OPEN ACCESS
Global Journal of Research in Engineering & Computer Sciences
Volume 01| Issue 01 | Sep-Oct | 2021
Journal homepage: https://gjrpublication.com/journals/
Original Research Article

Microwave generated steam decontamination of respirators: A thermodynamic analysis

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DOI: 10.5281/zenodo.5595284 **Submission Date:** 15 Aug. 2021 | **Published Date:** 06 Oct. 2021

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Abstract

During the two influenza pandemic's (caused by H1N1 and SARS-Cov-2), over the past twenty years, the use of experimental microwave generated steam (MGS), has shown potential, for decontamination of single-use face respirators and surgical masks. Recent review articles of the decontamination of single-use respirator and face mask has been primarily performed within the health sector, with a particular focus on the disinfection efficiency of the process. However, as with all processing data collected from different research sources, experimental conditions are not reported in a consistent manner. These reports generally provide an overview of MGS microwave conditions with insufficient detail to allow a standard microwave engineering review that enables the thermodynamic of the microwave treatment, to be obtained. The understanding of these parameters and how they influence the decontamination outcome is necessary for further development of the MGS process and enable it to help address some of Green chemistry goals (reduce the amount of harmful chemical products in the environment, and limit the number of respirators and masks required to be manufactured). This review reports on the MGS microwave conditions, then clarifies them in to standard microwave engineering terminology from which the thermodynamic of process can be obtained. In particular how the parameters: power (W), power density (W L^{-1}) and process energy budget (J) is reflected in steam generation as well as MGS decontamination of respirator and face mask outcome. The work reviews the treatment of N95-type respirators, surgical and medical masks, and in this context also considers microwave oven-related injuries and mask related fires. Using this knowledge, meaningful recommendations are made on the suitability of individual microwave ovens for decontamination treatment in addition the respirator to the suitability of respirator for use with the MGS decontamination process. Finally, general recommendations are provided for designing a microwave oven for MGS decontamination.

Keywords: H1N1, SARS-CoV-2, microwave oven, decontamination, respirator

INTRODUCTION:

In early 2020 the world health organization (WHO) recognized that the severe acute respiratory syndrome corona virus (SARS-CoV-2) was the cause of the 2019 pandemic [1]. Since then the world has undergone a dramatic shift in public perception of the role of governments, economic markets, and public healthcare. Governments and hospitals have struggled to care for their Covid-19 patient; research viable and effective vaccines, establish vaccine manufacture plants, and put in place vaccination programs. What started as a public health crisis however has also turned into an environmental issues due to the amount of single-use personal protective equipment, or PPE (e.g., N95 respirator and surgical masks), used and then discarded, in the treatment of Covid-19 patients [2, 3]. In 2006-7 there was an acknowledgement that US Strategic National Stockpile of N95 respirators would be in short supply when and if an influenza pandemic occurred [4, 5]. Now driven by acute shortages of respirators and surgical masks in the 2009 pandemic MGS decontamination of respirators studies and reuse have been under taken [6 - 13]. The 57 page heavily redacted accessible version of the 2016 UK exercise Cygnus report mentions PPE 5 times along with distribution and stockpiles of PPE [14]. Recent research (2020) has shown that the thermal inactivation profile of SARS-CoV-2 may be similar to the influenza virus strain which caused the 1918 pandemic and the 2009 HIN1 pandemic. The thermal inactivation process of these viruses are strongly linked to temperature with a decreasing survival time above a temperature of (60^{o}C plus) when compared to room temperature (25^{o}C), or lower as found in the domestic fridges (4 to 0^{o}C) / freezer (approximately -

18^oC) [15]. In addition the virus is passed-on by human-human contact, droplets and fomites (hard and soft surfaces, food surfaces and on food packaging). In the later case the surface has a significant effect on virus activity (at room temperature; plastic between 3 to 7 days glass, paper < 4 days and cardboard < 24 hours.

In 2020 Fischer et al [16] evaluated four different decontamination methods for SAR-CoV-2 virus inoculated N95-type respirators, ultraviolet radiation (260 to 285 nm), dry heat (70oC), vaporized hydrogen peroxide (VHP), and ethanol (70%). Their result revealed that UV and VHP could be performed three times on respirators, dry heat 1-2 times, whereas ethanol reduced N95 respirator integrity and should not be used. Microwave-generated steam (MGS) has also been used to decontaminate N95-type respirators. In 2020 four comparative (with other decontamination processes) and descriptive reviews of MGS decontamination of pathogenic virus inculcation N95 type respirators were published [17 - 20], and a futher review in 2021 [21]. Although these reviews described the experimental conditions and biological outcomes of [6, 7, 8, and 9] they did not evaluate the microwave energy conditions within the industrial and domestic microwave ovens that operated using a free running packaged cavity-magnetron frequency of fo = 2.45 ±0.1 GHz (λo ~12.2 cm) [22, 23, and 24].

More recently Pascoe et al (July 2020) [25] used an industrial grade microwave oven (NE-1853; Panasonic) along with a Tommy Tipee steam sterilizer to inactive *Staphylococcus aureus* (*S. aureus*) on a contaminated N95-type respirators. In general it was found that metal nose clips arc, or delaminate from the respirator body material during MGS treatments. Zalauf et al (June 2020) [26] used ceramic mugs, glass containers, and commercial microwave steam bags [8] as the water reservoir within a microwave oven to decontaminate MS2 phage inoculated respirators. Proof-of-principle experiments in the form cold atmospheric plasma have also been published in 2020. Chen et al (November 2020) [27] used a cross-field [28, 29] atmospheric pressure plasma jet (APPJ) to inactive SARS-CoV-2 on metal, plastic and leather surfaces, and Capelli et al (May 2021) [30] used dielectric barrier discharge generating a plasma treatment area of 551 cm^2 to inactive SARS-CoV-2 on plastic and metal surfaces. For these plasma systems, decontamination treatment of the outside and inside shell-like areas of N95 respirator require the plasma systems to be mounted on a computer numeric controlled (CNC) to facilitate full coverage of the N95 respirator, which has a typical face width 13.59 cm and length 11.7 cm [31]. This is not the case for MGS performed within a domestic microwave oven that employs a free-running packaged cavity-magnetron operating a frequency that approximates to the characteristic length of N95-type respirators. It should be also noted that steam sterilization of infant feeding equipment [32] is already acknowledged as a cost efficient and simple to use technology that extends into domestic home use.

During the two influenza pandemic's of this century, experimental MGS decontamination of respirator and surgical mask and their reviews, been primary performed within the health secretor, with a particular focus on the disinfection efficiency of the decontamination process. However as with all datasets collected from different research sources, experimental conditions are not reported in a consistence manner. This review focuses on the reported microwave conditions and to clarify the reported information using microwave engineering terminology from which the thermodynamic of MGS decontamination of respirators can be estimated. In particular how the parameter power density ($W L^{-1}$) and available energy budget ($J s^{-1} x s = J$) is reflected in the processed respirator outcome. The understanding of how these parameters influence the decontamination outcome making MGS a true green chemistry process: that reduce the amount of harmful chemical products in the environment, as well as limiting the number of respirators and masks require to be manufactured.

This article is constructed as follows: Section 2 collates the N95-type respirator, surgical and medical masks reported in this work; Section 3 examines the thermodynamics of MGS, and microwave oven hazards (microwave oven-related injuries and fires; Section 4 reviews reported MGS parameters for the N95-type respirators, surgical masks, and medical masks; section 5 evaluates the respirator and mask decontamination outcomes. Section 6 provides a discussion and recommendation for current user and future manufacture of respirators and microwave ovens.

