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**Towards large scale microwave treatment of ores: Part 1 – Basis of design, construction and commissioning**

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**Keywords**

Microwave; Ore; Copper; Pilot Scale; Fracture; Beneficiation

**Highlights**

- A pilot scale system for microwave treatment of ores is presented
- Materials handling concepts and justification for packed bed mass flow are discussed
- Microwave applicator and choke modelling is validated against real ores
- Control of material flow and presentation is discussed
- The operating microwave treatment system performance is described

**Abstract**

Despite over thirty years of work, microwave pre-treatment processes for beneficiation of ores have not progressed much further than laboratory testing. In this paper we present a scaleable pilot-scale system for the microwave treatment of ores capable of operating at throughputs of up to 150tph. This has been achieved by confining the electric field produced from two 100kW generators operating at 896MHz in a gravity fed vertical flow system using circular choking structures yielding power densities of at least $6x10^8$ W/m$^3$ in the heated mineral phases. Measured $S_{11}$ scattering parameters for a quartzite ore (-3.69±0.4dB) in the as-built applicator correlated well with the simulation (-3.25dB), thereby validating our design approach. We then show that by fully integrating the applicator with a materials handling system based on the concept of mass flow, we achieve a reliable, continuous process. The system was used to treat a range of porphyry copper ores.



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## 1 Introduction

Microwave treatment of metalliferous ores has long been investigated as a means to enhance the recovery of valuable minerals and reduce the comminution resistance of ores (Chen et al., 1984; Walkiewicz et al., 1988; Walkiewicz et al., 1989). The underpinning mechanism and textural characteristics of amenable ores has been described by Batchelor et al. (2015). Selective heating of microwave-absorbent sulphides and metal oxides deported in a microwave-transparent gangue matrix results in differential thermal expansion of the heated phase, yielding micro-fracture around grain margins (Batchelor et al., 2015; Jones et al., 2005, 2007; Kingman et al., 2004a; Kingman et al., 2004b; Kingman et al., 2000a). Subsequent downstream processing may then yield higher recovery of valuable mineral sulphides and/or lower specific comminution energy, compared to non-microwave treated ore.

While the mechanistic principles are well established, the scientific and engineering challenges of developing a commercial scale system are immense. Typical throughputs of a large copper mine can be in excess of 5,000 tph of milled ore (Brininstool, 2015) and a microwave based treatment system would need to handle equivalent throughputs. This is at least an order of magnitude higher than any other microwave process ever built.

The following paper details the design, commissioning and operation of a system which was the culmination of over fifteen years of research and development activity. This resulted in a high power microwave treatment process, capable of operating continuously at throughputs of up to 150tph, but crucially, scaleable up to several thousand tonnes per hour.

### *1.1 Microwave Processing of Ores – Technology Development Timeline*

In Figure 1, the key early activities which underpinned the development of the pilot-scale system are presented. The earliest work investigated heating rates of different minerals in kitchen microwaves (Chen et al., 1984), supported by measurements of their dielectric properties. The early to mid 90's saw higher power tests conducted in larger industrial multimode cavities. (Standish and Worner, 1991; Yixin and Chunpeng, 1996). The large number of propagating modes characteristic of these types of applicator makes characterising the interaction between the applied microwave energy and the material very difficult, even using the power of modern high performance computers. Whilst the mechanistic principals were beginning to be understood (Kingman et al., 2000a), it was found that reductions in energy inputs (from >>10kWh/t to <5kWh/t) and residence times (to yield higher throughputs) were required to realise an economically viable process (Kingman and Rowson, 1998).

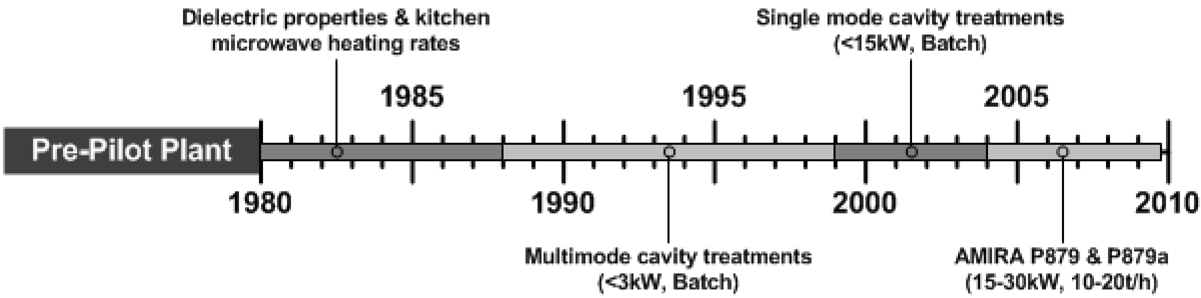


**Figure 1:** Early development of microwave processes for the treatment of ores

Focussed work using single mode cavities, post- 2000 resulted in reductions in the energy required, greater understanding of the breakage mechanism and also characterisation of the electromagnetic properties of such cavities (Kingman et al., 2004c; Kingman et al., 2000b; Robinson et al., 2010a). This yielded important information regarding the spatial distribution and intensity of electromagnetic energy within them. This enabled optimisation of their configuration, such that a well-defined area of high electric field was supported, sufficient to realise the power densities required. The first continuous belt-based processing systems were trialled under the AMIRA P879a programme around 2006 and were capable of processing ore at throughputs of 10 – 20tph and applied powers up to 30kW. Key learning outputs from this work were: the importance of integrating the materials handling system with the microwave cavity for process stability; and the design of choking structures. These were necessary to confine the electric field within the applicator in open-ended processing systems to prevent gradual warming of the load to optimise the thermal shock based fracture mechanism and achieve compliance with safety standards.

The work which directly supported the development and evaluation of the pilot-scale system is outlined in Figure 2. This began around 2010 with the development of a vertically aligned capsule which held ore fragments in place as a packed bed. This was moved though the applicator using a belt and pulley system and was effectively a pseudo vertical flow configuration. The key development arising from this work was the design of innovative circular choking structures through which the capsule moved. These confined the electric field in a relatively small zone centred on an open ended applicator. This minimised heat conduction of the heated phases to the bulk ore, thereby maximising stress in the ore matrix and yielding fracture at reasonably low energy inputs. If the circular chokes were



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not incorporated into the system, then there would exist a gradient in electric field intensity both above and below the vertically aligned applicator, which would introduce a gradual warming of the load at it passed through. Heat conduction to the bulk ore would then lessen the stresses generated through the differential thermal expansion of heated phases confined within a relatively non-heated bulk ore matrix. A detailed account of the mechanistic aspects and ore textures susceptible to such a process has been reported by Batchelor et al. (2015).

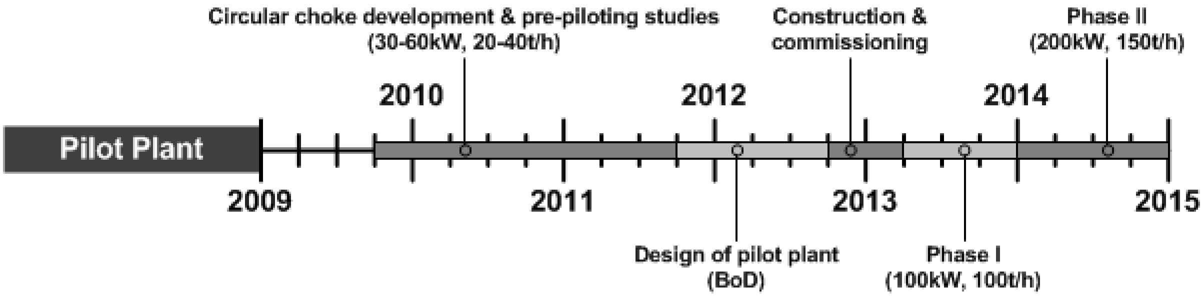


**Figure 2:** Key activities in the development and evaluation of the pilot-scale system

The design and testing of these choking structures was considered in detail in Katrib et al. (2017). The pre-piloting system was crucial in validating the performance of the circular choking structures, particularly with respect to confinement of the electric field in an essentially open-ended system, in order to meet health and safety and electromagnetic compatibility regulations.

### *1.2 Aims and objectives*

The aim of this work was to design and demonstrate the viability of a pilot-scale system that can be then be further scaled to a commercially relevant system for deployment at a mine site. Specific objectives for the pilot scale system were to:

- Demonstrate that metallurgical effects observed in pre-piloting batch scale testing could be re-produced in continuously flowing ore at pilot scale.
- Evaluate the impact on the system performance and process stability of feed ore presentation in the applicator. Specifically aspects such as particle size; shape; moisture content; voidage; mineralogy and ore texture
- Assess engineering issues such as wear and reliability of the system components
- Produce statistically large volume test samples for subsequent use in proposition analysis

The evaluation of the pilot-scale system addressed the key questions around electromagnetic engineering, materials handling design and optimisation, operability, sample generation / value quantification and techno-economic analysis.

## 2 Design Philosophy of the Pilot-Scale System

The engineering vision of the pilot-scale system was rooted in the concept of frequency scaling using a single mode cavity surrounding a vertically aligned tube used in pre-piloting studies as described in section 1.1. Based on flowing ore down a tube passing through an applicator section, the maximum throughput is defined by the cross-sectional area at the bottom of the converging hopper geometry above the inner cylindrical processing tube. It is assumed the hopper outlet and cylindrical processing tube are the same diameter. The maximum throughput is further defined by the flow properties of the handled ore and the system geometry.

In a single mode system which supports an area of well-defined electric field, in order to maximise the treatment efficiency, the tube should span as close to the full width of the applicator as possible. It then follows that the size of the applicator section then defines the width of the process tube and thereby the throughput. The applicator dimensions are fixed by the frequency of the applied microwave energy. Only specific frequencies are allowed for use and are defined in the Industrial, Scientific and Medical (ISM) bands. For a single mode applicator system based on the use of microwave energy at a frequency of 433MHz, the maximum theoretical throughput would be 1000tph, as waveguide at this frequency has an internal width of 584mm. The dependency of throughput on process tube diameter is show in Figure 3.

