Overview of Hybrid Microwave Technology

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Starting in the late 1980-s and continuing on through the mid- 1990's a series of research projects were carried out on a variety of waste remediation applications through collaborative efforts between Westinghouse Savannah River (now SRNL) and the University of Florida. All of these remediation methods made use of microwave hybrid heating in one form or another. The areas investigated included vitrification of simulated nuclear waste, destruction of electronic circuitry, transuranic wastes (TRU), tire waste, medical waste, fly ash, and gaseous aromatic hydrocarbons such as benzene, toluene and styrene. A brief overview of these projects is provided. Hybrid or microwave-assisted heating continues to be an important processing method and its application in the commercial sector and new research areas are briefly summarized as well.

Early Microwave Processing

The first microwave oven was built by Raytheon in 1946. The unit which was tested in a Boston restaurant weighed over 750 pounds and was 5.5ft tall. Industrial use became more prevalent after the development of practical choking systems for continuous processes in the early 1960's, with food processing as the primary end user [1-3]. By the 1970's and 80's with the advent of much smaller and more affordable ovens, microwaves began making their way into the homes across the US and are now found in 90% of American households. As interest in microwave processing grew, applications and research using microwave for waste remediation expanded, creating new fields of study, some of which are also discussed in this paper.

Background – Why Microwave Energy?

There were many potential advantages associated with microwave processing for waste remediation efforts. These included the following:

- Volume reduction
- Rapid heating, high temperature capabilities
- Selective heating
- Ability to treat wastes in-situ
- Portability of equipment
- Rapid/flexible process that can be made remote
- Energy savings

For some of the waste streams investigated, particularly those involving radioactive waste, immobilization of radioactive species sufficient to meet regulatory requirements for storage and transportation, along with volume reduction and ability to process remotely, were of primary importance.

Simulated High-Level Waste Vitrification

As a result of defense initiatives, a large volume of high-level radioactive waste was generated at facilities within the United States. In addition, European nations and Japan had quantities of radioactive materials from nuclear power plants to isolate and stabilize. After several decades of research, most nations selected vitrification and a series of engineered barriers to contain and store the waste.

The Defense Waste Processing Facility (DWPF) is the first facility in the US designed and operated to vitrify the radioactive waste generated at Savannah River (Figure 1). The facility houses 36 million gallons of liquid waste in 49 underground steel tanks. Construction of the DWPF began in late 1983, and began radioactive operations in March 1996. The DWPF is expected to produce approximately 6,000 canisters by 2019. A joule-heated melter is used to melt the waste/frit at a teperature of ~1150°C. The glass is then poured into stainless cannisters and welded shut. The canisters are stored on-site until a final repository is built.

Microwave processing of simulated Savannah River high-level radioactive waste was investigated at the University of Florida (UF). This work demonstrated the ability of microwave energy to heat both the base glass frit and the simulated waste using a 2.45GHz Raytheon microwave and a silicon carbide (SiC) susceptor. The data indicated that the glass began to readily absorb microwave energy shortly after passing the glass transition temperature, as shown in Figure 2 (Stage II) [4]. It was also shown that a very short processing time of approximately 60 minutes produced a homogenous glass. While the feasibility of using microwave energy to vitrify simulated wastes was demonstrated on the laboratory scale for the selected waste compositions studied, only highly demonstrated technologies with significant engineering and scientific experience and confidence, could be considered for use in a full-scale, production environment. This environment involves large-scale, remote processing operations and must accomodate a wide range of waste compositions. However, feasibility of using microwave technology, especially for processing of speciality radioactive wastes as well as many other types of wastes and potentially hazardous materials, was demonstrated.

Fig. 1. The Defense Waste Processing Facility at the Savannah River facility, Aiken, SC.

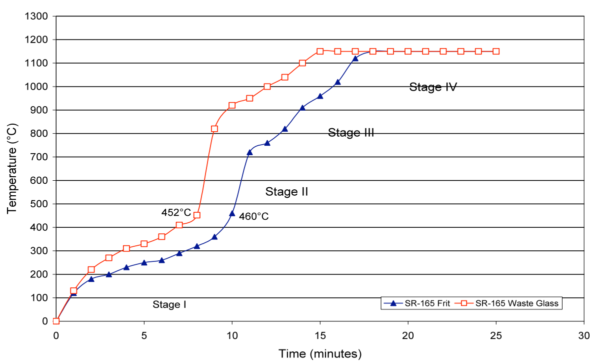


Fig. 2. Results of heating rate experiment with SR-165 frit and SR-165 simulated waste glass at 2.45GHz with SiC susceptor.

