | 29.38396396 | 2.4545946 | 12.76389189 | 7204.486865 |
| 132 | 27.0995045 | 29.43132883 | 2.3318243 | 12.12548649 | 7216.612351 |
| 133 | 27.26963964 | 29.47869369 | 2.2090541 | 11.48708108 | 7228.099432 |
| 134 | 27.43977477 | 29.52605856 | 2.0862838 | 10.84867568 | 7238.948108 |
| 135 | 27.60990991 | 29.57342342 | 1.9635135 | 10.21027027 | 7249.158378 |
| 136 | 27.78004505 | 29.62078829 | 1.8407432 | 9.571864865 | 7258.730243 |
| 137 | 27.95018018 | 29.66815315 | 1.717973 | 8.933459459 | 7267.663703 |
| 138 | 28.12031532 | 29.71551802 | 1.5952027 | 8.295054054 | 7275.958757 |
| 139 | 28.29045045 | 29.76288288 | 1.4724324 | 7.656648649 | 7283.615405 |
| 140 | 28.46058559 | 29.81024775 | 1.3496622 | 7.018243243 | 7290.633649 |
| 141 | 28.63072072 | 29.85761261 | 1.2268919 | 6.379837838 | 7297.013486 |
| 142 | 28.80085586 | 29.90497748 | 1.1041216 | 5.741432432 | 7302.754919 |
| 143 | 28.97099099 | 29.95234234 | 0.9813514 | 5.103027027 | 7307.857946 |
| 144 | 29.14112613 | 29.99970721 | 0.8585811 | 4.464621622 | 7312.322568 |
| 145 | 29.31126126 | 30.04707207 | 0.7358108 | 3.826216216 | 7316.148784 |
| 146 | 29.4813964 | 30.09443694 | 0.6130405 | 3.187810811 | 7319.336595 |
| 147 | 29.65153153 | 30.1418018 | 0.4902703 | 2.549405405 | 7321.886 |
| 148 | 29.82166667 | 30.18916667 | 0.3675 | 1.911 | 7323.797 |
| 149 | 29.9918018 | 30.23653153 | 0.2447297 | 1.272594595 | 7325.069595 |
| 150 | 30.16193694 | 30.2838964 | 0.1219595 | 0.634189189 | 7325.703784 |
| 151 | 30.33207207 | 30.33126126 | -0.000811 | -0.004216216 | 7325.699568 |
| 152 | 30.50220721 | 30.37862613 | -0.123581 | -0.642621622 | 7325.056946 |
| 153 | 30.67234234 | 30.42599099 | -0.246351 | -1.281027027 | 7323.775919 |
| 154 | 30.84247748 | 30.47335586 | -0.369122 | -1.919432432 | 7321.856486 |
| 155 | 31.01261261 | 30.52072072 | -0.491892 | -2.557837838 | 7319.298649 |
| 156 | 31.18274775 | 30.56808559 | -0.614662 | -3.196243243 | 7316.102405 |
| 157 | 31.35288288 | 30.61545045 | -0.737432 | -3.834648649 | 7312.267757 |
| 158 | 31.52301802 | 30.66281532 | -0.860203 | -4.473054054 | 7307.794703 |
| 159 | 31.69315315 | 30.71018018 | -0.982973 | -5.111459459 | 7302.683243 |
| 160 | 31.86328829 | 30.75754505 | -1.105743 | -5.749864865 | 7296.933378 |
| 161 | 32.03342342 | 30.80490991 | -1.228514 | -6.38827027 | 7290.545108 |
| 162 | 32.20355856 | 30.85227477 | -1.351284 | -7.026675676 | 7283.518432 |
| 163 | 32.37369369 | 30.89963964 | -1.474054 | -7.665081081 | 7275.853351 |
| 164 | 32.54382883 | 30.9470045 | -1.596824 | -8.303486486 | 7267.549865 |
| 165 | 32.71396396 | 30.99436937 | -1.719595 | -8.941891892 | 7258.607973 |
| 166 | 32.8840991 | 31.04173423 | -1.842365 | -9.580297297 | 7249.027676 |
| 167 | 33.05423423 | 31.0890991 | -1.965135 | -10.2187027 | 7238.808973 |
| 168 | 33.22436937 | 31.13646396 | -2.087905 | -10.85710811 | 7227.951865 |
| 169 | 33.3945045 | 31.18382883 | -2.210676 | -11.49551351 | 7216.456351 |
| 170 | 33.56463964 | 31.23119369 | -2.333446 | -12.13391892 | 7204.322432 |
| 171 | 33.73477477 | 31.27855856 | -2.456216 | -12.77232432 | 7191.550108 |
| 172 | 33.90490991 | 31.32592342 | -2.578986 | -13.41072973 | 7178.139378 |
| 173 | 34.07504505 | 31.37328829 | -2.701757 | -14.04913514 | 7164.090243 |