The maximum throughput is non-linear with increasing flow path diameter, due to basic area principles but also due to reduced solids flow rate for large particles compared to the flow area. Given that flow properties of ore do not scale, and the requirement to handle large particles in the pilot system, the 100tph pilot scale actually proved



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more challenging with-respect-to solids handling issues than would be a larger 1000tph system. To minimize these challenges, the large particles (>50mm) were screened from the bulk feed for the pilot scale work (Figure 3). This enabled the solids throughput rate to be maximized to best couple with the microwave processing requirements.

In order to define a clear route to scale-up, a 1000tph single mode microwave system was designed. The design approach was then validated by scaling back the throughput to the next ISM band of 896MHz, corresponding to a system throughput of 100tph (higher wavelength – smaller applicator). Technical risks could then be minimised, development costs could be managed to within acceptable limits and it also allowed the system to be situated close to University of Nottingham, rather than on a mine site. However, it must be emphasised that the design of both the 1000tph and 100tph systems was essentially the same – a single mode applicator through which ore is continuously flowed down though an inner processing tube, in which required electric field confinement was achieved by circular choking structures.

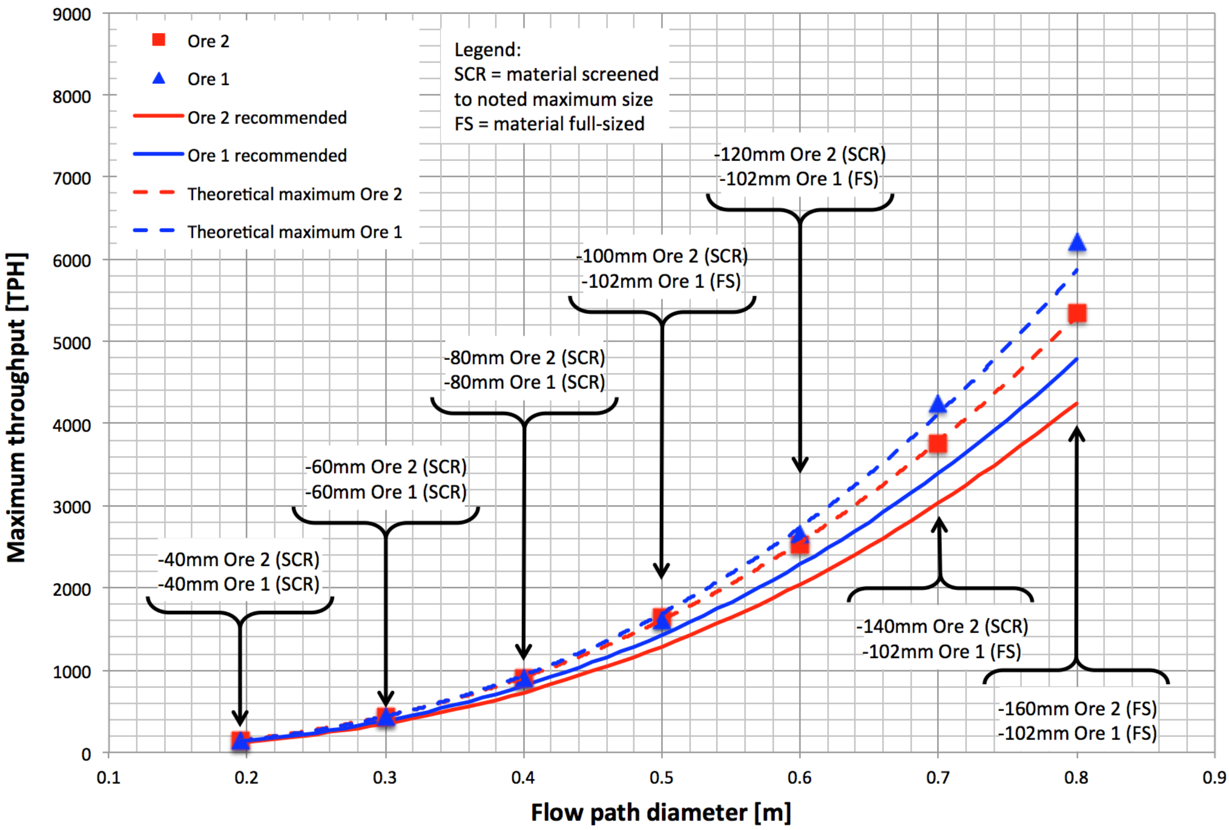


**Figure 3:** Dependency of throughput on process tube diameter for a vertical flow system

Critical to the success of the pilot-scale system was the integration of a continuous vertical flow microwave applicator, based on the use of corrugated circular chokes to confine the field (Katrib et al., 2017), with a materials handling system to yield a continuous flow process to treat porphyry copper ores.

## 3 Basis of Design

The performance of any microwave-based processing system (particularly continuous processes) is dependent on the integration of a suitably designed applicator with a competent and robust materials handling system. This is critical because the handling system presents the process material to the applicator such that the energy can be reliably and stably transferred to it. Therefore, it is then a cornerstone of the successful scale-up of any microwave based process.

A range of different concepts were evaluated during the design phase of the system for transporting material through the microwave applicator including free fall, vibratory feeders, belt conveyors and packed beds. These were evaluated against the following criteria: footprint; materials of construction; material velocity and residence time control (to control delivered energy dose to the ore); voidage (to prevent arcing) and dust control (to protect the microwave and sensor systems).



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A packed bed mass flow concept was judged to be the most suitable materials handling option for the system. It is similar to a free fall concept, except that the process material completely fills a tube or other handling system. Typically the material is held in place and is common in distillation and separation processes. By arranging the tube vertically, it can be filled from the top and the process material can be gravity fed through the tube by carrying away the material at the bottom using a conventional feeder. Providing that the appropriate material is selected for the tube, which is microwave transparent and exhibits the necessary mechanical robustness, this concept has stand-out advantages over those previously described. The voiding inherent to a free fall system is removed because the ore is essentially mechanically locked together. This also allows close control of residence time and energy dose. It is also scaleable because the essential design of the tube would not change to accommodate larger throughputs. As the system is enclosed, dust issues are also removed. By having the applicator aligned vertically, it also realises the smallest footprint of the systems considered. In terms of scalability, system performance and technical simplicity, a packed bed concept using a vertically aligned tube was taken forward in the design of the pilot scale system. The basis of design is shown in Table 1.

The proposed location of the pilot-scale system was to be close to the University of Nottingham in an industrial unit. Therefore, specifically for this system, its location imposed constraints in terms of plant foot print and height, which then fed into the BoD and would not be associated with a typical mine site. In addition, space available for storage of feedstock material was limited, which also imposed a constriction on the amount of feedstock that could be stored on site.

Single-mode microwave applicators are characterised by supporting a well-defined area of electric field, associated with the propagation of the first order mode at the frequency of the applied energy. However, such an applicator will be rendered ineffective if the energy delivered to it does not meet the requirements of the process. Currently the highest power microwave generators available commercially are 100kW systems operating at 896MHz in UK (915/922MHz in other regions of the world). The applicator is configured around a vertically aligned tube passing through the centre of the single mode applicator, the cross-sectional area of this tube then defines the system throughput. The waveguide used for transmitting the microwave energy at this frequency to the applicator is WR975 having dimensions 248 by 124 mm (width by height). To ensure that the maximum amount of material could be microwave-treated as it passes down through the system, the internal pipe spans the maximum width of the waveguide applicator. This is a $TE_{10n}$ single mode cavity supporting a well-defined area of high electric field. Allowing for fabrication and structural redundancy of the applicator as a whole, the internal diameter of the inner pipe is 199mm (having a wall thickness of 6 mm). The volume of the cavity is 0.015m$^3$, so 100kW of applied microwave power realises an electric field strength of 6.6x10$^6$W/m$^3$ in the bulk ore, which corresponds to between 6.6x10$^7$ (for 10% heated phases) and 6.6x10$^8$W/m$^3$ (for 1% heated phases), dependant on their abundance.

To ensure the material flowed through the system without blocking, the width of the inner pipe has to be at least five particle diameters, based on established bulk solids handling theory (Jenike, 1964). The coarsest single size particles which could be processed without blocking in the applicator and available from the mine site were in the size class -50.8+25.4mm. Coarser particles up to 76.2mm could potentially be flowed if run in lean phase with fines. Based on a bulk density of 1250 – 1700kg/m$^3$ (voidage 35 – 55%) and a maximum particle velocity of 2m/s, then yields the maximum throughput of the system at 100tph with an operational capacity of two minutes. While the system is continuous, it does not have a recycle capability and has a maximum storage capacity of only ~6t, therefore, total capacity and hence running time is limited by that of the out-feed hoppers downstream of the applicator. Given the semi-batch nature of the operation of the system, microwave start was required to be <1s. This is important as any ramping of the microwave power when the ore is in transport through the applicator, will result in a blend of material which has received a variable dose of microwave energy. By applying the power fully and near instantaneously, this then allows the system to generate the maximum amount of microwave-treated material. This also provides a clear demarcation between untreated and microwave-treated material, thus ensuring that the ore has been treated in the applicator at the defined energy dose.