Respirators and face mask

The American (N95) and European FFP2 type respirators are designed to achieve a very close facial fit and very efficient filtration of airborne penetrating particles. They are also considered to be a medical device. When new and fitted correctly respirators provide personal protection (filter ≥ 95% of 0.3 micron airborne particles, hence the term 95 in the America standard) and are tested in the direction of exhalation (inside to outside). The respirator barrier material is made of 4 layers of non-woven polypropylene, cellulose-polyester, and polypropylene. The surgical respirator (SN95) is a subclass of the N95-type respirator and is designed as a loose-fitting device that creates a physical barrier between the mouth and nose of the wearer and potential large droplet splashes and bodily fluid in the immediate environment (Table-1).

Table-1: Respirators and surgical masks listed in the 6 reviewed papers.

Company / Jurisdiction	N95 respirators	SN95 respirators	Medical masks
3M	8210 with aluminum nose clip	1860 and 1870 with aluminum nose clip	
Cardinal Health (CH)	N95 with aluminum nose clip		
Honeywell (Hw)	FF3 with aluminum nose clip and exhalation valve		
Kimberly-Clark (KC)	N95 with aluminum nose clip	PFR95 with aluminum nose clip	
Generic unbranded (GU)	PPE with aluminum nose clip		
Moldex (M)	2200N95 and 2201N95 metal free		
Public Heath Wales (PHW)	FF2 metal-free with exhalation valve		
EN14683: 2019			Type II and IIR Pleated polypropylene, 11cm PP/PV wire nose clip

The N95 standard is maintained by the American National Institute for Occupational Safety and Health (NIOSH) within which all N95-type respirators and surgical masks must pass class 1 flammability test [33]. The closely related equivalent European standards FFP1 (80% filter efficiency), FFP2 (94% filtering efficiency) and FFP3 (99% filtering efficiency) are maintained by the European Committee for Standardization (CEN). The WHO does not advise using respirators with exhalation valves as they are intended for industrial workers to prevent dust and particles from being breathed in as the valve closes on inhale. However, the valve opens on exhale, making it easier to breathe but also allowing any virus to pass through the valve opening.

Respirators and face masks are intended to be a single-uses device with a 4 to 8 hours use depending on used age. Unlike the above, cotton face masks that are handmade are not considered to be a medical device and certainly have not undergone BEF and flammability tests. However, it is estimated that using machine washing, between 50 and 70^{o}C, cotton masks may be used up to fifty times [3].

Microwave oven safety hazards

A number of authors have previously reported on the inoculation and decontamination of respirator and mask protocols using MGS [6, 7, 8, 9, 25, and 26]. Reference [6, 7, 8, and 9] are a response to 2009 H1N1 pandemic and those given in [25, 26] are examples to the response to the Covid-19 pandemic. The purpose of this section is to highlight the hazards of MGS when changing an ovens use from one of warming and reheating of food (typically, 400 to 450g of a microwave oven frozen ready meal; 5 to 10 minutes heating from -18 to 70^{o}C [34]) to one of MGS decontamination of respirators and face masks. The latter have typical open water bath volumes of 50 to 100 ml that require heating times of 2 to 3 minutes (without stirring!) for the generation of steam. This section therefore looks microwave superheating and steam bubble growth (section 3.1), as well as the thermodynamics of MGS (section 3.2). A hazard of heating liquid in a microwave oven is scalds and burns. Therefore section 3.3, presents two retrospective medical studies of microwave oven-related scald and burn injuries.

Microwave Superheating and steam bubble growth

The phenomenon of solvent superheating is well known and commonly used in microwave assisted chemistry [35, 36, and 37]. Unlike thermal hearting of liquid-phase water where heat is transferred from the outside to the inside (figure-1a) microwave energy heats water directly by the volume dielectric heating of the water molecules process (figure-1b). The phenomenon of superheating of water occurs when heat transfer in to the water volume is rapid and greater than the water evaporation rate. Under these conditions, steam bubble growth is slowed or stopped as the bubble external pressure and membrane surface tension is greater than the bubble internal vapor pressure. This causes the embryonic bubbles to remain at their nucleation sites, whether on the vessel wall or on salt crystals and other mineral impurities within the liquid-phase water. At one atmosphere pressure, the water temperature must therefore be raised above 99.9^{o}C for the steam bubbles to growth. For example, removing nucleation sites by replacing tap water with distilled water is one way of slowing bubble growth, another way of reducing bubble growth to use a new glass vessel with clean surfaces with no scratches, or sharp edges. For volume dielectric heating and superheating to take place the vessel on the revolving glass carousel of a domestic microwave oven [22 -24 and, 34 - 37].

At one standard atmospheric pressure, microwave superheating of liquid-phase water results in an increase temperature of some 3 to 5 degrees above 99.9°C before boiling starts, plus an associated additional energy storage. Now if the microwave power is turning-off just below the new and higher boiling temperature, followed by manually removing the vessel out of the oven, the homogeneity of the superheating water will be disrupted. This disruption inevitably causes suppressed steam bubbles located at their nucleation sites to breakaway and due to their buoyancy swirl upwards and grow in size as they reach the liquid-phase surface During this stage of bubble growth the internal vapor pressure exceeds local external pressure causing bubble surface tension to be broken and water vapor explodes out of the water surface (figure-1c). The exploring bubbles, along with additional detached bubbles that are forced to the surface add to the violent steam eruption, where upon the oven-cavity is filled with steam. Once the oven-door is opened, the trapped steam purse out in an upwards direction with the potential of spraying hot steam on to the persons who is attempting to retrieving the heated vessel out of the oven-cavity.

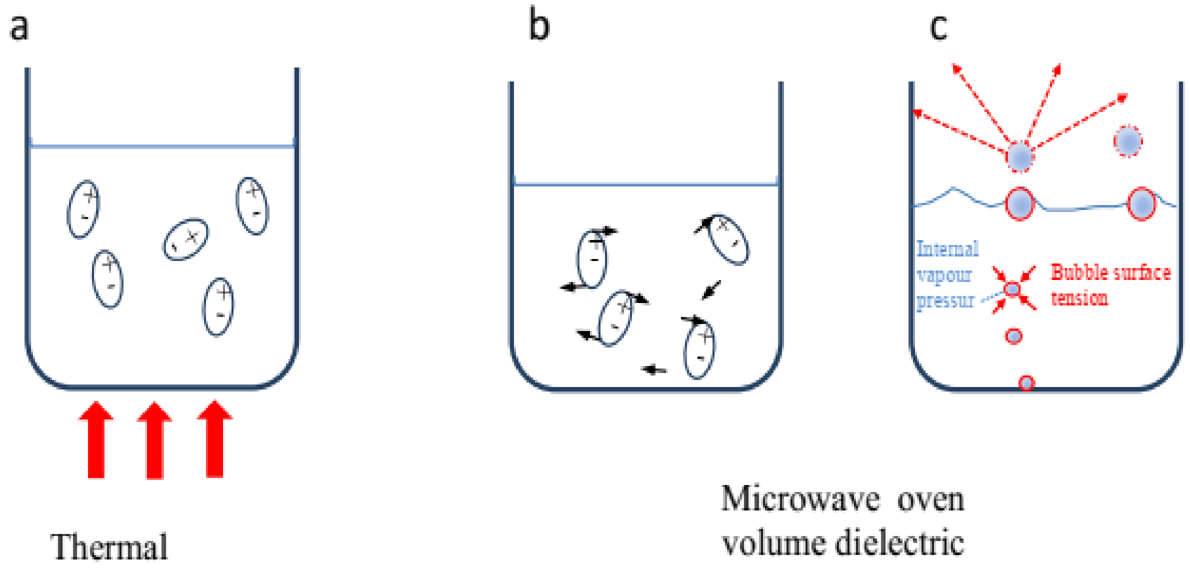

Fig-1: Thermal heating a) microwave heating process b) and microwave superheating of water c).