| | | | | | |
|---|---|---|---|---|---|
| 174 | 34.24518018 | 31.42065315 | -2.824527 | -14.68754054 | 7149.402703 |
| 175 | 34.41531532 | 31.46801802 | -2.947297 | -15.32594595 | 7134.076757 |
| 176 | 34.58545045 | 31.51538288 | -3.070068 | -15.96435135 | 7118.112405 |
| 177 | 34.75558559 | 31.56274775 | -3.192838 | -16.60275676 | 7101.509649 |
| 178 | 34.92572072 | 31.61011261 | -3.315608 | -17.24116216 | 7084.268486 |
| 179 | 35.09585586 | 31.65747748 | -3.438378 | -17.87956757 | 7066.388919 |
| 180 | 35.26599099 | 31.70484234 | -3.561149 | -18.51797297 | 7047.870946 |
| 181 | 35.43612613 | 31.75220721 | -3.683919 | -19.15637838 | 7028.714568 |
| 182 | 35.60626126 | 31.79957207 | -3.806689 | -19.79478378 | 7008.919784 |
| 183 | 35.7763964 | 31.84693694 | -3.929459 | -20.43318919 | 6988.486595 |
| 184 | 35.94653153 | 31.8943018 | -4.05223 | -21.07159459 | 6967.415 |
| 185 | 36.11666667 | 31.94166667 | -4.175 | -21.71 | 6945.705 |