The applicator was designed using average bulk dielectric properties of a quartzite ore previously described (Katrib et al., 2017) and used on both the Phase I and II test programmes (defined as Ore 1 herein). Of the ores supplied to the test programme, this quartzite had the lowest dielectric loss. That is, the lowest proportion of microwave energy absorbent phases. As such, when the applicator is filled with this ore, it will exhibit the lowest degree of wave attenuation. The strength of electric field propagating out of the open-ended applicator is then greatest for this ore. By designing the choking structures against this 'worst case' ore, system compliance was ensured against European Union (EU) Directive 89/336/EEC (Directive, 1989) with regard to Electromagnetic Compatibility (EMC) and Occupational Health and Safety Exposure (OHS) Limits. These being an average -32dB measured at 10m from source and 5mW/cm$^2$ respectively. A further sensitivity analysis was also performed for each of the other ores to be tested to ensure that the safety and technical performance of the applicator and chokes were not changed despite a small variation in the bulk dielectric properties of the different ore types. The bulk measured



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dielectric properties for the ore type 1, 2 and 3 in the -50.8 +25.4 mm size class processed in the pilot plant are presented in Table 2.

**Table 1**

Basis of Design for the pilot-scale system

| Parameter | Aspect | Requirement | Notes |
|---|---|---|---|
| Design Scope and Operability | System Size | Max Footprint 540m$^2$, Height <10m | Restriction imposed by plant location |
| | Capacity | 6 tonnes (4 × 1.5t discharge bulk bags) | Per run (up to 3 runs per day) |
| | Throughput | 10 – 150 tonnes per hour | To inform design of 1000tph system |
| | Service & Operability | Modular design of applicator to replace liners and maintainance requirements | |
| Microwave System | Power & Frequency | 2 × 100kW at 896 ± 10MHz | |
| | Power Density | ≥ 6 ×10$^6$W/m$^3$ | In the bulk ore |
| | Energy Dose | 0.1 – 20 kWh/t | Dependant on applied power and throughput |
| | Start up/Shut down | <1s | |
| | Material velocity through heated zone | 0.2 – 2.0 ms$^{-1}$ | |
| | Voidage | 35 – 55% | |
| | Applicator internal diameter | 0.2m | Vertically aligned tube |
| | Health and Safety / Electromagnetic CompatabilityCompliance (EMC) | <5mW/cm$^2$* | EMC with European Legislation* |
| Feed Ore | Particle size Range | 0 – 75mm | Nominal 25 – 50mm |
| | Content of heated phases | 1 - 10% by weight | |
| | Bulk density | 1250 – 1700kg/m$^3$ | |
| | Bulk dielectric properties | ε' ~3.2 ε" 0.18 | Values used in applicator design |

Note: * - Occupational Health and Safety Limit. Electromagnetic Compatability (EMC) requirements defined in European Union Council Directive 89/336/EEC. International Commission on Non-Ionizing Radiation Protection (ICNIRP) limits at 896MHz are 2.24mW/ cm2.

**Table 2**

Dielectric properties and density data of the ores processed through the pilot plant

| Ore Type | Dielectric Constant (ε') | Loss Factor (ε") | Bulk Density (kg/m$^3$) |
|---|---|---|---|
| 1 | 3.2 ± 0.04 | 0.18 ± 0.03 | 1,470 |
| 2 | 3.6 ± 0.08 | 0.60 ± 0.13 | 1,640 |
| 3 | 3.2 ± 0.05 | 0.17 ± 0.01 | 1,460 |

Another key consideration in the specification of the system is upper limit on the treatment energy required. The process would be uneconomical if more energy is required in the pre-treatment of the ore then is saved in downstream processing. Preliminary value analysis shows that treatment energies above 2kWh/t may not be economical for a host mine site. However, this value is highly dependent on a range of factors including (but certainly not limited to) plant location, utilities and capital expenditure costs, labour costs and commodity prices. The apron feeder was capable of feeding 10-150t/h and the microwave generator capable of supplying 10-100kW (both limited by a 10% turndown ratio). Therefore, doses in the range of 0.1-20kWh/t were achievable in the system.

The initial system had a maximum throughput of 100tph, through a single applicator and 100kW generator at a frequency of 896MHz. This system was then used to generate microwave treated ore samples under the Phase I commissioning programme. The system was then modified by adding a second applicator in series with the first, running off a second 100kW generator and increasing the throughput of the system to 150tph by optimising the materials handling system. The addition of a second applicator in series with the first was undertaken to improve the homogeneity of the electric field distribution through the cross-sectional area of the applicator. This Phase II work programme was then used to generate treated ore samples under an optimised treatment regime for subsequent metallurgical analysis. A detailed analysis of the ore samples generated from the Phase I and II programmes is reported in the second part of this paper (Batchelor et al., 2017).



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### *3.1 General System Overview*

In the present configuration, ore is held in a specifically designed mass flow hopper at the top of the microwave applicator and choke arrangement held in a vertical position. This hopper is supplied with ore by a material transport system comprising of bulk in-feed hoppers and associated conveyors. The hopper and associated equipment has been designed to achieve mass-flow of material to avoid segregation and to ensure that a consistent packed bed of material could flow at the fastest possible velocity with minimal voidage to maximise throughput. Material held in the hopper above the applicator is drawn down a tube through the upper choking sections, passing through a box section of waveguide into which the microwave power is applied, before moving out of the applicator after passing through the lower choking sections. The material flows down the inner processing tube as a packed bed controlled by an apron feeder at the bottom of the system. As this conveyor runs, it draws material out from the base of the tube drawing material downwards. The throughput of the system is then controlled by the speed of the apron/belt feeder. The general arrangement of the system is shown in Figure 4.

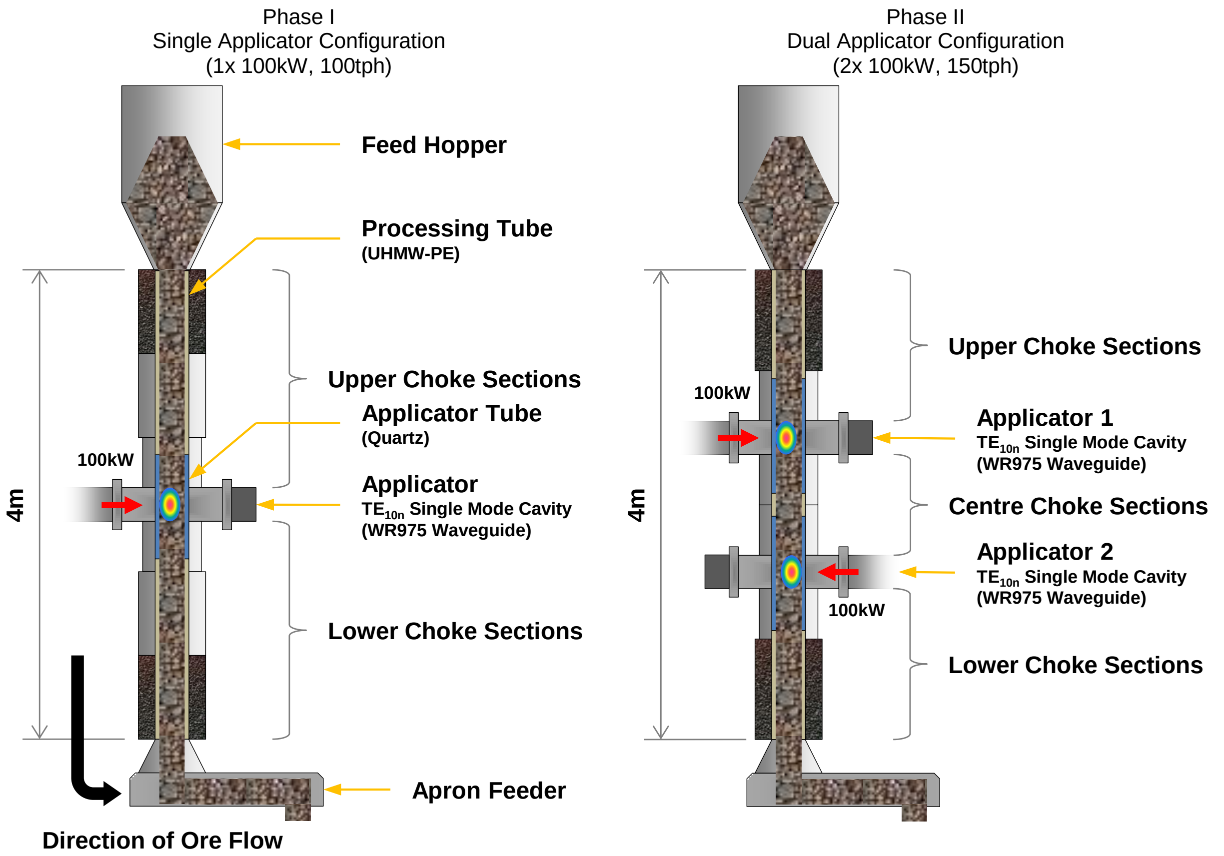


**Figure 4:** Vertical flow configuration of the 100tph single applicator (left) and 150tph dual applicator systems (right)

The pilot plant layout is illustrated in Figure 5 and the treatment sequence was as follows. Feed material was loaded from bulk bags into feed bins A01-A04 by jib crane J01. Separate feed materials (i.e. primer, ore sample or ore fines) could be charged into separate feed bins where necessary. A fine primer material was loaded first in the treatment sequence to protect the quartz tube lining the applicator from the impact of falling ore fragments. The primer was comprised of <5mm low purity silica sand, which was similar in dielectric properties to the non-sulphide gange minerals in the ore sample. The materials were then charged or blended onto conveyor C05 by feeding at different rates from feed bin discharge conveyors C01-C04. The primer or ore/fines material was carried to bin A05 by bucket elevator E01 and transfer conveyor C06. Bin A05 is the mass flow hopper used to feed the microwave applicator tube AT01. The bin contained level sensors to prevent over-filling at high level, to initiate microwave shutdown procedures at low level and to start/stop the feed system to maintain the level between the low and high levels during continuous runs. Apron feeder FD01 controlled the throughput and microwave generators M01 and M02 provided microwave power, the combination of which controls the microwave treatment energy dose. FD01 discharges material to slewing conveyor C08 which swings between four discharge bulk bags DB01-DB04 over the course of the run.