Thermodynamics of MGS

To quantify the MGS decontamination process in terms of thermal energy input and output, the thermodynamics of the process is explored. The thermodynamic approach is based on calorimetry, where the transfer of heat is measured into and out of a system (equation (1) [22, 23, and 38] and is the standard method of calibrating the available power from the cavity-magnetron into the oven-cavity [39]. The calorimetric calibration method uses 500 to 1000 g water dummy load within an open bath method. However the MGS decontamination typically uses between 50 to 60 g of water in an open bath thereby bringing a degree of uncertainty to the measurement due to the placement and rotation of the open water bath within the multimode oven-cavity along with the assumption that the water dielectric properties are not temperature dependent. Equations (1) and equation (2) are used in the calorimetric calculation for heating water.

$$P = mC\frac{\Delta T}{t} \qquad (1)$$

Where P is the applied thermal power in units of Watts (J.s^{-1}, or W), m is the mass of the water (kg m^{-3}), C is the specific heat capacity of water (4.184 J g^{-1} K^{-1}), ΔT is the change in water temperature (final temperature - initial temperature, and t is the heating time measured in seconds.

$$Q = mC\Delta T \qquad (2)$$

Where Q is the specific heat to raise the amount water through the temperature range: the final temperature is assumed to be just below boiling (99.9°C).

In the following worked example it is assumed that the open water bath container is thermally transparent (Erné and Snetsinger uses a glass teapot [38]). The worked example uses 100 g of water with an initial starting temperature of 22°C which is raised to 99.9°C in 1 minute (60s). Applying equation (1), an applied thermal power value of 544 W is obtained.

Assuming that the water is superheated the final water temperature maybe closer to 103 to 105°C. Using *ΔT* value of 105°C, equation (1) yields an applied thermal power of 579 W. At this point, turning-off the power source and then immediately distributing the superheated water (by dropping a rough surface object in the water, or picking-up the bath) the addition stored energy instantaneously (< 1s) converters part of the liquid-phase water into steam. The thermal power in this phase conversion approximates to 579 - 544 = 35 W, leaving the remaining liquid-phase water to suddenly drop to 99.9°C.

Using the knowledge that the latent heat vaporization of water (AH_{vap}) = 2.26 kJ g^{-1}, and the estimation of 1 g of water yields 1.67 L of steam [38] the above example can be extended. For example, 35 W of heating converts 0.015 g of liquid-phase water into approximately 0.009 L of steam. As the primary aim of a MGS is to sterilize surfaces, or in this case decontaminate a respirator, adding 120 seconds of heating time at a rate of 544 W will yield 65.28 kJ of heating, which in turn converts approximately 29.6 g of liquid-phase water into approximately 49.5 L of steam?

Microwave oven-related scald and burns

To demonstrate this real hazard in handling of volume dielectric heating, consider the case of food-stuffs as presented in Table-2 (Thambiraj et al 2013 [40]). This retrospective study provided details of over 21 years of microwave oven-related injures recorded in USA emergency departments between 1990 and 2020. Over this period there were estimated to be 155,959 injuries or 21 individuals per day over this period. The data in Table-2 reveals that adults primarily received scalds and burns to the hand and fingers (40%) followed by the head and neck (16%). For the under18 year of age group, the reverse occurs (hand and fingers 20% and head and neck 26%) indicating the relative height of the two groups to the counter-top position of most domestic Microwave ovens.

Table-2: Type of microwave oven-related scalds and burns presented to hospital ED in the USA between 1990 and 2010 [40].

Area of body injury	Adults %	Under the age of 18 %
Hand and fingers	40	20
Head and neck	16	26
Lower extremity	13	16
Arm	12	13
Other	19	25
Total	100 %	100 %

Table-3: Microwave oven-related facial burns presented to a UK regional burns unit (2008 to 2016)and outcome [41].

Age (M/F)	Source	Scald-burn area of body	Outcome
31 (F)	Un-pierced canned potatoes	Forehead, cheeks, right lower eyelid and eye	Continued to be treated by ophthalmology 16 months later
68(F)	Un-pierced canned potatoes	Unilateral face and cornea abrasions	No complications
26 (F)	Un-pierced canned potatoes	Forehead, nose, left cheek, shoulder and arm	No complications
59 (F)	Un-pierced canned potatoes	Upper and low lip mucosa and anterior palate	No complications
21 (F)	Boiled egg	Forehead, nose, eyelids, cornea burns	No complications
50 (M)	Poached egg	Periodical scald, right corneal abrasion	No complications
42 (F)	Poached egg	Right nostril and left neck	No complications
28 (F)	Boiled egg	Right cheek, upper eyelid and right neck and right eye corneal abrasion	No complications

A more recent microwave oven-related injury retrospective analysis involved eight patient from a UK regional burns unit between 2008 and 2016 has also been published, Bagirathan et al 2016 [41]. Out of the eight patients all but one was male and their ages ranged between 21 to 64 years, with a mean age 41. The patient injures were from microwaved un-pierced cans of potatoes, poached eggs and un-pierced boiled eggs, all of which exploded when removed from the oven. The medical analyses and outcome is given in Table-3. This Table reveals that the eight patients received scalds and burn to the right-side of face including the eyes (in one case to shoulder and arm). Six out of the eight cases were attempting to remove pressurized food items (un-pierced cans and eggs) from the oven. It appears that after considering the relative position of countertop domestic microwave oven to the patients at the time of the accident, the injuries are consistent with the process of removing a heated vessel from the oven while the door is opened by the left and where the opened door shields the left-side of the body. It is reasonable to assume the people who had these accidents had unintentionally produce steam within the oven cavity which is clearly the opposite for the MGS decontamination process.

Microwave oven-related fires

In 2007 Viscusi et al [42] use a domestic microwave oven (Sharp R-305KS) to decontaminate N95 respirators at a measure average power of 750 W for 4 minutes and found the respirators body melted at the end of the melt nose clip. From early-on in the 2019 Covid-19 pandemic, there have been emerging reports on the WWW of microwave oven fires related to the sanitization of face masks [43, 44]. The origin of these fires may be in part due to auto-ignition of the mask material and the PP/PVC single- or double-core metal nose clip, that are typically 11 to 12 cm in length and approximate to the free running packaged cavity-magnetron frequency (fo = 2.45 ±0.1 GHz (λo ~12.2 cm)). Under these co-operating electromagnetic conditions a standing-wave-structure is generated on the nose clip within the face mask.

Under these microwave irradiation conditions consider what happens to the long and thin PP/PVC coated metal nose clip material in the near empty microwave oven. Under these 'unloaded' conditions a number of reactions may generally occur. Firstly, a portion of the wave energy penetrates the metal (typically 2 to 4 microns) and interacts with free elections within this surface region causing an electrical current to flow. As the increases, high voltage stress (V cm^{-1}) at sharp edges and surface irregularities cause free electrons to be liberated causing a local gas breakdown (initially a corona discharge that quickly progresses in energy to form a spark or arc with sufficient temperature to ignite and burn the PP/PVC coating, followed by melting of the wire core). Secondly, the rest of the wave energy is reflected from the metal surface back into cavity. Thirdly, if the microwave irradiation continues, the reflected microwave energy reinforces the microwave standing waveform within the cavity to such a level that the reflected energy disrupts the operation of the magnetron, thus causing the respirator to be set on fire causing the oven's internal circuits to stop working, or in the extreme case setting the oven on fire.