Fourth warming instance

| Time | Bag Temperatur | Take-up Plate Te | Delta_T | Energy_transfer | Cumulative_energy_transfer |
|---|---|---|---|---|---|
| 0 | 4.604166667 | 32.54583333 | 27.94166667 | 145.2966667 | 145.2966667 |
| 1 | 4.806026114 | 32.55105619 | 27.74503008 | 144.2741564 | 289.5708231 |
| 2 | 4.976161249 | 32.59842106 | 27.62225981 | 143.635751 | 433.2065741 |
| 3 | 5.146296385 | 32.64578592 | 27.49948954 | 142.9973456 | 576.2039197 |
| 4 | 5.31643152 | 32.69315079 | 27.37671927 | 142.3589402 | 718.5628599 |
| 5 | 5.486566655 | 32.74051565 | 27.253949 | 141.7205348 | 860.2833947 |
| 6 | 5.65670179 | 32.78788052 | 27.13117873 | 141.0821294 | 1001.365524 |
| 7 | 5.826836925 | 32.83524538 | 27.00840846 | 140.443724 | 1141.809248 |
| 8 | 5.99697206 | 32.88261025 | 26.88563819 | 139.8053186 | 1281.614567 |
| 9 | 6.167107195 | 32.92997511 | 26.76286792 | 139.1669132 | 1420.78148 |
| 10 | 6.337242331 | 32.97733998 | 26.64009765 | 138.5285078 | 1559.309988 |
| 11 | 6.507377466 | 33.02470484 | 26.51732738 | 137.8901024 | 1697.20009 |
| 12 | 6.677512601 | 33.07206971 | 26.39455711 | 137.251697 | 1834.451787 |
| 13 | 6.847647736 | 33.11943457 | 26.27178684 | 136.6132915 | 1971.065078 |
| 14 | 7.017782871 | 33.16679944 | 26.14901657 | 135.9748861 | 2107.039965 |
| 15 | 7.187918006 | 33.2141643 | 26.0262463 | 135.3364807 | 2242.376445 |
| 16 | 7.358053141 | 33.26152917 | 25.90347603 | 134.6980753 | 2377.074521 |
| 17 | 7.528188276 | 33.30889403 | 25.78070575 | 134.0596699 | 2511.134191 |
| 18 | 7.698323412 | 33.3562589 | 25.65793548 | 133.4212645 | 2644.555455 |
| 19 | 7.868458547 | 33.40362376 | 25.53516521 | 132.7828591 | 2777.338314 |
| 20 | 8.038593682 | 33.45098863 | 25.41239494 | 132.1444537 | 2909.482768 |
| 21 | 8.208728817 | 33.49835349 | 25.28962467 | 131.5060483 | 3040.988816 |
| 22 | 8.378863952 | 33.54571836 | 25.1668544 | 130.8676429 | 3171.856459 |
| 23 | 8.548999087 | 33.59308322 | 25.04408413 | 130.2292375 | 3302.085697 |
| 24 | 8.719134222 | 33.64044809 | 24.92131386 | 129.5908321 | 3431.676529 |
| 25 | 8.889269358 | 33.68781295 | 24.79854359 | 128.9524267 | 3560.628955 |
| 26 | 9.059404493 | 33.73517782 | 24.67577332 | 128.3140213 | 3688.942977 |
| 27 | 9.229539628 | 33.78254268 | 24.55300305 | 127.6756159 | 3816.618593 |
| 28 | 9.399674763 | 33.82990754 | 24.43023278 | 127.0372105 | 3943.655803 |
| 29 | 9.569809898 | 33.87727241 | 24.30746251 | 126.3988051 | 4070.054608 |
| 30 | 9.739945033 | 33.92463727 | 24.18469224 | 125.7603997 | 4195.815008 |
| 31 | 9.910080168 | 33.97200214 | 24.06192197 | 125.1219943 | 4320.937002 |
| 32 | 10.0802153 | 34.019367 | 23.9391517 | 124.4835888 | 4445.420591 |
| 33 | 10.25035044 | 34.06673187 | 23.81638143 | 123.8451834 | 4569.265774 |
| 34 | 10.42048557 | 34.11409673 | 23.69361116 | 123.206778 | 4692.472552 |
| 35 | 10.59062071 | 34.1614616 | 23.57084089 | 122.5683726 | 4815.040925 |
| 36 | 10.76075584 | 34.20882646 | 23.44807062 | 121.9299672 | 4936.970892 |
| 37 | 10.93089098 | 34.25619133 | 23.32530035 | 121.2915618 | 5058.262454 |
| 38 | 11.10102611 | 34.30355619 | 23.20253008 | 120.6531564 | 5178.91561 |
| 39 | 11.27116125 | 34.35092106 | 23.07975981 | 120.014751 | 5298.930361 |
| 40 | 11.44129638 | 34.39828592 | 22.95698954 | 119.3763456 | 5418.306707 |
| 41 | 11.61143152 | 34.44565079 | 22.83421927 | 118.7379402 | 5537.044647 |
| 42 | 11.78156665 | 34.49301565 | 22.711449 | 118.0995348 | 5655.144182 |
| 43 | 11.95170179 | 34.54038052 | 22.58867873 | 117.4611294 | 5772.605311 |
| 44 | 12.12183693 | 34.58774538 | 22.46590846 | 116.822724 | 5889.428035 |
| 45 | 12.29197206 | 34.63511025 | 22.34313819 | 116.1843186 | 6005.612354 |
| 46 | 12.4621072 | 34.68247511 | 22.22036792 | 115.5459132 | 6121.158267 |
| 47 | 12.63224233 | 34.72983998 | 22.09759765 | 114.9075078 | 6236.065775 |
| 48 | 12.80237747 | 34.77720484 | 21.97482738 | 114.2691024 | 6350.334877 |
| 49 | 12.9725126 | 34.82456971 | 21.85205711 | 113.630697 | 6463.965574 |
| 50 | 13.14264774 | 34.87193457 | 21.72928684 | 112.9922915 | 6576.957866 |
| 51 | 13.31278287 | 34.91929944 | 21.60651657 | 112.3538861 | 6689.311752 |
| 52 | 13.48291801 | 34.9666643 | 21.4837463 | 111.7154807 | 6801.027233 |
| 53 | 13.65305314 | 35.01402917 | 21.36097603 | 111.0770753 | 6912.104308 |
| 54 | 13.82318828 | 35.06139403 | 21.23820575 | 110.4386699 | 7022.542978 |
| 55 | 13.99332341 | 35.1087589 | 21.11543548 | 109.8002645 | 7132.343242 |