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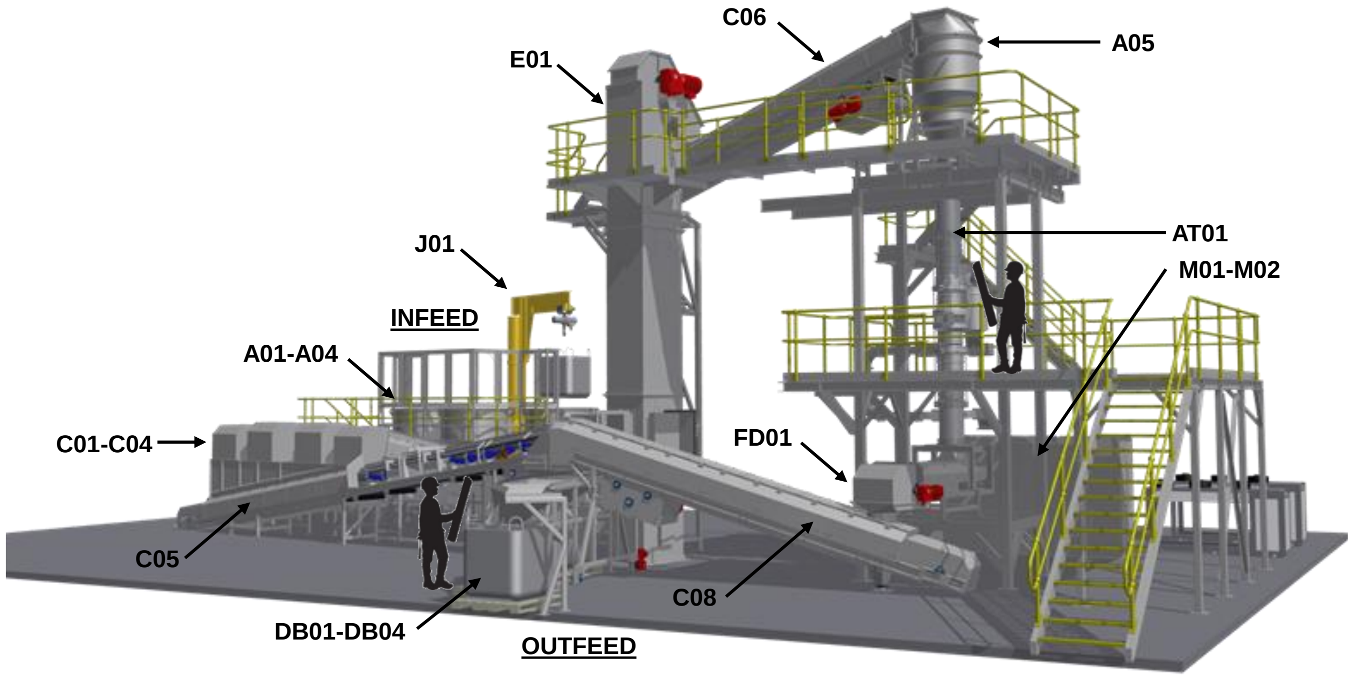


**Figure 5:** Pilot plant layout

## 4 Applicator and Choking Structures for a 100tph Continuous System

Katrib et al. (2017) described continuous flow circular cavity designs to process copper ore at a frequency of 896MHz. The use of corrugated circular chokes for field confinement is critical, as it minimises the propagation of an electric field strength gradient either side of the applicator. This gradient would then lead to incremental warming of the ore, as it moves through the applicator and an inevitable loss of energy through heat transfer to the bulk rock matrix (Bradshaw et al., 2007). By confining the field using the choking structures, the ore remains close to ambient temperatures until it enters the applicator. Subsequent rapid heating of the susceptible phases confined by the comparatively cold matrix, then results in uneven thermal expansion. This uneven thermal expansion produces differential stress around the phase boundaries within the ore and leads to fracturing. In addition to optimising the breakage process, the confining chokes when coupled with resistive chokes filled with carbon foam also serve to achieve compliance with both United Kingdom (UK) Environmental Health and Safety Legislation (EHS) and Electromagnetic Compatibility (EMC) Legislation (British Standard, 2010). In addition to providing the necessary system performance, the optimised choking structures also importantly serve to minimise plant height and footprint - factors which are a major capital cost driver.

Two distinct types of choking structures are used in the applicator. The first are the concentric rings of variable geometry immediately above and below the single mode cavity. These so called *reactive chokes* reflect the escaping power back into the applicator and serve to increase the efficiency of the process. They are a series of pure capacitive steps and confine the field of the first propagating modes from the cavity. The response of the chokes depends on the geometry (tube diameter), homogeneity and dielectric properties of the load (the material in the applicator). The tube diameter and the dielectric properties will dictate how many modes (energy carried by the electromagnetic radiation) will propagate. Each choking structure either side of the applicator has been shown to have an attenuation of -30dB to a distance of 40cm away from the applicator. In addition to these reactive chokes, the system also incorporates *resistive chokes* to achieve compliance with EMC legislation. These are comprised of dense carbon foam wrapped around the inner process tube which further attenuate the residual energy. Considered together the action of the reactive and resistive chokes serve to achieve a total attenuation of -120dB, or a reduction of $1x10^{12}$ times when the discharge power is compared to the input power. This effectively means that for an input power of 100kW, the outputted power from either outlet of the choking structures is one million times less than the equivalent signal strength of a mobile phone. The reactive and resistive chokes incorporated together with the single mode cavity are shown in Figure 6.



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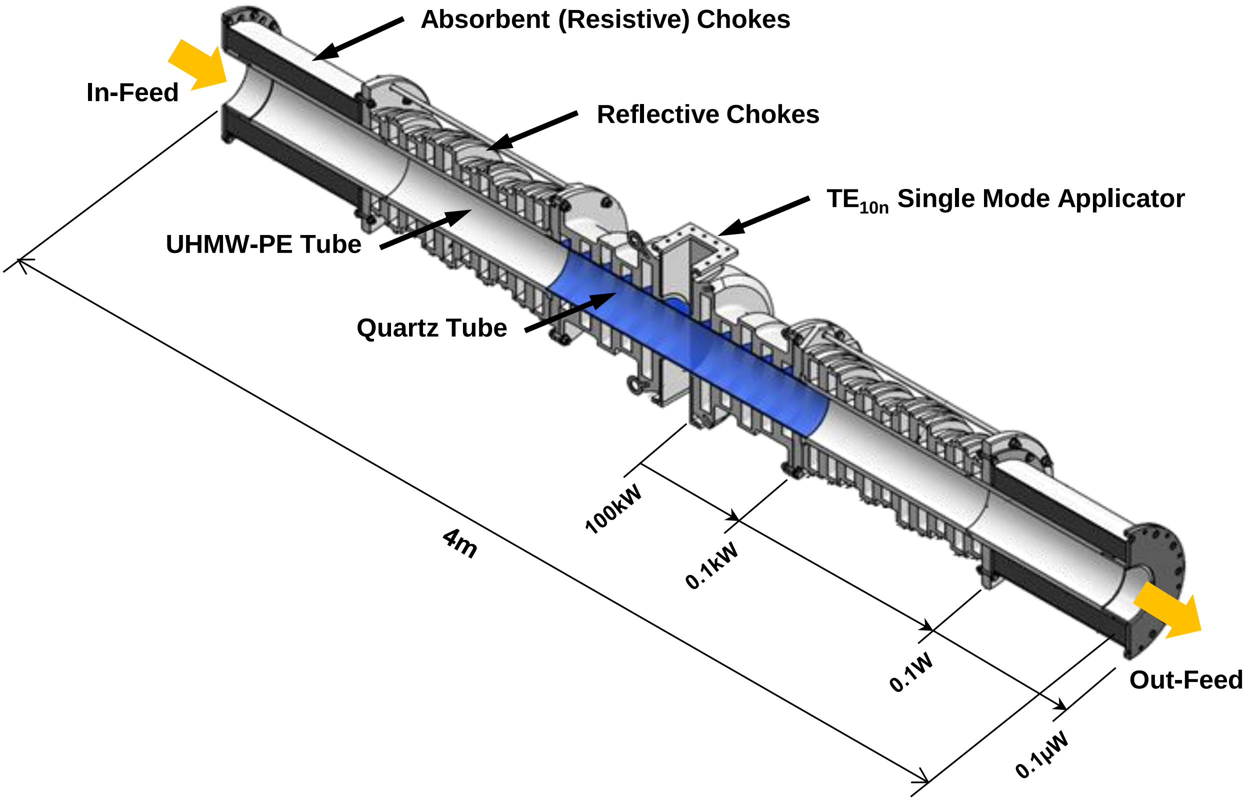


**Figure 6:** Reactive and resistive choking structures developed to confine the electric field in the single mode cavity whilst allowing ore to flow continuously

Careful consideration was also given to material selection for the inner pipes. In the $TE_{10n}$ cavity section a quartz liner was used having a total length of 1147mm, 6mm wall thickness and 199mm internal diameter. The reasons for selecting this material were three-fold: it allowed visualisation of bulk material flow during processing; was dielectrically stable with temperature; and had dielectric properties similar to the bulk ore non-heating gangue material, thereby allowing the microwave energy to be transmitted through it without significant reflections occurring. Above and below the quartz liner, the remainder of the process tube was made from Ultra-High Molecular Weight Polyethylene (UHMW-PE). The degree of electric field attenuation in these sections of the applicator is such that the process tube is much less susceptible to potential thermal effects. UHMW-PE was selected as despite having a lower melting point, it exhibited greater mechanical robustness. This tubing ran through the remaining reactive chokes and the resistive chokes to the discharge chute of the in-feed hopper and the out-feed transition to the apron feeder above and below the applicator respectively. Over the course of the Phase I and II test programme, over 900 tonnes of material was processed through the system with only light scoring of the inner components.