The photograph in figure-2ad provides a of a type-I medical face mask (a) below which are three embedded single-core metal nose clips that have been removed from three separate masks. The embedded dielectric material is either: polypropylene (PP) or polyvinylchloride (PVC) with a dielectric strength of 150 to 250 kV cm^{-1}. The first nose clip was removed from a pristine mask (b); second nose clip was removed from 4-hour used mask and then microwave irradiated with a 800 W rated cavity-magnetron within a 20 liter Blue Sky BMG20-8 microwave oven [23], the third nose clip is removed from a 6-hour used mask and treated with for the same microwave irradiation conditions (d). The irradiation experiments reveal that used nose clips may have different burn profiles for the same irradiation conditions. In the case of (c), the dielectric PP/PVC has burned through near the middle of the wire, whereas for (d) the dielectric PP/PVC has protected the wire leaving the exposed the wire ends to melt and evaporate (burn). The experimental outcome indicates the used state of the metal nose clip determines how it reacts with the microwave irradiation and hence the fast mask burn characteristics. A second set of used Type-I mask soaked in tap water for one minute and then irradiated at full power yield similar arcing characteristics. [***N.B. These experiments should never be performed at home***].

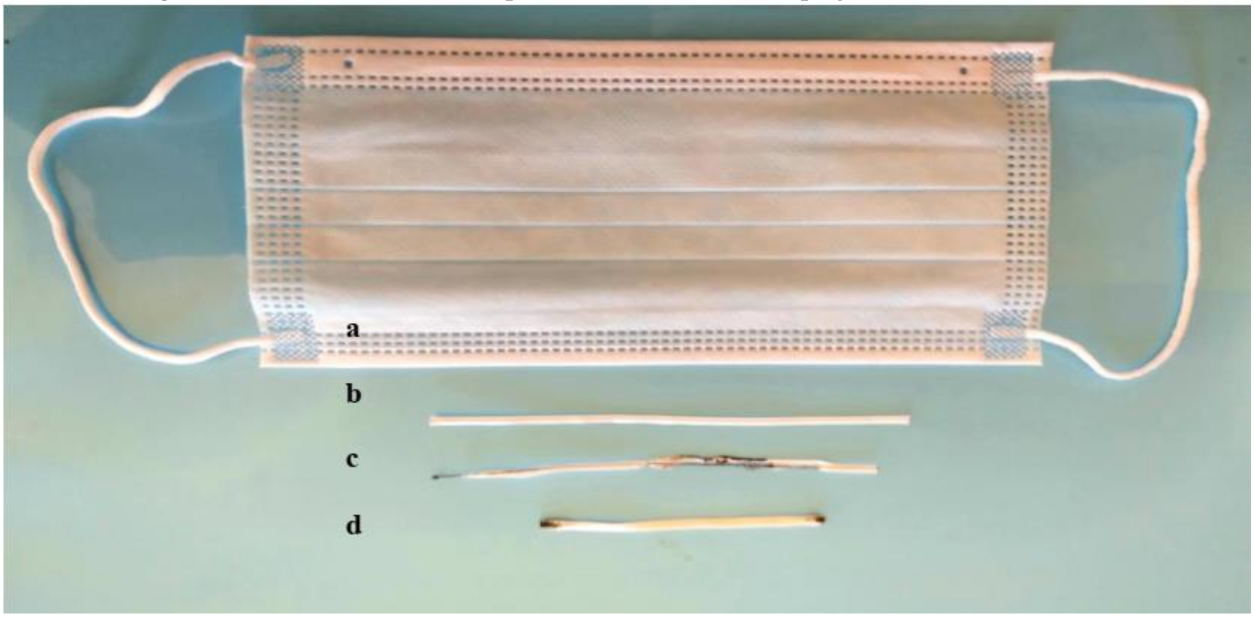

Fig-2: ad. Type-I medical mask a), PP/PVC single metal core nose clip removed from medical mask b), nose clip taken from 4 hour used mask, irradiated at 800W for 20 seconds in Blue Sky microwave oven c), nose clip taken from 6 hour used mask, irradiated at the same power conditions d).

Reported MGS parameters for N95-type respirators and masks

This section presents six MGS decontamination papers, four from the 2009 Pandemic era (Table-4) and two from the Covid-19 Pandemic era (Table-5). The motivation behind all six papers is the same: to address the lack of availability of respirators and surgical mask during the pandemic, by decontaminating previously used respirators. From a microwave engineering point of view the six papers reviewed gave comparatively little information on the available microwave power, power density, and total process energy budget, all three of which are needed to make a meaningful comparison between the reported respirator outcomes. To access the required microwave data, secondary supporting papers [12, 13, 42, 45, and 46] and manufacture information where have been used.

To aid the reader in understanding the microwave power terminology is used, a brief commentary on how the power, power density values are used in this work.

- Microwave oven power rating. This value is obtained from the oven manufacture and relates to the the line voltage (110, or 240 Vac) power consumed by the oven. The authors [47, 48] have noted this value mistakenly used as the rated cavity-magnetron power
- Rated magnetron power. This is the continuous wave (CW) value obtained from the oven and cavity magnetron manufacture. The values relates to the maximum output power of the magnetron when impedance matched into a dumpy load, typically water
- Measured (available) cavity-magnetron power. This value is based microwave irradiation within the oven's cavity, and is based on the open water bath calorimetry measurement [22, 23, 24, and 38]
- Power density is a mathematical construct that divides the available or rated cavity-magnetron power by the oven-cavity volume. The value (W/ft^3, or W L^{-1}) allows a comparison between different microwave ovens. When the cavity-magnetron rated (or available) power is divided by a sub unit of the oven-cavity volume a unrealistic power density is obtained that infers a greater rated (or available) power that could be possibly obtained. In this work the original cavity volume is reported, either in units of cubic feet or liter, and then units of W L^{-1} are used to avoid any miss-understanding
- Process energy budget relates to the rated (or, available) power of the cavity-magnetron times the irradiated time and is measured in units of Joule (J). given that the irradiated time varies between 60 to 180 seconds, the cavity-magnetron warm-up time (typically 3s) [48] does not significantly the calculated process energy budget
- The open water bath, or sterilizer - respirator combination forms an impedance load. As the water and respirator, or mask, have differing dielectric properties that change temperature, this work uses the term complex-load to represent the combined dielectric properties of water volume and respirator, or mask combination
- To measure the surface temperature of the complex-load liquid crystal irreversible temperature indicator strips [22, 25, and 49] may be used
- Near-filed probes within a multimode microwave oven-cavity may be used to detection sparks and arc within the cavity, followed by monitoring and control circuitry to automatically shut-down the oven before an electrical fire is initiated [47, 50]

Bergman 2010

Following on from Viscui et al publication of MGS decontamination of SN95 respirators [45], the research group response to the 2009 H1N1 Pandemic was to study the three-cycle (3X) decontamination of 3 N95 particle and 3 SN95 respirators [6]. Each of the six respirators was placed outside down on top of two pipette open water bath, each filled with 50 ml of 20^{o}C tap water as the steam source. The complex-load was then placed in a Shape R-305KS microwave oven (rated 1100 W cavity-magnetron illuminating a 1 ft^3 oven-cavity (28.3 L)) and irradiated at a measured (available) power = 750 W that equates to calculated power density 26.5 W L^{-1} and a process energy budget of 90 kJ for each of three cycles. Between each cycle, the open water bath was refilled and the respirators were allowed to dry for one hour then test for particle efficiency. During the MGS decontamination, no sparks or arcs from the metal nose clips was observed. Sparking was only observed when the water bath was removed as in the case of Viscusi [41]. One N95 respirator experienced a slight melting of the head straps following the first cycle. In addition SN95 respirators experienced partial separation of the inner foam nose cushion from the filter media, see figure-2.