| | | | | | |
|---|---|---|---|---|---|
| 56 | 14.16345855 | 35.15612376 | 20.99266521 | 109.1618591 | 7241.505101 |
| 57 | 14.33359368 | 35.20348863 | 20.86989494 | 108.5234537 | 7350.028555 |
| 58 | 14.50372882 | 35.25085349 | 20.74712467 | 107.8850483 | 7457.913603 |
| 59 | 14.67386395 | 35.29821836 | 20.6243544 | 107.2466429 | 7565.160246 |
| 60 | 14.84399909 | 35.34558322 | 20.50158413 | 106.6082375 | 7671.768484 |
| 61 | 15.01413422 | 35.39294809 | 20.37881386 | 105.9698321 | 7777.738316 |
| 62 | 15.18426936 | 35.44031295 | 20.25604359 | 105.3314267 | 7883.069743 |
| 63 | 15.35440449 | 35.48767782 | 20.13327332 | 104.6930213 | 7987.762764 |
| 64 | 15.52453963 | 35.53504268 | 20.01050305 | 104.0546159 | 8091.81738 |
| 65 | 15.69467476 | 35.58240754 | 19.88773278 | 103.4162105 | 8195.23359 |
| 66 | 15.8648099 | 35.62977241 | 19.76496251 | 102.7778051 | 8298.011395 |
| 67 | 16.03494503 | 35.67713727 | 19.64219224 | 102.1393997 | 8400.150795 |
| 68 | 16.20508017 | 35.72450214 | 19.51942197 | 101.5009943 | 8501.651789 |
| 69 | 16.3752153 | 35.771867 | 19.3966517 | 100.8625888 | 8602.514378 |
| 70 | 16.54535044 | 35.81923187 | 19.27388143 | 100.2241834 | 8702.738561 |
| 71 | 16.71548557 | 35.86659673 | 19.15111116 | 99.58577803 | 8802.32434 |
| 72 | 16.88562071 | 35.9139616 | 19.02834089 | 98.94737263 | 8901.271712 |
| 73 | 17.05575584 | 35.96132646 | 18.90557062 | 98.30896722 | 8999.580679 |
| 74 | 17.22589098 | 36.00869133 | 18.78280035 | 97.67056182 | 9097.251241 |
| 75 | 17.39602611 | 36.05605619 | 18.66003008 | 97.03215641 | 9194.283398 |
| 76 | 17.56616125 | 36.10342106 | 18.53725981 | 96.39375101 | 9290.677149 |
| 77 | 17.73629638 | 36.15078592 | 18.41448954 | 95.7553456 | 9386.432494 |
| 78 | 17.90643152 | 36.19815079 | 18.29171927 | 95.1169402 | 9481.549434 |
| 79 | 18.07656665 | 36.24551565 | 18.168949 | 94.47853479 | 9576.027969 |
| 80 | 18.24670179 | 36.29288052 | 18.04617873 | 93.84012939 | 9669.868099 |
| 81 | 18.41683693 | 36.34024538 | 17.92340846 | 93.20172398 | 9763.069823 |
| 82 | 18.58697206 | 36.38761025 | 17.80063819 | 92.56331857 | 9855.633141 |
| 83 | 18.7571072 | 36.43497511 | 17.67786792 | 91.92491317 | 9947.558054 |
| 84 | 18.92724233 | 36.48233998 | 17.55509765 | 91.28650776 | 10038.84456 |
| 85 | 19.09737747 | 36.52970484 | 17.43232738 | 90.64810236 | 10129.49266 |
| 86 | 19.2675126 | 36.57706971 | 17.30955711 | 90.00969695 | 10219.50236 |
| 87 | 19.43764774 | 36.62443457 | 17.18678684 | 89.37129155 | 10308.87365 |
| 88 | 19.60778287 | 36.67179944 | 17.06401657 | 88.73288614 | 10397.60654 |
| 89 | 19.77791801 | 36.7191643 | 16.9412463 | 88.09448074 | 10485.70102 |
| 90 | 19.94805314 | 36.76652917 | 16.81847603 | 87.45607533 | 10573.1571 |
| 91 | 20.11818828 | 36.81389403 | 16.69570575 | 86.81766993 | 10659.97477 |
| 92 | 20.28832341 | 36.8612589 | 16.57293548 | 86.17926452 | 10746.15403 |
| 93 | 20.45845855 | 36.90862376 | 16.45016521 | 85.54085912 | 10831.69489 |
| 94 | 20.62859368 | 36.95598863 | 16.32739494 | 84.90245371 | 10916.59734 |
| 95 | 20.79872882 | 37.00335349 | 16.20462467 | 84.2640483 | 11000.86139 |
| 96 | 20.96886395 | 37.05071836 | 16.0818544 | 83.6256429 | 11084.48703 |
| 97 | 21.13899909 | 37.09808322 | 15.95908413 | 82.98723749 | 11167.47427 |
| 98 | 21.30913422 | 37.14544809 | 15.83631386 | 82.34883209 | 11249.8231 |
| 99 | 21.47926936 | 37.19281295 | 15.71354359 | 81.71042668 | 11331.53353 |
| 100 | 21.64940449 | 37.24017782 | 15.59077332 | 81.07202128 | 11412.60555 |
| 101 | 21.81953963 | 37.28754268 | 15.46800305 | 80.43361587 | 11493.03917 |
| 102 | 21.98967476 | 37.33490754 | 15.34523278 | 79.79521047 | 11572.83438 |
| 103 | 22.1598099 | 37.38227241 | 15.22246251 | 79.15680506 | 11651.99118 |
| 104 | 22.32994503 | 37.42963727 | 15.09969224 | 78.51839966 | 11730.50958 |
| 105 | 22.50008017 | 37.47700214 | 14.97692197 | 77.87999425 | 11808.38958 |
| 106 | 22.6702153 | 37.524367 | 14.8541517 | 77.24158884 | 11885.63117 |
| 107 | 22.84035044 | 37.57173187 | 14.73138143 | 76.60318344 | 11962.23435 |
| 108 | 23.01048557 | 37.61909673 | 14.60861116 | 75.96477803 | 12038.19913 |
| 109 | 23.18062071 | 37.6664616 | 14.48584089 | 75.32637263 | 12113.5255 |
| 110 | 23.35075584 | 37.71382646 | 14.36307062 | 74.68796722 | 12188.21347 |
| 111 | 23.52089098 | 37.76119133 | 14.24030035 | 74.04956182 | 12262.26303 |
| 112 | 23.69102611 | 37.80855619 | 14.11753008 | 73.41115641 | 12335.67418 |
| 113 | 23.86116125 | 37.85592106 | 13.99475981 | 72.77275101 | 12408.44694 |
| 114 | 24.03129638 | 37.90328592 | 13.87198954 | 72.1343456 | 12480.58128 |