### *4.1 Characterisation and Validation of Single Applicator System Performance*

The electromagnetic field confinement of the choking structures in the as built applicator was evaluated by measuring the scattering parameters ($S_{11}$ reflection coefficient) of ores used in the test programme as a function of moving the sliding short position. The $S_{11}$ reflection coefficient describes the ratio of reflected signal intensity to that of the incident signal. The microwave in-feed waveguide was decoupled from the system and replaced with a WR975 co-axial to waveguide transition, in turn connected to a Vector Network Analyser (VNA). Experimental measurement of $S_{11}$ was undertaken in the frequency range of 866 – 933MHz, corresponding to the magnetron frequency variation. This variation arises from the physical change in magneton component dimensions during operation. Three ores were used in the applicator field confinement validation process. Two size fractions of each ore were evaluated (-50.8+25.4 mm and -12.7+6.35 mm), in addition to a blend. Each blend was comprised of the following three fractions: 35% -50.8+25.4mm; 32.5% -25.4+12.7mm; and 32.5% -12.7+6.35mm

The modal mineralogy of these ores is described previously in Batchelor et al. (2015). The applicator column was filled with one of the size classes of the ores defined in Batchelor et al. (2017). Then the position of the sliding short was changed in 10mm increments between 160 and 380mm and the $S_{11}$ measurements recorded at each position. Measurements were repeated five times by slowly jogging the feed conveyor to move the blended ore down through the applicator column after each completed set.



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### *4.2 Validation of EHS and EMC Compliance*

Before the applicator was installed in the plant, the attenuation performance was measured and compared to that of the simulation to ensure compliance with the required OHS and EMC legislation. The central portion of the applicator – defined as the single mode cavity and the first five reactive choking corrugations either side of it (including quartz liner) was filled with Ore 1, then WR975 round to rectangular transitions attached to either end. Three co-axial to WR975 waveguide transitions were then attached to the infeed and outlet of the applicator and the microwave in-feed section of the applicator with a Vector Network Analyser. A sliding short was conneted to the microwave out-feed section of the applicator. The three port scattering parameters $S_{21}$, $S_{31}$, $S_{23}$ were then measured. The $S_{21}$ and $S_{31}$ parameters could be directly correlated with the confinement field attenuation the system produces.

The attenuation is around 10dB greater at the centre frequency of 896MHz. The field confinement is therefore better in the as built applicator, than that predicted by simulation and more than exceeds that required for compliance with EHS and EMC legislation (British Standard, 2010).

### *4.3 Optimum Short Position*

The applicator waveguide section itself is terminated using a moveable sliding short. By moving the position of this short, the position of the incident and reflected waves can be superimposed on each other to adjust the position of the area of highest electric field intensity (the ‘hot spot’). This then serves to optimise the material treatment efficiency. As a function of sliding short position (as per the experimental measurement), the average power density was calculated within the quartz liner of the applicator for each of the ores. This analysis allowed the determination the optimum short positon for the operation of the plant. It showed that the applicator exhibits a non-uniform power density through its cross-sectional area. To determine the optimum sliding short positon, the Power Uniformity Index (PUI) (Tiwari et al., 2011) was calculated (Eq. 1):

$$PUI = \frac{\frac{1}{V_{vol}} \int V_{vol} sqrt((Q - Q_{av})^2) dV_{vol}}{Q_{av}} \qquad 1$$

Where: PUI is Power Uniformity Index, $V_{vol}$ is material volume in $m^3$; Q integral of the power density in $Wm^{-3}$ and $Q_{av}$ ($Wm^{-3}$) is the defined as the volume integral of the power density divided by the material volume as per Eq. 2:

$$Q_{av} = \frac{1}{V_{vol}} \int V_{vol}\, Q dv_{vol} \qquad 2$$

The lower the value of PUI, the more uniform the power density through the volume of the applicator. If PUI is zero then there is no variation in power density in the calculated volume of the load. An example PUI evaluation for Ore 1 is presented in Figure 7.

Considering Ore 1 (Figure 7) the variation in PUI as a function of short position is similar for the -50.8+25.4mm and bended size fractions. A lower value of PUI is found for the -12.7+6.35mm size class. It is suggested that by reducing the size of the material, the copper sulphides are more uniformly distributed with the bulk, coupled with better packing within the applicator and therefore higher bulk density results in a more homogenous load. The optimum short position was therefore 270mm and was used during the production of the sighter test samples. The $S_{11}$ attenuation for the blended ores was compared to the simulated values to validate the system performance and are presented in Table 3.

It can be seen from Table 3 that the experimentally derived value of $S_{11}$ of the Ore 1 is in excellent agreement with that derived from the simulation. For Ore 2 and 3 a larger degree of variance is observed. It is suggested that this is due to the higher proportion of microwave absorbent phases in these ores (Batchelor et al., 2017), which may be contained in as little as 30% ore the particles. (John et al., 2015). Due to the random distribution of the particles in the applicator, the distribution if heated phases is very different on each repeat measurement of the scatting parameters, because the ore is replaced with new material each time by jogging the apron feeder. This leads to dielectric spatial inhomogeneity of the load, which manifests itself as the increased standard distribution of the $S_{11}$ parameter derived from the experimental measurement for 2 and 3.



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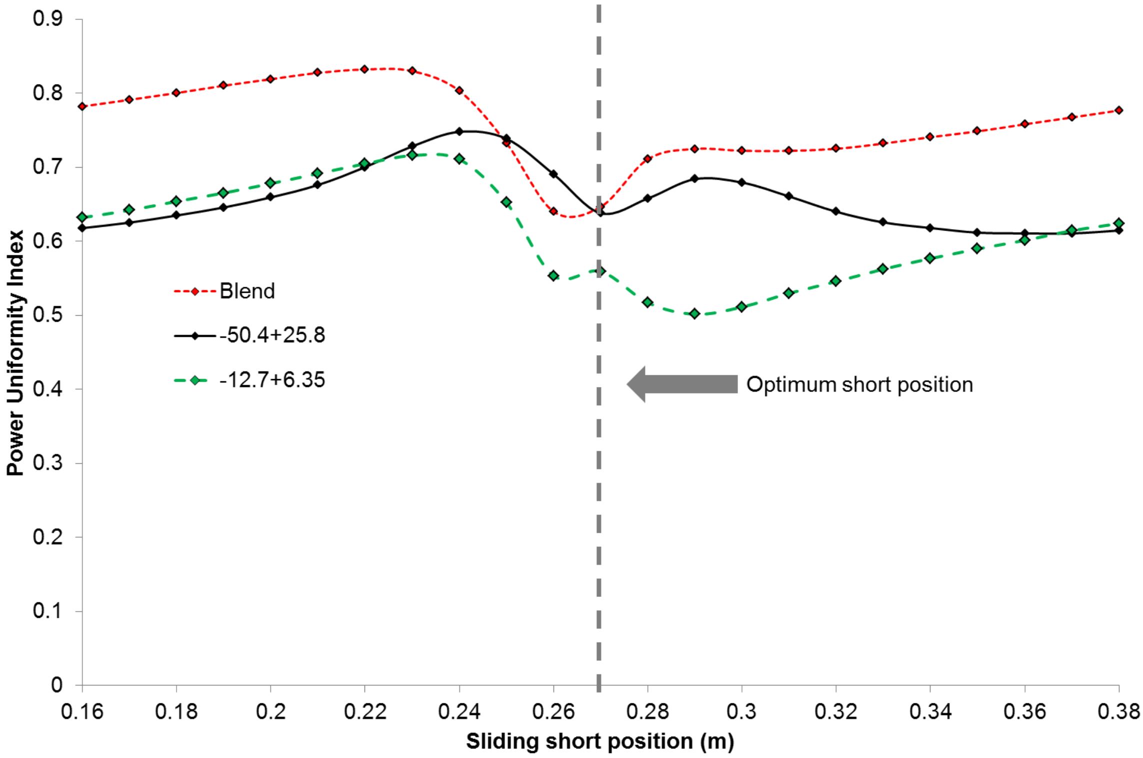


**Figure 7:** Example PUI analysis as a function of sliding short position for the Ore 1

**Table 3**

Experimental vs simulated S11 scattering parameters for the three ore blends

| Ore Type (Blended) | $S_{11}$ (dB) | |
|---|---|---|
| | Experimental Value | Simulation |
| 1 | -3.7 ± 0.40 | -3.25 |
| 2 | -11.3 ± 2.9 | -7.13 |
| 3 | -9.6 ± 2.0 | -6.83 |

## 5 Integration of Materials Handling with Electromagnetic Design

In microwave based systems one of the key challenges is the reliable delivery of power to the process material. This is dependent on the effective integration of the materials handling system with the applicator (Bradshaw et al., 2007; Buttress et al., 2016; Robinson et al., 2010b; Shang et al., 2006). The presentation of the process material in the applicator is critical to matching the impedance of the load to the transmission line so that power transfer can be optimised and the propensity for the system to generate process arcs in certain systems minimised. Arcing occurs when the electric field strength exceeds the breakdown voltage of air in the applicator itself and is particularly prevalent in ore systems where sharp edges on the rocks lead to severe electric field concentrations.

In the present system, based on a column of ore moving down through the applicator as a packed bed, the prevention of blockages was also a fundamental consideration in the design of the bulk solids handling systems used in the plant. Blockages in the lower area of the process tube could result in a stationary load in the applicator, which if occurring during processing, could result in thermal runaway as the heated phases of the ore become progressively more microwave absorbent as their temperature increases. An absence of material in the applicator occurring as a result of a blockage above it would result in high reflected powers and the possibility of damaging the generator magnetron.

To address these issues, bulk solids storage and handling theory first developed by Jenike and Johanson (Jenike, 1955; Jenike, 1961) was used in the design of the hopper and material interfaces between the applicator in- and out-feed sections. This was supported by multiple redundancies configured into the control system to action an immediate shutdown of the plant if such a situation occurred.