Weapons Dismantlement/Electronic Circuitry and Off-Gas Treatment

As a result of several international treaties, the US engaged in a process of decomissioning stockpiles of nuclear weapons. A portion of this program was the destruction of all electronic circuitry associated with these systems. Also, the safe disposition of electronic wastes from many consumer products (e-wastes), became of increaseing importance. Among the objectives of the Savannah River/UF program was the "destruction beyond all recognition" of all circuitry provided and immobilization of potentially hazardous waste constituents into stable vitreous forms. Several different types of boards and components were presented for destruction, which included unclassified firesets, trajectory switches, tungsten-based transistors, commercial circuitry and a 55 gallon drum of unclassified circuitry from the B&W Pantex defense waste processing facility located in Amarillo, Texas.

In order to completely destroy the waste, a basic processing scenario was developed and is shown in Figure 3 [7]. The equipment used during the project went through a series of modifications over time, but a majority of the experiments were carried out in a tandem microwave system similar to the one shown in Figure 4. Organic combustion and vitrication experiments were carried out in the lower microwave oven. A second microwave was connected to the combustion chamber to treat the off-gases that evolved during the combustion process. The tandem microwave addressed four key issues that made it technically and economically viable – volume reduction, treatment of secondary wastestream (emissions), immobilization of hazardous components, and recovery of valuable material for re-use.

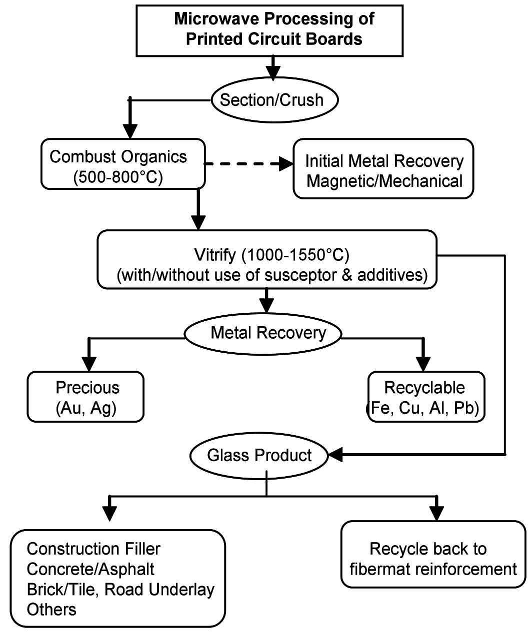


Fig. 3 Flow chart showing various steps in the microwave processing of electronic circuitry.

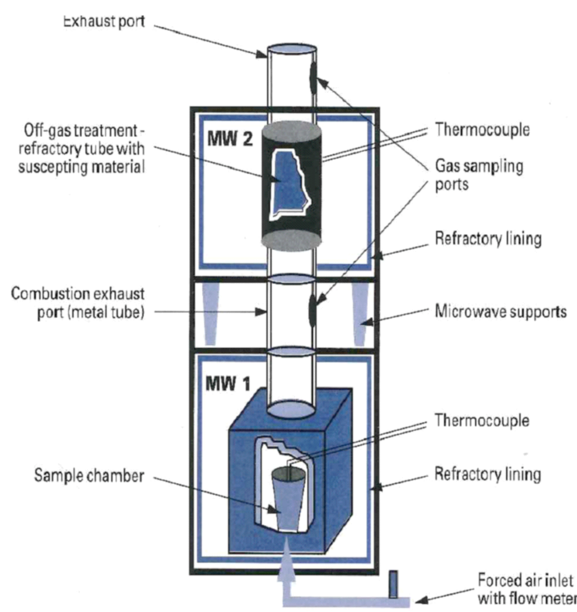


Fig. 4 Schematic illustration of trandem microwave processing system.

Both microwaves units operated at 2.45GHz, with power levels ranging from 850-900W. In some cases, glass frit was added to the circuitry, but depending on the composition of the board, there was often sufficient silica and other glass components within the board to create a durable glass wasteform. Silicon carbide was used in some cases to to achieve the high temperatures necessary to melt the silica, and in all cases to decompose the offgases.