| | | | | | |
|---|---|---|---|---|---|
| 115 | 24.20143152 | 37.95065079 | 13.74921927 | 71.4959402 | 12552.07722 |
| 116 | 24.37156665 | 37.99801565 | 13.626449 | 70.85753479 | 12622.93476 |
| 117 | 24.54170179 | 38.04538052 | 13.50367873 | 70.21912939 | 12693.15389 |
| 118 | 24.71183693 | 38.09274538 | 13.38090846 | 69.58072398 | 12762.73461 |
| 119 | 24.88197206 | 38.14011025 | 13.25813819 | 68.94231857 | 12831.67693 |
| 120 | 25.0521072 | 38.18747511 | 13.13536792 | 68.30391317 | 12899.98084 |
| 121 | 25.22224233 | 38.23483998 | 13.01259765 | 67.66550776 | 12967.64635 |
| 122 | 25.39237747 | 38.28220484 | 12.88982738 | 67.02710236 | 13034.67345 |
| 123 | 25.5625126 | 38.32956971 | 12.76705711 | 66.38869695 | 13101.06215 |
| 124 | 25.73264774 | 38.37693457 | 12.64428684 | 65.75029155 | 13166.81244 |
| 125 | 25.90278287 | 38.42429944 | 12.52151657 | 65.11188614 | 13231.92433 |
| 126 | 26.07291801 | 38.4716643 | 12.3987463 | 64.47348074 | 13296.39781 |
| 127 | 26.24305314 | 38.51902917 | 12.27597603 | 63.83507533 | 13360.23288 |
| 128 | 26.41318828 | 38.56639403 | 12.15320575 | 63.19666993 | 13423.42955 |
| 129 | 26.58332341 | 38.6137589 | 12.03043548 | 62.55826452 | 13485.98782 |
| 130 | 26.75345855 | 38.66112376 | 11.90766521 | 61.91985912 | 13547.90768 |
| 131 | 26.92359368 | 38.70848863 | 11.78489494 | 61.28145371 | 13609.18913 |
| 132 | 27.09372882 | 38.75585349 | 11.66212467 | 60.6430483 | 13669.83218 |
| 133 | 27.26386395 | 38.80321836 | 11.5393544 | 60.0046429 | 13729.83682 |
| 134 | 27.43399909 | 38.85058322 | 11.41658413 | 59.36623749 | 13789.20306 |
| 135 | 27.60413422 | 38.89794809 | 11.29381386 | 58.72783209 | 13847.93089 |
| 136 | 27.77426936 | 38.94531295 | 11.17104359 | 58.08942668 | 13906.02032 |
| 137 | 27.94440449 | 38.99267782 | 11.04827332 | 57.45102128 | 13963.47134 |
| 138 | 28.11453963 | 39.04004268 | 10.92550305 | 56.81261587 | 14020.28395 |
| 139 | 28.28467476 | 39.08740754 | 10.80273278 | 56.17421047 | 14076.45816 |
| 140 | 28.4548099 | 39.13477241 | 10.67996251 | 55.53580506 | 14131.99397 |
| 141 | 28.62494503 | 39.18213727 | 10.55719224 | 54.89739966 | 14186.89137 |
| 142 | 28.79508017 | 39.22950214 | 10.43442197 | 54.25899425 | 14241.15036 |
| 143 | 28.9652153 | 39.276867 | 10.3116517 | 53.62058884 | 14294.77095 |
| 144 | 29.13535044 | 39.32423187 | 10.18888143 | 52.98218344 | 14347.75314 |
| 145 | 29.30548557 | 39.37159673 | 10.06611116 | 52.34377803 | 14400.09691 |
| 146 | 29.47562071 | 39.4189616 | 9.94334089 | 51.70537263 | 14451.80229 |
| 147 | 29.64575584 | 39.46632646 | 9.82057062 | 51.06696722 | 14502.86925 |
| 148 | 29.81589098 | 39.51369133 | 9.69780035 | 50.42856182 | 14553.29782 |
| 149 | 29.98602611 | 39.56105619 | 9.575030079 | 49.79015641 | 14603.08797 |
| 150 | 30.15616125 | 39.60842106 | 9.452259809 | 49.15175101 | 14652.23972 |
| 151 | 30.32629638 | 39.65578592 | 9.329489539 | 48.5133456 | 14700.75307 |
| 152 | 30.49643152 | 39.70315079 | 9.206719268 | 47.8749402 | 14748.62801 |