Heimbuch 2011

Heimbuch et al inculcated six N95-type respirators with H1N1 virus and then decontaminate them using MGS. A Panasonic Inverter microwave oven (rated 1250 W cavity-magnetron illuminating a 1.6 ft^3 (45 L) oven cavity) was used in the study [7]. The Panasonic model type was obtained from Air Force Research Laboratory report number: AFRL-RX-TY-TR-2010-0070 [46] from which the microwave rated power density is calculated. The decontamination of H1N1 influenza virus inoculated N95 particle and surgical respirators was the subject of the MGS experiments. For the delivery of steam, a 100 ml of 22 to 25^{o}C tap water split between to plastic open water baths with perforated tops were used, a single inculcated respirator was placed on top to form the complex-load. Microwave irradiation was 120 seconds at full rated power 1250 W (calculated power density = 27.1 W L^{-1} and a process energy budget of 150 kJ.

Fisher 2011

Fisher et al [8] used the same 28.3 liter Shape R-305KS microwave oven as Bergman et al [6] and Viscui et al [13, 42, and 45]. Their goal being to evaluate the use of two commercially available microwave steam bags (here with called a sterilizer) for decontamination of MS2 bacteriophage (a surrogate for 2009 H1N1 strain of influenza) inculcated six types of N95 respirators. In each experiment a single inoculated respirator was placed in 2 types of sterilizer: Medela: Quick clean micro-steam bag and (5.1 x 3 x 9.6 inches) and; the Munchkin: steam guard bag (5.1 x 3 x 9.6 inches). The steam bags have an inner pleat where the respirator is placed, an integral Ziploc seal and exhaust vent. The sterilizer - respirator load underwent microwave irradiation for 90 seconds at a measured power = 750 W (calculated power density = 26 W L^{-1} and process energy budget of 66.5 kJ.

Table-4: MGS open water bath process and sterilizer process. The respirator is placed above the open water bath, or with the sterilizer, to form a complex-load that is placed on a revolving glass carousel within the oven-cavity.

Author	Microwave rated power (W)	Microwave power density	Open water bath, or sterilizer	Irradiation time (s)	Energy budget (kJ)
First 3X decontamination experiments					
Bergman 2010 [6]	Sharp R-305KS 1100: [a]	750 W/ft^3 (measured) (26.5 W L^{-1})	2 plastic pipette open baths (11.7 x 8 x 5 cm) each filled with 50 ml of tap water	120	90
Heimbuch 2011 [7]	Panasonic Inverter 1250: [b]	781 W/ft^3 (rated) (27.7 W L^{-1})	2 plastic open baths (12 x 8 x 4.5 cm) with perforated top each filled with 50 ml of tap water	120	150
MS2 bacteriophage surrogate for 2009 H1N1 strain of influenza contamination					
Fisher 2011 [8]	Sharp R-305KS 1100: [a]	750 W/ft^3 (measured) (26 W L^{-1})	2 types of 2.2 L plastic steam bags, each filled with 60 ml tap water	90	65.5
A/H5N1 strain of influenza virus contamination					
Lore 2012 [9]	Panasonic Inverter 1250: [b]	781 W/ ft^3 (rated) (27.7 W L^{-1})	Open water bath with perforated top filled 50 ml tap water	120	150

Fisher et al 2010 [12] is not included as mask coupons were used in the MGS decontamination experiments. Viscusi et al [13] is not included as no pathogenic virus contamination was in the MGS decontamination experiments. Microwave oven data taken form [12, 13, 42, and 45] [a]. Microwave oven model type taken from [46] [b].

Lore 2012

Lore et al [9] used the same Panasonic inverter oven as Heimbuch et al [7]. The Panasonic model type was obtained from [46], from which the microwave power density is calculated. The decontamination of A/H5N1 influenza virus-laden surgical respirators was the subject of the MGS experiments. The inoculated respirator was placed on top of a 50 ml tap water filled plastic open bath with perforated top lids where the inculcated respirator is placed. The complex-load was then microwave irradiated for 120 seconds at full rated power = 1250 W (calculated power density = 27.1 W L^{-1} and a process energy budget of 150 kJ. In all MGS experiments it was reported that no sparking from the respirator metal nose clips was observed.

Pascoe 2020

Pascoe et al [25] response to shortages of N95/FFP2 respirators caused by the SARS-CoV-2 pandemic was to study MGS decontamination of four respirators and type-II medical masks that where virus laden with *S. aureus*. An industrial Panasonic microwave oven (NE-1853; with two 2.45 GHz, 900 W rated cavity-magnetrons (one located at the top, and one located at the bottom of the oven cavity) was used for the study (fig 3a). The two cavity-magnetrons illuminate a 18 liter stainless-steel cavity that does not use a carousel to rotate food-stuff, but a rotating antenna in front of each waveguide iris aperture to distribute the microwave energy around the oven-cavity [51, 52]. A Tommee Tippee sterilizer (27 x 26.5 x 17.5 cm) filled with 100 ml or 200 ml of distilled water was used as the steam source in which the respirator is placed along with irreversible temperature indicator. The complex-load decontamination procedure used: 200 ml of

20°C DI water at microwave irradiation time of 90 seconds at rated power = 1800 W (calculated power density = 100 W L^{-1}, and a process energy budget of 162 kJ.

Zulauf 2020

Zulauf et al [25] used two unspecified microwave ovens that are rated at 1100 and 1150 W, respectively. Photos of the microwave oven indicate one cavity-magnetron and an estimated cavity volume of 44 to 55 liters. A 10 cm diameter ceramic mug (without Ziploc bags and within a Ziploc bag) and a glass container (17 x 17 x 7.5 cm) were used as the steam source that contained an initial 60 ml DI-water. Initial ceramic cup complex-load experiments revealed there was insufficient steam coverage of the respirator leading to poor decontamination outcome. When used within a Ziploc bag the bags, it was found that the bag melted, thereby presented a scald or burn hazard when retrieving the respirator. For this reason the ceramic cup and Ziploc bag are considered unsuitable for respirator decontamination purposes, and is not further reported upon in this work.

Table-5: MGS open water bath and sterilizer process. The respirator or mask is placed above the water bath, or within the sterilizer.

Author	Microwave rated power (W)	Microwave power density	Sterilizer	Irradiation Time (s)	Energy budget (kJ)
S. aureus surrogate for SARS-CoV-2 contamination					
Pascoe 2020 [24]	Panasonic NE-1853: 2 x 900 [c] magnetrons (one top, one bottom)	1.8 kW/0.635ft^3 (rated) (100 W L^{-1})	Tommy Tipee sterilizer filed with 200 ml DI-water	90	162
MS2 bacteriophage surrogate for SARS-CoV-2 contamination					
Zulauf 2020[25]	2 ovens used: 1100 and 1150	Estimated to be 20 to 25 liter 44 to 55 W L^{-1}	Glass container 17 x 17 x 7.5 cm filled with 60 ml DI-water	180	198 and 207

The Panasonic NE-1853 uses a rotating antenna in the waveguide apertures to deflect the microwave energy in the oven-cavity (not a rotating carousel on which the complex-load is placed on) [c].