Treatment of the volatile emissions involved the decomposition of a variety of aromatic hydrocarbons that included the following: benzene, toluene, ethylbenzene, styrene, napthalene, m/p xylene, 1,3,5 trimethylbenzene, and 1,2,4 trimethylbenzene. Most of these are listed in the Clean Air Act of 1990 as hazardous air pollutants [7]. As the polymers in the circuit boards were treated, the off gases were funneled to the upper microwave chamber via a directed air flow through the bottom of the lower chamber. The gases passed through a series of reticulated SiC filters designed both to heat the gases and increase residence time within the chamber. Using the same set-up, experiments were conducted using conventional heating for comparison. To determine the efficacy of the system, gas chromatography-mass spectroscopy (GCMS) data was collected both before and after treatment. Gas samples were collected using Tenax-TA air traps. Temperature and air flow were varied to determine optimum conditions. Some early results are shown in Table 1, and indicate a reduction in concentration of hazardous species by factors of 10 to 1000X. As shown in Figure 5, results indicate that microwave energy (same temperatures and flow rates) was more effective in most cases in decomposing benzene when compared to conventional radiant heating (similar results were achieve for toluene and styrene) [7]. These tests and data demonstrated the feasbility of using microwave energy for effective destruction of a variety of electronic wastes and safe immoblization of potentially hazardous componentes into a stabilitzed vitreous product.

Tires, Medical, and TRU Wastes

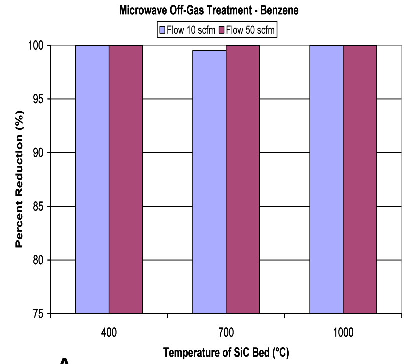
In the US, approximately 465,000 tons of medical waste is generated every year, with an estimated growth rate of 7-10% per year [8,9]. The number of tires discarded annually is estimated to be over 250 million, with an additional 3 billion used tires in landfills and other storage facilities [8].

The medical waste consisted of drapes, syringes, tubing, IV bags, sharps, and gauze (no biological waste was used in this

Table 1. Results from Microwave Treatment of Emission Resulting from Destruction of Electronic Circuitry.

COMPOUND	TEST SR-8 (ng)		TEST SR-9 (ng)	
	Before	After	Before	After
Benzene*	5839	22	1416	140
Toluene*	8147	16	4216	159
Ethylbenzene*	1147	nd**	4557	5
Styrene*	1667	6	20012	38
Naphthalene*	356	nd	2404	28
m/p Xylene*	2259	nd	511	nd
1,3,5 Trimethylbenzene	1564	nd	379	64
1,2,4 Trimethylbenzene	905	nd	172	nd

* Listed as hazardous air pollutants in Clean Air Act 1990
** nd denotes not detected (<1ppb)



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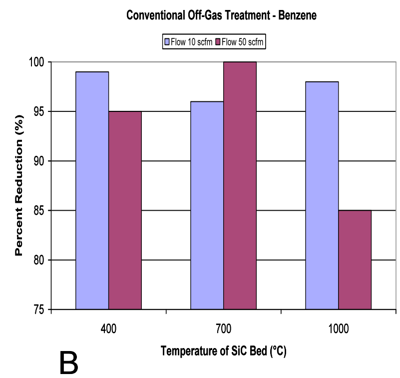

B

Fig. 5 Comparison of microwave and conventional heating on the decomposition of benzene gas: A) microwave treatment, B) conventional treatment.

study). The transuranic wastes generally consisted of gloves, wipes and other expendable laboratory supplies contaminated with low-level radioactive materials (simulated waste was used in the study).

Both the transuranic and medical wastes were processed in the tandem microwave. They required a susceptor to heat the materials to the desired temperatures to ensure destruction of the samples and enable sufficient reduction in volume. Volume reductions of 60-90% were achieved for the TRU wastes, with similar results for medical waste.

Tires contained a large amount of carbon and did not require hybrid heating. In this process, microwave energy was used to break the S-S and S-C bonds while leaving the C-C bonds intact (de-vulcanize but not de-polymerize). The treated tire material could then be added back into the tire-making process to make new tires with a higher degree of recycled material than previously possible [8].

Other Microwave/Hybrid Heating Applications

The collaborative efforts between Savannah River and the University of Florida resulted in numerous technical reports and six patents. Research continues in the use of microwave energy and microwave assisted processing for waste remediation and for a wide variety of applications. Several companies have built upon and expanded this early work and have also patented new and large-scaled microwave waste remediation systems. A brief overview of some of these efforts are as follows:

Commercial Applications: Several companies have patented microwave waste treatment systems (Sanitec, EnviroWave Energy, LLC, and Molecular Waste Technologies).