# Appendix E: Supplementary Tables

**Tests of Normality**
**(Shapiro-Wilk Test)**

| | Warming Sequence No | df | Sig. |
|---|---|---|---|
| Effective Power | 1 | 24 | 0.609 |
| | 2 | 24 | 0.884 |
| | 3 | 24 | 0.743 |
| | 4 | 24 | 0.177 |

(Table 1: Normality testing for effective power output data when groups according to position within the batch of warming instances)

**Comparison between means for effective power output according to bag ID**
**(ANOVA)**

Dependent Variable: Effective Power Output (W)
(Bonferroni method)

| Bag ID (I) | Comparison group (J) | Mean Difference (I-J) | Std. Error | Significnce* | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| 1 | 2 | 1.05167 | 3.44414 | 1.000 | -8.2355 | 10.3388 |
| | 3 | -3.87458 | 3.44414 | 1.000 | -13.1617 | 5.4125 |
| | 4 | -4.46125 | 3.44414 | 1.000 | -13.7484 | 4.8259 |
| 2 | 1 | -1.05167 | 3.44414 | 1.000 | -10.3388 | 8.2355 |
| | 3 | -4.92625 | 3.44414 | 0.936 | -14.2134 | 4.3609 |
| | 4 | -5.51292 | 3.44414 | 0.677 | -14.8000 | 3.7742 |
| 3 | 1 | 3.87458 | 3.44414 | 1.000 | -5.4125 | 13.1617 |
| | 2 | 4.92625 | 3.44414 | 0.936 | -4.3609 | 14.2134 |
| | 4 | -0.58667 | 3.44414 | 1.000 | -9.8738 | 8.7005 |
| 4 | 1 | 4.46125 | 3.44414 | 1.000 | -4.8259 | 13.7484 |
| | 2 | 5.51292 | 3.44414 | 0.677 | -3.7742 | 14.8000 |
| | 3 | 0.58667 | 3.44414 | 1.000 | -8.7005 | 9.8738 |

* The mean difference is significant at the 0.05 level

(Table 2: Results of a one-way ANOVA in which effective power output observed for each of the four physical bags, regardless of position within a warming series, was the factor; p-value > 0.05 reveals no significant differences between the four bags of simulated blood prepared for use in this study)

**Description of effective power output data**

| | | | Statistic | Std. Error |
|---|---|---|---|---|
| Effective Power (W) | Mean | | 172.0423 | 1.22304 |
| | 95% Confidence Interval for Mean | Lower Bound | 169.6143 | |
| | | Upper Bound | 174.4703 | |
| | 5% Trimmed Mean | | 172.5066 | |
| | Median | | 176.9600 | |
| | Variance | | 143.599 | |
| | Std. Deviation | | 11.98327 | |
| | Minimum | | 146.29 | |
| | Maximum | | 192.59 | |
| | Range | | 46.30 | |
| | Interquartile Range | | 16.72 | |
| | Skewness | | -0.836 | 0.246 |
| | Kurtosis | | -0.631 | 0.488 |

(Table 3: Table demonstrating characteristics of all the data collected)