Figure-3: provides a bar-graph of the calculated microwave oven power density for each of the authors. In all, but Pascoe el al and Zulauf et al, the power density falls within the range of 26.5 to 27.7 W L^{-1}. The power density for Pascoe el at is nearly 4 times greater is primarily due to the using two 900 W rated cavity-magnetrons as compared to the other 5 authors who use one cavity-magnetron ovens, In the case of Zulauf et al the power density is estimated to be in the range of 44 to 55 W L^{-1}.

The two contrasting water reservoir methods (open water bath or sterilizer) have been reported for MGS decontamination of respirators and masks. The sterilizers are designed for > 1000 W rated microwave ovens because the carousel drive coupling reduces the cavity working height of many 800 W rated domestic microwave ovens. For example, the Tommee Tippee sterilizer will not fit into the 20 liter Blue Sky BMG20-8 microwave oven [22].

For the open water bath, it is reasonable to assume that the steam temperature and pressure equilibrates thought-out the oven-cavity. Whereas for the sterilizer, steam temperature and pressure is locally enhanced due to the reduced mass transport out of the sterilizer exhaust system, thereby enabling local steam condensation on the respirator. It is from these observations' that this section alters from a chorological analysis to one of water reservoir type analysis.

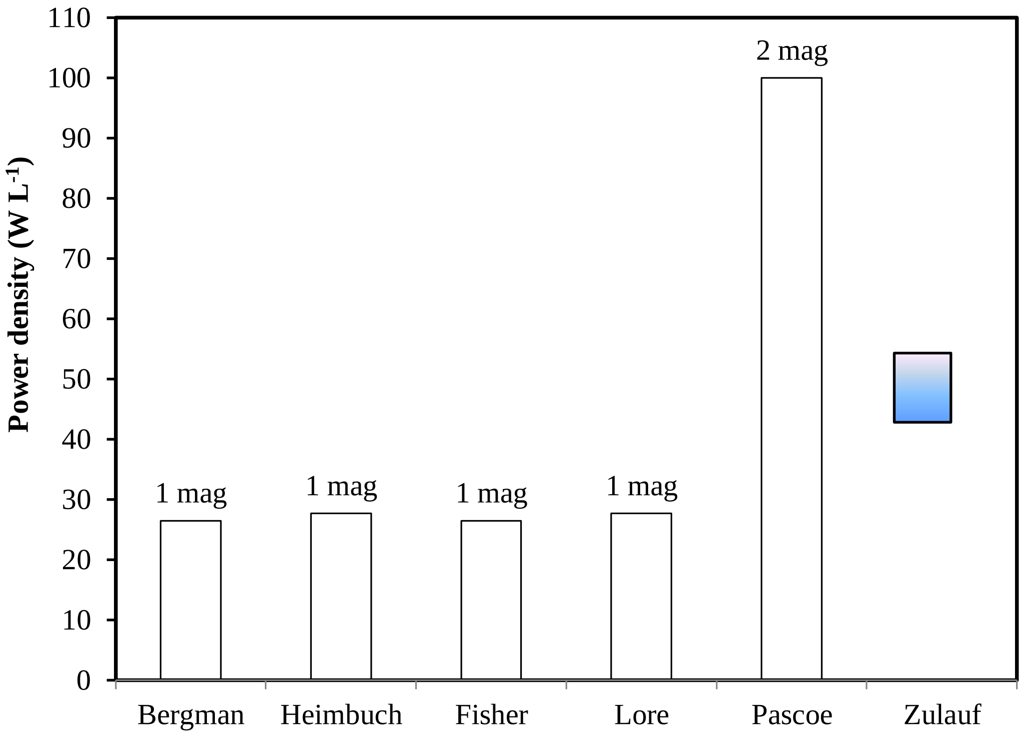

Fig-3: Bar-chart representing microwave power density for the six reviewed authors. Zulauf et al is estimated to be 44 to 55 W L^{-1}.

Table-6: Input and output energy calculations for open water bath decontamination process.

Author	Energy input calculations		Energy output calculations				
	Power (W)	Process budget (kJ)	Water (g)	99.9°C - room temperature *(ΔT)* [h]	heat energy Q (kJ) used to reach 99.9°C	Energy for steam conversion (kJ)	Liquid (g) into *steam (L)*
Bergman [6]	750	90	100	80	33.5	56.5	25 *41.7*
Heimbuch [7]	1250	150	100	76.5	32	118	52.2 *87.2*
Lore [9]	1250	150	50	78	16.3	133.7	59.2 *98.8*
Zulauf [26]	1100 1150	202.5 [i]	60	78	19.6	185.3 [i]	81.8 *136.6*

The grey shading of Bergman et al (2010) data differentiates the average measured rather than a rated cavity-magnetron power. When the water room temperature is not given, it is assume to be 22°C [h]. Mean process budget for the two magnetrons [i].

The thermodynamic input and output energy parameters of the open water bath method [6, 7, 9, and 26] are presented in Table-6, where the calculated input power and process energy budget is given in columns 2 and 3; columns 4 and 5 list the amount of water heated and the heated temperature range. Column 6 lists the estimated heat energy (Q) required to heat the water to 99.9°C, using the specific heat formula (see equation 2). The last two columns show the remaining energy that is available to convert liquid-phase water into steam.

The tabulated data reveals Bergman et al steam production has the potential to generate 41.7 L of steam, which is typically less than a half of Heimbuch (87.2 L of steam) and Lore (98.8 L of steam). However, Zulauf has the greatest potential of producing steam (136.6 L). The most plausible explanation for this outcome is that is the available power in

Bergman experiments has been measured and known to be an average of 750 W. Whereas; Heimbuch, Lore and Zulauf use rated cavity-magnetron powers values of 1000 to 1250 W within their oven cavities.

The thermodynamic input and output energy parameters of the sterilizer process [8, 25] are presented in Table-7. The notable difference between the sterilizer processes of Fisher and Pascoe is the available energy for steam conversion and the amount steam generated within the sterilizer. Generality Pascoe has twice the available energy and steam as compared to Fisher. It should be noted that Fisher reports the average measured power that is 68 % of rated power (1100 W) of the cavity-magnetron. Pascoe's data, therefore appears is an over estimation available power within the oven-cavity.

Table-7: Input and output energy calculations for sterilizer decontamination process.

Author	**Energy input calculations**		**Energy output calculations**				
	Power (W)	**Process budget (kJ)**	**Water (g)**	**99.9°C - room temperature (*ΔT*) [h]**	**heat energy Q (kJ) used to reach 99.9°C**	**Energy for steam conversion (kJ)**	**Liquid (g) into *steam (L)***
Fisher [8]	750	65.5	60	78	19.6	45.9	20.3 *34*
Pascoe [25]	1800	162	200	80	66.9	95.1	42 *70.2*

The grey shading of Fisher data differentiates the average measured rather than a rated cavity-magnetron power.