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The following sections describe the design of these materials handling components and their integration to provide effective material transport though the applicator.

### *5.1 Feed Hopper*

The applicator feed hopper was designed to achieve mass flow as it is discharged. That is, that all the material is in motion as it moves out of the hopper (Jenike, 1964). This behaviour eliminates the formation of stagnant regions in the hopper and affords a "first-in, first-out" flow sequence, which provides a constant solids stress at the outlet and a more uniform velocity profile during operation. This is critical because if the bulk material is a blend of particle size fractions and the hopper itself does not exhibit mass flow properties, then discharge of the material can exhibit a range of non-uniform flow phenomena. For example funnel flow, which is characterised by stationary material around the outer edges of the hopper and preferential discharge of material in the centre above the outlet. This can often lead to particle segregation on discharge and the formation of a stable rathole should the handled bulk solids be cohesive. Sifting may also occur whereby particles segregate by size. This leads to segregation though the material bed, with larger particles concentrated away from the fill point and smaller particles directly below the fill point (Johanson, 1978). Withdrawing particles by mass flow tends to remix the fines and coarse at the hopper outlet, whereas in funnel flow distinct pockets of fines and coarse flow from the hopper.

For many materials, flow problems can be eliminated by ensuring that a mass flow pattern exists in the hopper. The first step in achieving mass flow is to ensure that the converging walls are steep enough, and have friction low enough, to allow the bulk materials to slide along them. Flow properties tests were performed by the Jenike approach similar to that shown by Craig and Hossfeld (2002). Given the highly frictional nature of the ore, coupled with building layout restrictions, a hopper-in-hopper BINSERT® design (Johanson, 1982) was implemented (note that the BINSERT® is a registered trademark to Jenike & Johanson). This has the benefit of achieving mass flow while reducing the overall hopper height compared to a traditional simple cone.

Figure 8 shows the as designed mass flow hopper used to evaluate flow behaviour (left) and sited above the applicator in the pilot plan (right). Note the elevated feed conveyor feeding material into the top of the bin.

**Figure 8:** Applicator mass flow hopper simulated to evaluate flow behaviour (left) and in-situ above the applicator in the pilot plant (right)

The outlet of the hopper must also be large enough to prevent cohesive and mechanical interlocking arches from forming. Given the relatively large particle size and low moisture of the handled ore, cohesive arches were secondary in the pilot plant. Arching due to mechanical interlocking was far more important due to the requirement to handle large particles in a small hopper. The outlet geometry was modified from a simple cone to minimize the mechanical interlocking arching potential. The geometry also allowed a higher discharge rate compared to a simple cone.

The hopper was designed for handling ore having an average bulk density ~1300kgm$^{-3}$ and a nominal feed size -50.8+25.4mm. At a discharge rate of 100tph, average material residence time in the hopper is 36 seconds, with the hopper having a total working capacity of approximately 1 tonne.

### *5.2 Applicator Transition System and Apron/Belt Feeder*

In order to maintain mass flow through the applicator and prevent blockages caused by mechanical bridging of the particles at the in-feed (mass flow hopper outlet) and out-feed ends of the applicator (interface with downstream feeder), transition sections at these points were designed. The geometry of the mass flow hopper outlet was previously described in Section 5.



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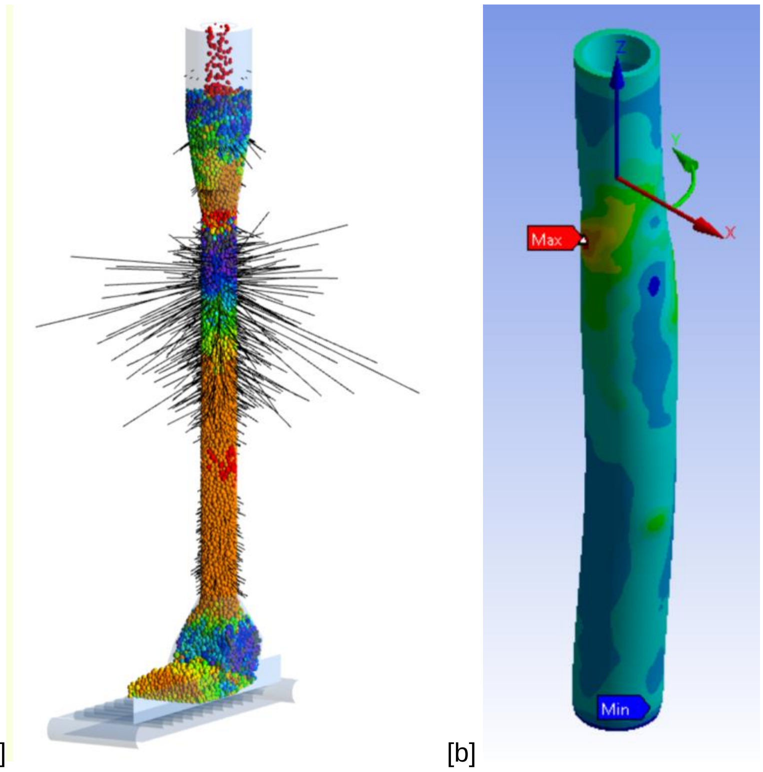
As is typical with bulk solids handling projects, the withdrawal of product from the bottom of the system controls the flow of solids above. This is no different to the pilot plant design. A belt feeder interface was used to control the discharge rate in the pilot plant. In addition to preventing blockages, the interface with the belt feeder that controls material flow through the system also prevents pulsatile flow as a result of the characteristic particle flow behaviour when the ore is transported as a packed bed.

As material flows through the vertical applicator tube a dilation wave propagates upward at a time period consistent with the system geometry, material properties and flow rate. This dilation wave results in transient loads applied to the applicator tube. An example is given in Figure 9. Discrete Element Method (DEM) analyses were conducted to calculate the pulsatile loads. The software is proprietary to Jenike & Johanson.

Minimizing the pulsatile loads, or dilation wave, minimized the loads applied to the applicator tube which ensured robust system operation. Failure of the treatment tube due to high stresses could result in damage to microwave system components. Finite element analyses were conducted to ensure the design minimized the tube stresses.




[a] [b]

**Figure 9:** [a] Pulsatile loads calculated on the applicator tube as a result of flowing solids and dilation wave; [b] stress calculation due to pulsatile loads

### *5.3 Control of Arcing*

Arcing is a common issue in microwave based processing systems. It is undesirable because it can damage the material being processed, materials of construction of the applicator and the magnetron housed in the generator itself. It may also reduce the efficiency of the system, as microwave power is transferred to the arc event rather than into heating the process material. In order to produce samples for subsequent metallurgical testing, it was necessary to use single size classes of the test ores, rather than use a typical Run of Mine (ROM) size distribution as this would then enable evaluation of the fracture process as a function of particle size. Commissioning tests showed that processing of these single size classes (-50.8+25.4mm) led to void spaces within the packed bed as it moved through the applicator. Further voiding was created due to pulsatile flow of the ore at throughputs greater than 70tph. As material is moved out from the lower transition onto the apron feeder, momentary interruption of the downward flow occurred. This was identified as material moving as packets onto the apron feeder caused by temporary mechanical interlocking of the material in the lower transition section. This then transiently held the ore in place in the applicator. When this is removed by the apron feeder, the ore in the applicator drops down to fill the void, resulting in increase in transient voiding and the observed 'pulsing' of material flow.

The voiding created as a result of running a single size class is shown in Figure 10 (left). Here the microwave infeed section of waveguide has been removed after interlocking the system so that the distribution of material in the applicator can be observed. The consequence of these transient voids is sporadic arcing as shown in Figure 10



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(right). This image was captured from a digital video camera held in a port of the in-feed waveguide facing the quartz tube.

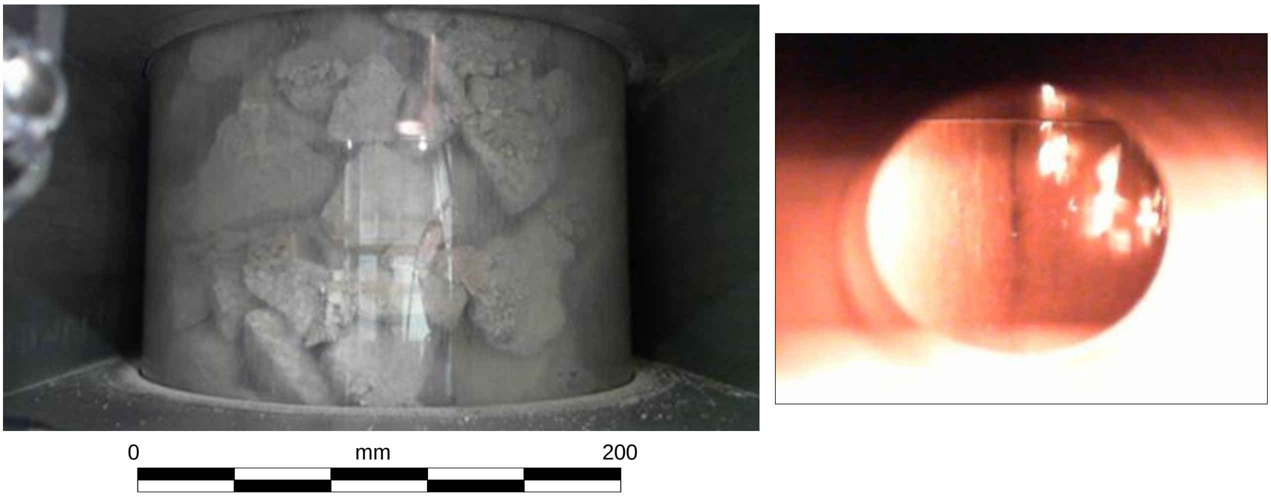


**Figure 10:** -50.8+25.4 mm single size class ore feed stationary in the quartz liner of the applicator. Note the void distribution between the particles (left). Process arcs of the same ore during operation, taken from a camera sighted in the waveguide looking at the quartz tube (right).