Sanitec has a long-established track record of sterilizing and treating medical wastes. The first Sanitec system was installed at Forsyth Memorial Hospital, Winston-Salem, NC in March of 1990. The company has systems operating throughout the US and in several foreign countries and has processed in excess of 500 million pounds of medical waste. The process consists of grinding the feed, which reduces the volume by ~80%, moistening with steam, and then heating in a series of microwave ovens. Sanitec is recognized within the industry as "the most widely used and regulatory accepted alternate system in the U.S." (Infectious Wastes News, December 1994) [10].

EnviroWave Corporation reported on its website that it completed the testing phase for its first commercial microwave-based scrap tire and mixed plastics in November of 2009. The system was to be installed in Ohio in late 2009-early 2010 and was expected to be operational within 60-90 days. The unit is capable of processing 50 to 60 tons of scrap tires or mixed plastics daily. Other units intended for delivery in 2010 and 2011 are capable of processing of 70 to 80 tons per day [11].

Molecular Waste Technologies located in Marietta, Georgia has also patented a very comprehensive microwave waste system to process and recycle organic landfill wastes [12].

Laboratory Scale Research: The list below summarizes some of the significant research performed in a variety of areas of microwave waste treatment.

Sewage Sludge: Researchers at Guangdong University in China investigated the efficacy of microwave energy for treating excess sewage sludge (ESS). The sludge is a mixture of water, organic and pathogenic organisms, and inorganic solids. Microwave treatment increases the solubilization of solids, which in turn speeds decomposition and production of biogas. The study concluded that microwave energy could be an energy efficient means to treat the ESS; however, it was limited by the water content of the sludge (lower water content, better efficiency; higher water content, more energy required to achieve same results) [13].

Electronic Industry Sludge: Jothiramalingam et al reported use of microwave heating for processing industrial wastewater sludge, with copper ions remaining in the sludge even after acid extraction processes. Additives were used to assist in stabilizing the copper ions (barium manganate, sodium sulphate, α-and γ alumina) or in some cases (referred to as hybrid microwave heating), the air was pumped out of the microwave chamber and replaced with nitrogen or carbon dioxide. The system operated at 2.45GHz, power levels of 600-800W, and time intervals ranging from 3 to 12 minutes. Processed samples were subjected to Toxicity Characteristic Leaching Procedure (TCLP), with the lowest leaching levels achieved by the addition of Na_2S (1.73g/40g sludge) processed in a nitrogen atmosphere for 9 minutes [14].

Residual Food and Sewage Waste: Martin et al have investigated the use of electron beam (EB) and microwave irradiation for the sterilization of wastes generated by vegetable oil plant. Their data that some organisms were more susceptible to the EB irradiation, while others were more affected by microwave exposure; therefore, a combination of the two methods produced the greatest reduction of microorganisms. The tests also demonstrated that the irradiation time and the upper limit of required EB absorbed dose, which ensured a complete sterilization effect, could be reduced by a factor of two by combining microwave energy with EB irradiation [15].

Flyash: Several groups have reported success in using microwave energy to process fly ash materials. Fang et al at Penn State reported successful sintering of Class F (coal burning) flyash in as little as 10-20 minutes using a 2.45GHz, 900W microwave, and porous zirconia susceptor [16]. Researchers at the National Taiwan University reported successful sintering of flyash from a municipal solid waste incinerator using microwave energy [17]. Querol et al reported a method for the synthesis of zeolites from flyash material. The study indicated that there was little difference in the zeolite material prepared using microwave assisted and conventional methods; however, processing time was drastically reduced via microwave processing (30 min vs. 24-48 hours) [18].

Microwave-Induced Plasmas (MIP): Destefani and Siores examined the used of MIP for treatment of exhaust from internal combustion engines. The system used the exhaust itself to create a nonthermal plasma that is ignited by a microwave source [19]. By pulsing the microwave energy using a 50% duty cycle, the plasma was sustained and an energy savings of approximately 40% was realized [20].

Conclusions

Microwave and microwave-assisted processing have been shown on both a laboratory and commercial level to be effective methods for successfully treating a wide variety of waste materials. As the population of the world continues to grow, resources are depleted, and landfills reach capacity, new methods for managing and reclaiming waste streams will become increasingly important. While microwave energy is not applicable for all waste steams, continued research and development of microwave technologies is believed to be an essential component in the responsible management of our environment.

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