At this point is worth looking the industrial Panasonic NE-1853 microwave oven used by Fisher and making a comparison with a domestic microwave oven. Figure 4a shows a simple schematic of how the NE-1853 magnetron(s) are positioned around the microwave cavity and hence the oven-cavity illumination. As there is no rotating glass carousel is used, by default, the complex-load is placed central on the floor of the oven-cavity where the bottom cavity magnetron is located. It is not hard to visualize that the emerging scattered (due to the rotating antenna [50, 51]) microwave energy dielectric volume heats the complex-load directly, before passing into the open cavity and then be reflected back of the cavity walls. In contrast, the top cavity-magnetron illuminates the upper portion of the complex-load before passing into the liquid-phase water portion of the load. In addition to direct line-of-sight-illumination, scattered (incoherent) microwave energy is reflected of the cavity walls to the complex-load, and the cavity-magnetron waveguide iris where some of the energy enters and modulates the standing wave ratio (SWR) at the cavity-magnetron is frequency pulled within its operating bandwidth.

Figure-4b depicts the typical case for a domestic microwave oven where the complex-load is placed on a rotating glass carousel from where it is side illuminated by the single cavity-magnetron. In this scenario, dielectric volume heating of the complex-load is achieved as it rotates through the electromagnetic standing wave field patterns. The scattered (incoherent) microwave energy from the complex-load is reflected at the cavity walls, and waveguide iris where some of the energy enters and alters the SWR within the cavity-magnetron waveguide. Ultimately the time modulations (carousel rotation rate) of the SWR, frequency push/pulls the cavity-magnetron within its operating band.

These two differing modes of volume dielectric heating may be sufficient for food-stuff, where heat is allowed to conduct through the food once the energy is turned-off, this however may set-up different heating pathways in the complex-load as the liquid-phase water is turned in steam that is designed to condense on to a respirator, or mask. This difference in the mode of dielectric heating has a bearing on the choice of which microwave oven is suitable for the sterilizer decontamination process. This aspect is further explored in section 6.

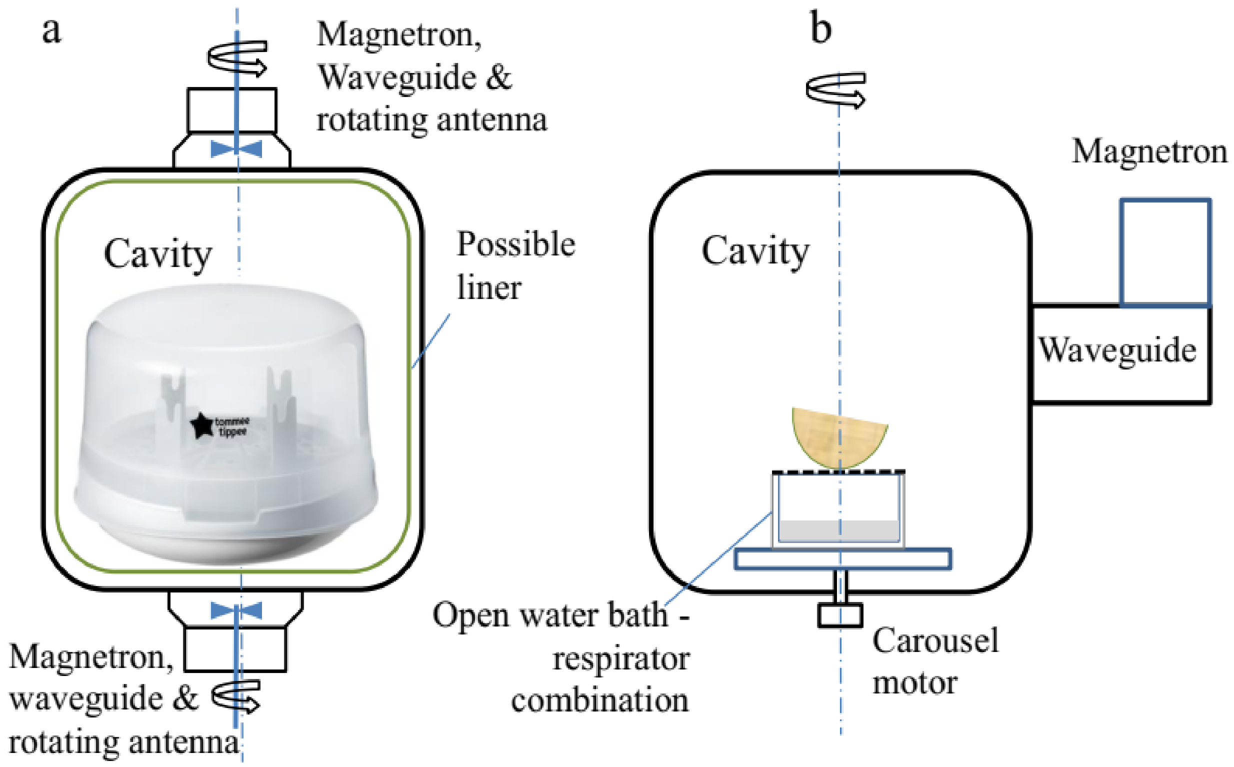

Fig-4ab. Front view Schematic of an industrial microwave oven a), and front view schematic of a domestic microwave oven b). In each case, the door and outer oven casing has been removed to show the complex-load intended position.

Respirators and mask outcome

Table-8 provides details on the 1X decontamination studies which reported on the N95 and SN95 respirators and which passed the BEF and arc test. A number of 3M-SN95 respirators however failed the adhesion test due the inner foam separated from the inner body of the respirator. Water absorption / retention test (WAR-test) was only reported by Zulauf et al with a level of < 1 mg [26]. Here the lack of reporting in the early works [6, 7, and 8] suggests a lack of awareness for the need of a WAR-test. Nevertheless if no WAR-test is included in MGS decontamination protocol the respirator will pass fit for reuse. Adhesion separation in two cases also highlights further bonding work is also required.

As with the open water bath protocol, a sterilizer protocol failed BEF, arc and adhesion between nose clip and material outcome may prevent a respirators or masks being re-used. Based on the N95 respirator isolation work of Mardimae et al [4], Fisher et al [8], has proposed an additional protocol failure for sterilizers. This being a one-hour WAR-test, where that rational being that the wearer will find a wet respirator uncomfortable and are unlikely to reuse the respirator. The sterilizer first cycle (1X) outcomes (BEF, arc, material adhesion, and one-hour WAR-test) for Fisher and Pascoe are shown in Table-9

Table-8: Reported first cycle (1X) MGS open water bath respirator decontamination parameters.

Author	Water volume	Respirator	Outcome			
			BEF	Arc	Adhesion	WAR-test
Bergman [6]	100 ml tap-water	3 x 3M-N95 3 x 3M-SN95	Pass Pass	Pass Pass	Pass Failed [d]	Not reported
Heimbuch [7]	100 ml tap-water	3 x 3M-N95 3M-SN95-1 3M-SN95-2 3M-SN95-3	Pass Pass Pass Pass	Pass Pass Pass Pass	Pass Pass Failed [e] Pass	Not reported
Lore [9]	50 ml tap-water	3M-1860 3M-1870	Pass Pass	Pass Pass	Pass Pass	Not reported
Zulauf [26]	60 ml DI-water	3M-1860	Pass	Pass	Pass	< 1mg

MGS caused all SN95 to experience partial separation of the inner foam nose cushion. Two of the 3M-SN95 experienced a slight melting of the head straps [d].

MGS caused one (SN95-2) to experience a slight separation of the inner foam nose cushion [e].

Table-9: Reported first cycle (1X) MGS sterilizer respirator decontamination parameters.