It quickly became apparent during commissioning of the system that in order to reliably deliver power to the single size classes needed for the Phase I sighter testing, the use of a filler material to close out the voids and improve material flow at high throughput was required. This necessitated the blending of size classes together for each of the test ores. Of course in a real process the feed would be present as a distribution, rather than as single size classes so this aspect of the work was particular to the pilot scale operation. It is included here to give guidance to the reader as to the importance of bulk density of the feed column of ore to both the maximisation system throughput but also the reliable delivery of power to it.

### *5.4 Modification of Mass Flow Hopper to Control of Blend Segregation*

Flow testing of a 50:50 mix of -50.8+25.4mm and -12.7+6.35mm Ore 3 through the applicator revealed propensity to segregate the material on transport through the applicator Figure 11 (left). This again was found to induce transient voids and associated process instability through arcing. It was found that on filling of the mass flow hopper, the in-feed discharge conveyor was non-uniformly distributing the material. Preferential loading of the far side of the hopper (Figure 11, right) then lead to segregation by size class as the material was fed into the applicator. This was primarily a consequence of the building height restriction that resulted in the conveyor and mass flow hopper positioning.

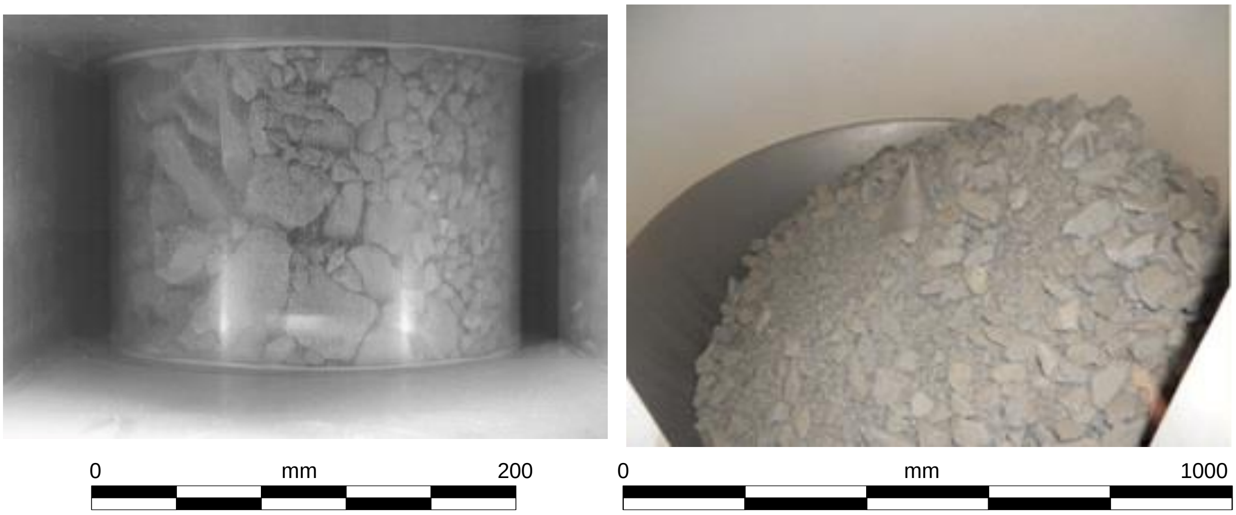


**Figure 11:** Blend segregation in applicator (left) due to off centre loading in mass flow hopper (right)

The results of subsequent discreet element (DEM) modelling of the particle flow reflected that observed during sighter tests. To address the problem, a distributor system was developed to ensure that blended material transferred into the hopper was evenly loaded. This comprised of a hood positioned in the path of the inflowing ore and a distributor cone directly below it. The original design and the subsequent modification is shown in Figure 12.



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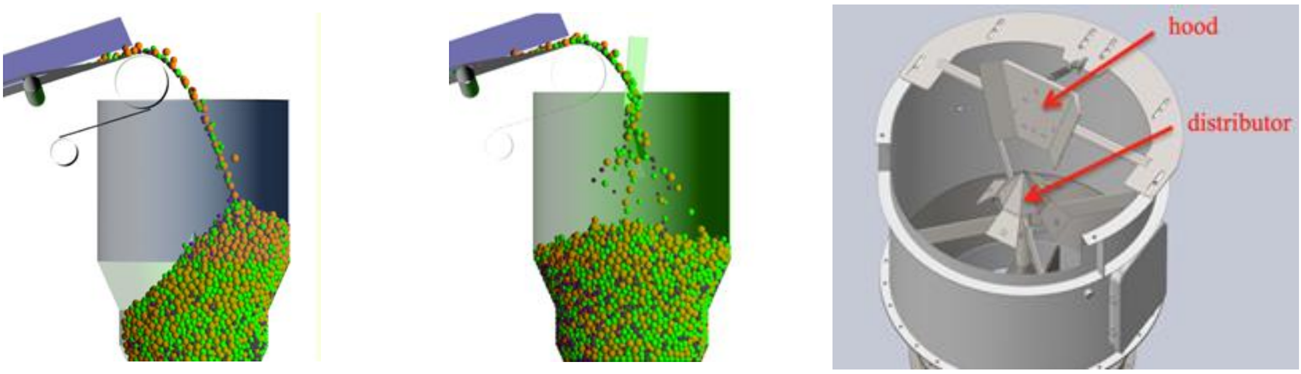


**Figure 12:** Discrete element modelling of particle flow in mass flow hopper showing preferential loading of blended ore (left); loading on addition of hood and distributor (centre); design of hood and distributor (right)

Segregation was also found to occur due to side-to-side segregation of product on the conveyor filling the mass flow hopper. Modifications to uniformly load the conveyor solved the side-to-side conveyor loading issue.

The results of the hopper and conveyor modifications can be seen in Figure 13. In the blended material no segregation by size class during transport through the applicator was observed. In addition, a significant reduction in the void distribution was achieved. This then led to a significant increase in process stability, with a correspondingly marked reduction in arc frequency during the production of test samples.

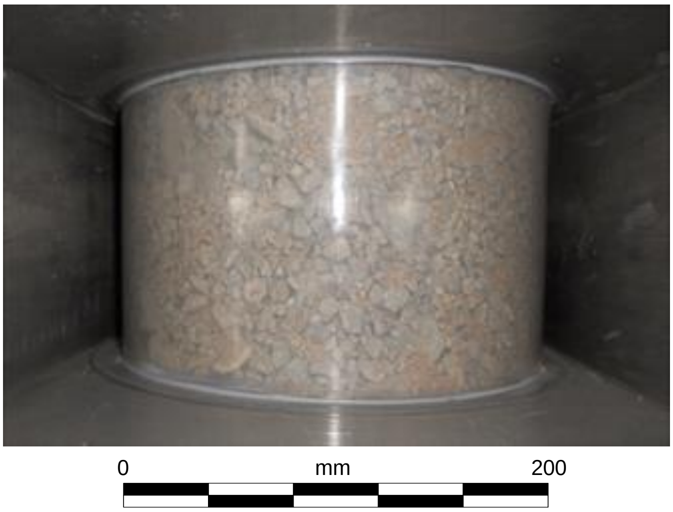


**Figure 13:** Applicator evenly filled with blended 50:50 -50.8+25.4 and -12.7+6.35mm monzonite ore after hopper modifications

## 6 Phase II – Dual Applicator Configuration and Throughput Scaling to 150tph

Following evaluation of the sighter test results (Batchelor et al., 2017) the potential for improving the system performance was investigated by increasing the homogeneity of treatment in the applicator and by increasing the throughput.

Section 4.3 presented the distribution of power density within the applicator and optimum position of the 'hot spot' as a function of sliding short position. Due to the presence of this hot spot, ore particles were inevitably not treated at the same level of intensity, resulting from the non-uniform distribution of electric field intensity within the treatment zone as ore particles flow through the applicator. The power density then created in each phase of the particle is then also variable. Previous work has shown that micro-fracture around grain margins and resulting macro-fracture though the matrix is dependent on the evolved power density in the heated phases of each specific particle (Jones et al., 2005). For a particular ore fragment, beneficial effect is then dependant on which position in the applicator it moves through and its specific mineralogy. Given that only a quarter of the applicator cross-sectional area supports the highest power density, the probability of a susceptible ore fragment passing through the hot spot is much reduced. To this end, a second applicator was installed in series with the first. By off-setting the 'hot spots' of the two applicators, a greater volume of the process ore passes through an area of high electric field intensity, so resulting in a much greater proportion of the ore being exposed to the highest powers, thereby increasing the performance of the system. The addition of a second applicator in series with the first necessitated an increase in system throughput to maintain equivalent energy doses across the Phase I and Phase II testing programmes. Particularly those tests conducted at relatively low energy doses. By increasing the throughput of the system from



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100tph to 150tph, achieved by increasing the speed of the apron feeder, the material residence time on the applicator is decreased from 0.58 to 0.38 seconds.

In order to effectively move ore through the applicator at this increased throughput, it was necessary to 'fluidise' the particles in fine material. This took the form of a mixture of Ore 1 and 2 in the size class -6.35+00mm. The bulk ore was run as a lean phase having composition 40% ore, 60% ore fines.

### *6.1 Dual Applicator Configuration*

The central portion of the applicator comprises the single mode cavity and four reactive choking structures above and below it. To create the dual applicator system, a second applicator (built to the same specifications) was added in series with the original. Given a fixed height between the hopper and apron feeder, the outer reactive chokes were removed, and the length of the resistive choking structures increased to maintain the total 4m length of the applicator. The as installed dual applicator is shown in Figure 14. Again a quartz liner was used in the central portion of the applicator. To maintain the integrity of the quartz liners given they are sited in series, a UHMW-PE ring situated in the centre of the middle choke corrugation was used as a spacer.