**Mean effective power output according to warming sequence**

Effective Power (W)

| Warming Sequence No | Mean Effective Power (W) | N | Std. Deviation |
|---|---|---|---|
| 1 | 153.1075 | 24 | 4.12033 |
| 2 | 174.2892 | 24 | 4.42765 |
| 3 | 179.1663 | 24 | 3.65489 |
| 4 | 181.6063 | 24 | 3.92434 |
| Total | 172.0423 | 96 | 11.98327 |

(Table 4: Table contrasting the effective power output observed for each position within the batches of warming instances)

**Comparison between means for effective power output according to warming sequence number (RM-ANOVA)**

Dependent Factor: Effective Power Output (W)
(Bonferroni method)

| Warming Sequence No (I) | Comparison group (J) | Mean Difference (I-J) | Std. Error | Significnce* | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| 1 | 2 | -21.18167* | 1.16672 | < 0.001 | -24.32774 | -18.03559 |
| | 3 | -26.05875* | 1.16672 | < 0.001 | -29.20483 | -22.91267 |
| | 4 | -28.49875* | 1.16672 | < 0.001 | -31.64483 | -25.35267 |
| 2 | 1 | 21.18167* | 1.16672 | < 0.001 | 18.03559 | 24.32774 |
| | 3 | -4.87708* | 1.16672 | < 0.001 | -8.02316 | -1.73101 |
| | 4 | -7.31708* | 1.16672 | < 0.001 | -10.46316 | -4.17101 |
| 3 | 1 | 26.05875* | 1.16672 | < 0.001 | 22.91267 | 29.20483 |
| | 2 | 4.87708* | 1.16672 | 0.00040 | 1.73101 | 8.02316 |
| | 4 | -2.44000 | 1.16672 | 0.23553 | -5.58608 | 0.70608 |
| 4 | 1 | 28.49875* | 1.16672 | < 0.001 | 25.35267 | 31.64483 |
| | 2 | 7.31708* | 1.16672 | < 0.001 | 4.17101 | 10.46316 |
| | 3 | 2.44000 | 1.16672 | 0.23553 | -0.70608 | 5.58608 |

* The mean difference is significant at the 0.05 level

(Table 5: Results of RM-ANOVA which demonstrates the degree of statistical significance for the difference between the effective power outputs observed for each position within the batches of warming instances)

**Comparison between means for take-up plate start-temperature according to warming sequence number (RM-ANOVA)**

Dependent Variable: Take-Up Plate Start-Temperature ($^{o}$C)
(Bonferroni method)

| Warming Sequence No (I) | Comparison group (J) | Mean Difference (I-J) | Std. Error | Significnce* | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| 1 | 2 | -7.96667* | 0.19458 | < 0.001 | -8.4913 | -7.4420 |
| | 3 | -9.06250* | 0.19458 | < 0.001 | -9.5872 | -8.5378 |
| | 4 | -9.36667* | 0.19458 | < 0.001 | -9.8913 | -8.8420 |
| 2 | 1 | 7.96667* | 0.19458 | < 0.001 | 7.4420 | 8.4913 |
| | 3 | -1.09583* | 0.19458 | < 0.001 | -1.6205 | -0.5712 |
| | 4 | -1.40000* | 0.19458 | < 0.001 | -1.9247 | -0.8753 |
| 3 | 1 | 9.06250* | 0.19458 | < 0.001 | 8.5378 | 9.5872 |
| | 2 | 1.09583* | 0.19458 | < 0.001 | 0.5712 | 1.6205 |
| | 4 | -0.30417 | 0.19458 | 0.729 | -0.8288 | 0.2205 |
| 4 | 1 | 9.36667* | 0.19458 | < 0.001 | 8.8420 | 9.8913 |
| | 2 | 1.40000* | 0.19458 | < 0.001 | 0.8753 | 1.9247 |
| | 3 | 0.30417 | 0.19458 | 0.729 | -0.2205 | 0.8288 |

* The mean difference is significant at the 0.05 level

(Table 6: Results of RM-ANOVA which demonstrates the degree of statistical significance for the difference between the mean take-up plate start-temperatures observed for each position within the batches of warming instances)