Author	Sterilizer and water volume	Respirator	Outcome			
			BEF	**Arc**	**Adhesion**	**1-hour WAR-test**
Fisher [8]	Medela and Munchkin. 60 ml tap water	3M-1860	Pass	Pass	Pass	Failed (9.2 g)
		3M-1870	Pass	Pass	Pass	Pass
		3M-8210	Pass	Pass	Pass	Failed (8.2 g)
		CH-N95	Pass	Pass	Pass	Failed (11.2 g)
		KC-PFR95	Pass	Pass	Pass	Pass
		M-220095	Pass	Pass	Pass	Pass
Pascoe [25]	Tommee Tippee sterilizer. 100 or 200 ml DI-water	KC-N95	Pass	Pass	Pass	Not performed
		GE-PPE	Pass	Pass	Failed [f]	Not performed
		Hw-FFP3	Pass	Failed [g]	Pass	Not performed
		PHW FF2:	Pass	Pass	Pass	Not performed
		Type-II	Failed	Pass	Not applicable	Not performed

Separation between nose clip and respirator body [f]. The nose clip arcing leading to the production of holes in the bridge region of the respirator [g].

In Table-9 it can be seen that the MGS decontamination process passes the BEF, arc adhesion test in all six cases, but fails in three (3M-1860, 3M-8210, and Cardinal Health N95). The striking feature of the failed cases however is the amount of water retention in some of the respirators (9.2g, 8.2g and 11.2g) as compared to < 1mg for the open water bath 3M-1860 respirator in Table-8, row 5. Pascoe did not report on the WAR-test making the comparison limited. As regards to the calculated steam production valve of 34 L in Table-7, this value is sufficient when condensed (20 g) to account for the liquid-phase water retention values measured by Fisher. Indeed the estimated value is a near factor of 2 which enables lost of steam through the exhaust vents to prevent an over pressurization of the sterilizer. The tabulated data also indicates that there is a clip to respirator bonding issue along with an arcing issue in some cases. The arcing and adhesion issue are addressed further in the discussion section.

DISCUSSION AND RECOMMENDATIONS

This reviewed has considered the therm odynamic and microwave engineering and technology aspects of six key MGS papers [6, 7, 8, 9, 25, and 26] in the field of MGS decontamination of N95 respirators and surgical masks, between 2010 and 2020. As with all datasets collected from different research sources, experimental conditions are not reported in a consistence manner. Where the reported experiment condition was insufficient a further 7 papers and reports are used as a data resource for the 6 key papers. However, there is still gapes in the knowledge data-base and therefore some assumptions have had to be made. The authors of this review have used their knowledge of microwave-oven plasma engineering [22 -24 and 47 - 50] to fill in the gaps in the context of microwave oven type and oven-cavity volume.

The power source of MGS decontamination of respirators and masks is based on the CW operation of a cavity-magnetron. This setting is usually the highs power setting found on domestic microwave ovens. Given that there is no pulse width modulation involved, a simple thermodynamic (energy input balanced with the energy output) of the MGS decontamination process for both open water bath and sterilizer has been analyzed. The thermodynamic analysis has highlighted the lack of consistent reporting of the measured available power within the oven-cavity. However, data mining of supporting papers and reports allows a reasonable estimation of the process energy budget and its pathway between the raising of the liquid-phase water temperature and the production of steam, thereby allowing a meaningful comparison between published MGS decontamination papers to be made.

Recommendations

Microwave generation of steam decontamination of used respirators and face masks for reuse has the potential to help address the key principles of green chemistry: namely, the reduction in harmful chemicals, bio-hazardous waste, and a reduction in respirator and face masks waste. To reach this potential by conventional scaling-up of one unit per function is one approach; however this practice is faced with challenges from the stringent controls of green chemistry. This work therefore recommends a two stage progression in the advancement MGS decontamination of N95 respirators. First provide recommendation for current microwave oven use and the selection of new microwave oven for MGS decontamination. Second, scale-out batch processing based on green chemical engineering and process intensification [24, 53]. This entails that respirator, sterilizer, and microwave oven designs are linked through their strengths rather than their weakness. Using this approach the risk is spread across all the key components of the MGS N95 respirator decontamination process. The following subsections outline these recommendations.

Current microwave oven checks and test for MGS decontamination use

- Remove grill option, if fitted
- Check for signs for cavity surface and joint corrosion. Corrosion will reduce the Q-factor of the cavity leading to a reduction in available cavity-magnetron power. Ultimately leading over heating of the oven damage to oven
- Domestic microwave ovens are not normally designed for the amount of steam generated within a few minutes that is encounter in MGS decontamination. Establish that the oven has steam vents at the back of oven. Built-in door steam vents have the potential for scalding when retrieving a respirator or mask from the oven
- If the available power of the cavity-magnetron is not known, then a calorimetric test should be performed to gain the average available cavity-magnetron power. A minimum available power of 750 W is required.

New microwave oven selection for MGS decontamination

The would-be buyer of a microwave oven is faced with a number of choices for MGS decontamination purposes. The following guidelines in selecting a microwave:

- Use a minimum of 20 L free working oven-cavity with no wall returns
- An oven with no grill option
- Minimum rated cavity-magnetron of 1000 W to allow for available power of 750 W. Ideally a calorimetric test for available power should be performed before purchase
- CW mode of cavity-magnetron operation if possible
- Children proof operation if possible

Future respirator and mask manufacture

Whilst preserving the integrity, filtering function and proper seal of N95-type respirators and mask, new manufacturing technologies need to be researched and implemented to make the compatible with the MGS decontamination process.

- To prevent arcing, metal nose clip need to be replaced with non-conducting and thermally stable (80 to 110^{o}C) polymers or composites materials
- New bond adhesion technology, or embedding, for securing the polymer, or composite, nose clip to the respirator should be investigated with the aim of being both steam and microwave irradiation proof to a three cycles (3X)
- Make respirator post MGS decontamination comfortable for the wearer, by lowering the water absorption and retention properties of respirator. This may be achieved using a hydrophobic coating. This is practically required for surgical masks that have foam components

Future sterilizer manufacture

Current commercial sterilizers are designed for the sterilization of infant feeding equipment. Manufactures of this equipment are in a good position to redesign their equipment for the following

- Redesign the equipment to specifically hold a single or multiple N95 respirators or masks
- Incorporate anti superheating (¼ wavelength metal electrodes) device [22]

Future microwave oven manufacture

Future microwave ovens may be redesigned to make them compatible MGS decontamination of N95-type respirators and masks. Some of the issues to be considered are as follows.

- Microwave oven manufactures need to provide information of the averaged available cavity-magnetron power when calibrated with a 500 to 1000 g water dummy load [39]
- The microwave oven needs to have a minimum 20 L free space for a sterilizer
- To prevent scalding while retrieving respirator and mask, steam vent extraction port to the rear of the oven should be included. In addition a means of draining liquid-phase water out of the oven’s cavity
- Children proof lock system need to be considered to prevent scaled and burns when retrieving respirators and mask, see recommendations in [40, 41]
- Incorporate a near-filed probes within microwave oven-cavity to detection arcing followed by control circuiting to automatically shut-down the oven before an electrical fire is initiated [50]
- Many industrial microwave ovens use stainless steel for the oven-cavity for ease of cleaning; however at microwave frequencies the surface resistivity of stainless-steel is higher than wall materials made from nickel

electroless plated mild steel. To keep wall losses to a minimum and oven-cavity *Q*-factor to the highest, the cavity should made from nickel plated steel with a cosmetic painted finish [50]

Conflict of interest
The authors declare they have no conflicts of interest.

Acknowledgements

We thank the organizers of the Chemistry World Conference, September 6th, 2021 (Webinar) for inviting us to give a keynote talk on the subject of MGS decontamination of respirators, and the conference delegates for giving their constructive comments.

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