**Comparison between means for bag end-temperature according to warming sequence number (RM-ANOVA)**

Dependent Variable: Bag End-Temperature ($^{o}$C)
(Bonferroni method)

| Warming Sequence No (I) | Comparison group (J) | Mean Difference (I-J) | Std. Error | Significnce* | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| 1 | 2 | .39583* | 0.12364 | 0.011 | 0.0625 | 0.7292 |
| | 3 | .62917* | 0.12364 | < 0.001 | 0.2958 | 0.9625 |
| | 4 | .75417* | 0.12364 | < 0.001 | 0.4208 | 1.0875 |
| 2 | 1 | -.39583* | 0.12364 | 0.011 | -0.7292 | -0.0625 |
| | 3 | 0.23333 | 0.12364 | 0.374 | -0.1000 | 0.5667 |
| | 4 | .35833* | 0.12364 | 0.028 | 0.0250 | 0.6917 |
| 3 | 1 | -.62917* | 0.12364 | < 0.001 | -0.9625 | -0.2958 |
| | 2 | -0.23333 | 0.12364 | 0.374 | -0.5667 | 0.1000 |
| | 4 | 0.12500 | 0.12364 | 1.000 | -0.2084 | 0.4584 |
| 4 | 1 | -.75417* | 0.12364 | < 0.001 | -1.0875 | -0.4208 |
| | 2 | -.35833* | 0.12364 | 0.028 | -0.6917 | -0.0250 |
| | 3 | -0.12500 | 0.12364 | 1.000 | -0.4584 | 0.2084 |

* The mean difference is significant at the 0.05 level

(Table 7: Results of RM-ANOVA which demonstrates the degree of statistical significance for the difference between the bag end-temperatures observed for each position within the batches of warming instances)

**Comparison between means for warming cycle duration according to warming sequence number (RM-ANOVA)**

Dependent Variable: Warming Cycle Duration (s)
(Bonferroni method)

| Warming Sequence No (I) | Comparison group (J) | Mean Difference (I-J) | Std. Error | Significnce* | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| 1 | 2 | 24.70833* | 1.45884 | < 0.001 | 20.7746 | 28.6421 |
| | 3 | 30.04167* | 1.45884 | < 0.001 | 26.1079 | 33.9754 |
| | 4 | 32.62500* | 1.45884 | < 0.001 | 28.6912 | 36.5588 |
| 2 | 1 | -24.70833* | 1.45884 | < 0.001 | -28.6421 | -20.7746 |
| | 3 | 5.33333* | 1.45884 | 0.003 | 1.3996 | 9.2671 |
| | 4 | 7.91667* | 1.45884 | < 0.001 | 3.9829 | 11.8504 |
| 3 | 1 | -30.04167* | 1.45884 | < 0.001 | -33.9754 | -26.1079 |
| | 2 | -5.33333* | 1.45884 | 0.003 | -9.2671 | -1.3996 |
| | 4 | 2.58333 | 1.45884 | 0.479 | -1.3504 | 6.5171 |
| 4 | 1 | -32.62500* | 1.45884 | < 0.001 | -36.5588 | -28.6912 |
| | 2 | -7.91667* | 1.45884 | < 0.001 | -11.8504 | -3.9829 |
| | 3 | -2.58333 | 1.45884 | 0.479 | -6.5171 | 1.3504 |

* The mean difference is significant at the 0.05 level

(Table 8: Results of RM-ANOVA which demonstrates the degree of statistical significance for the difference between the warming cycle duration observed for each position within the batches of warming instances)

**Comparison between total energy added according to warming sequence number (RM-ANOVA)**

Dependent Variable: Total Energy Added (J)
(Bonferroni method)

| Warming Sequence No (I) | Comparison group (J) | Mean Difference (I-J) | Std. Error | Significnce* | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| 1 | 2 | 172.34167 | 142.84815 | 1.000 | -212.8488 | 557.5321 |
| | 3 | 295.98333 | 142.84815 | 0.246 | -89.2071 | 681.1738 |
| | 4 | 176.07917 | 142.84815 | 1.000 | -209.1113 | 561.2696 |
| 2 | 1 | -172.34167 | 142.84815 | 1.000 | -557.5321 | 212.8488 |
| | 3 | 123.64167 | 142.84815 | 1.000 | -261.5488 | 508.8321 |
| | 4 | 3.73750 | 142.84815 | 1.000 | -381.4529 | 388.9279 |
| 3 | 1 | -295.98333 | 142.84815 | 0.246 | -681.1738 | 89.2071 |
| | 2 | -123.64167 | 142.84815 | 1.000 | -508.8321 | 261.5488 |
| | 4 | -119.90417 | 142.84815 | 1.000 | -505.0946 | 265.2863 |
| 4 | 1 | -176.07917 | 142.84815 | 1.000 | -561.2696 | 209.1113 |
| | 2 | -3.73750 | 142.84815 | 1.000 | -388.9279 | 381.4529 |
| | 3 | 119.90417 | 142.84815 | 1.000 | -265.2863 | 505.0946 |

* The mean difference is significant at the 0.05 level

(Table 9: Results of RM-ANOVA which demonstrates the degree of statistical significance for the difference between the total energy added observed for each position within the batches of warming instances)