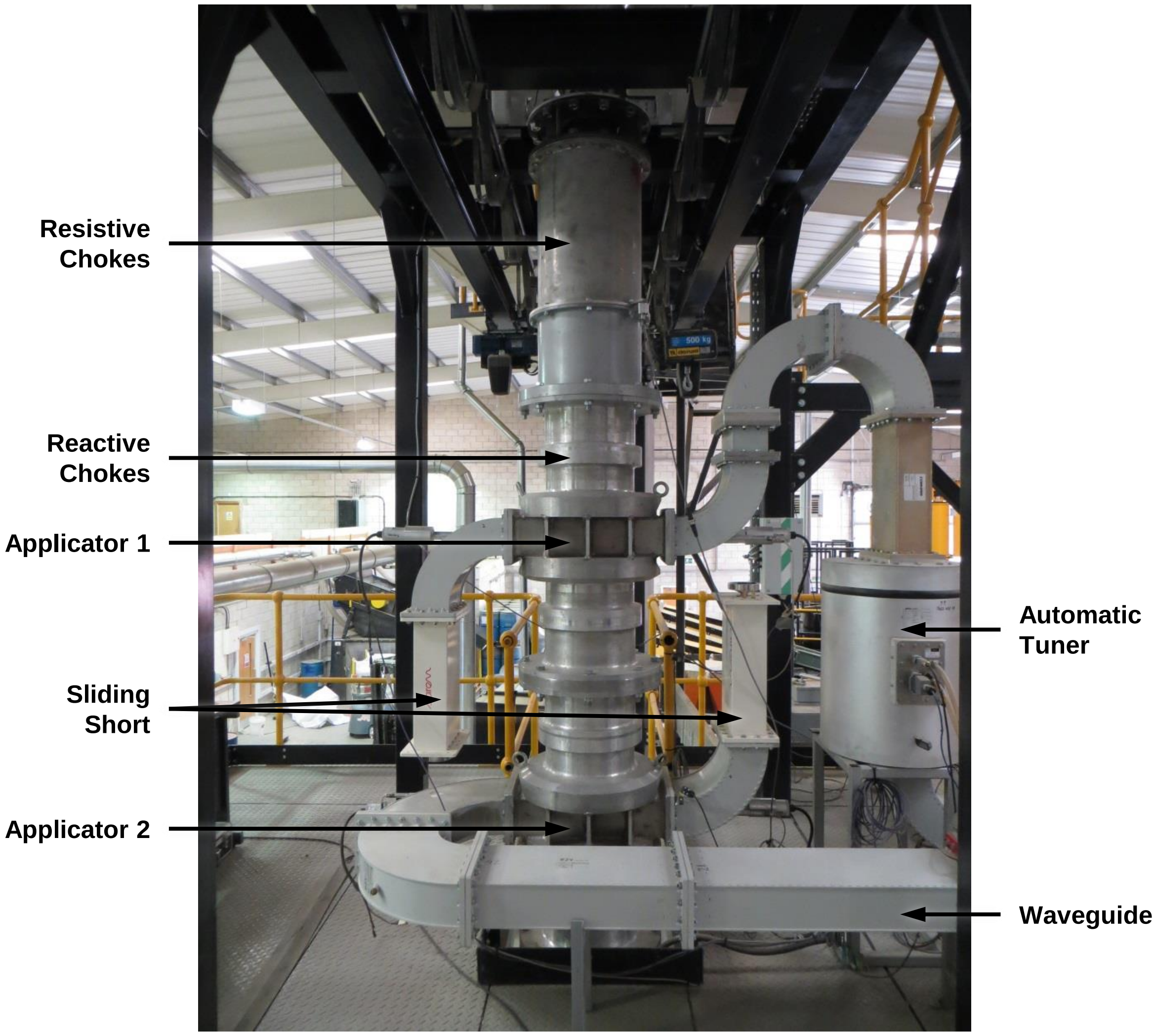


**Figure 14:** As installed dual applicator configuration

Again as described in Section 4.1, the scattering parameters of the dual applicator configuration were measured for the Ore 1 and 2 and compared to those derived from FDTD based simulation in CONERTO®. The positions of the two 'hot spots' in the dual applicator configuration are shown in Figure 15 at the optimum short positions of 270mm.



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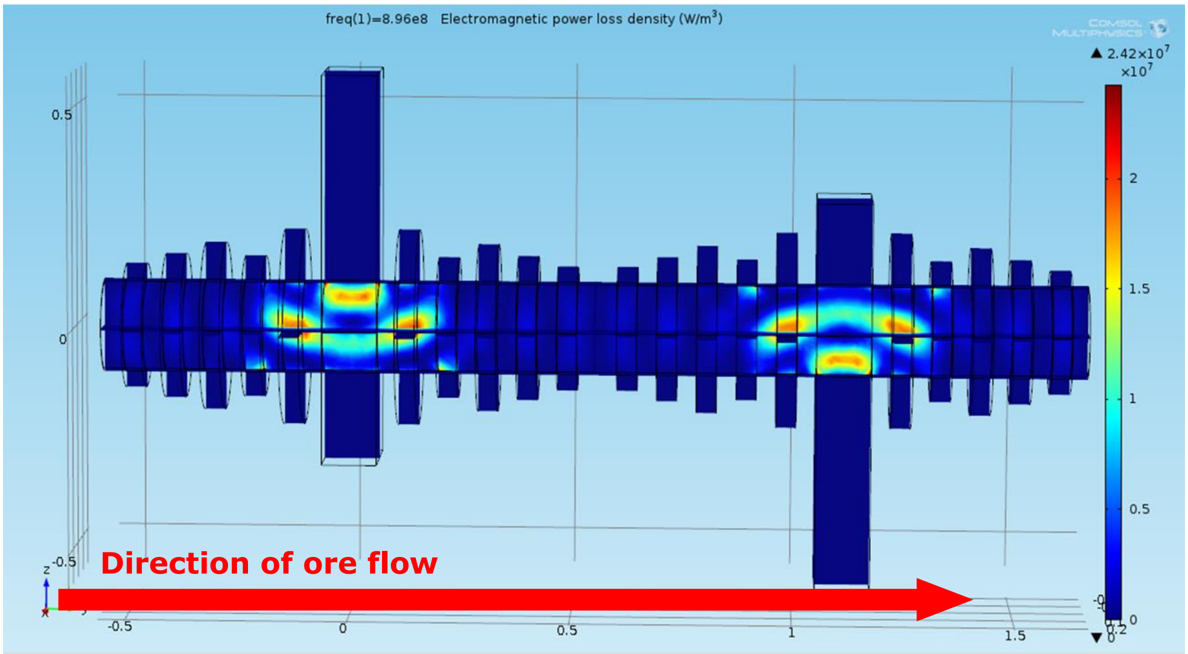


**Figure 15:** Simulation of the positioning of the two 'Hot Spots' in the Dual Applicator Configuration for Ore 1

A comparison of the distribution of electric field intensity at the optimum short position for the single and dual applicator configurations is shown in Figure 16. It can be seen that when two applicators are used in series, the cross sectional area of the process tube which supports the highest electric field intensity is much larger.

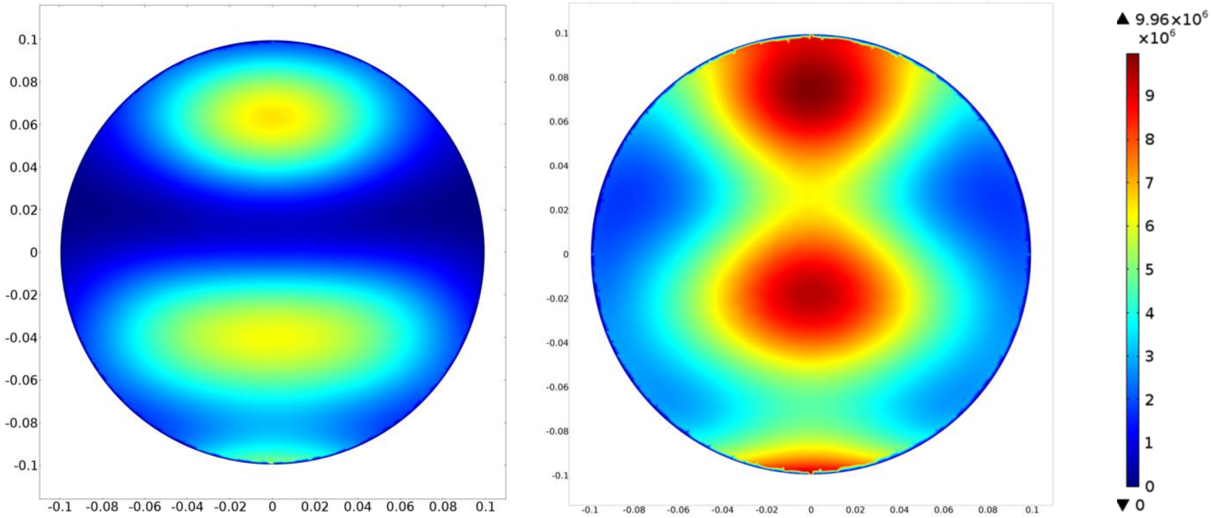


**Figure 16:** the distribution of the electric field intensity inside the quartz liner, shown in cross section, sighting down the applicator from above for single (left) and dual applicators (right) at the optimum short position

Using Eq. 1 and Eq. 2, the PUI could then be calculated for two applicators in series. This is shown in Figure 17. It can be seen from Figure 17 that the PUI (0.27) is reduced by half when two equivalent applicators are used in series compared to the single applicator (PUI 0.64). This corresponds to an approximate doubling of the cross-sectional area of the process tube which supports the highest electric field intensity. It then follows that twice the volume of ore is exposed to this electric field intensity in the modified system. As such, the treatment efficiency is greatly increased when two applicators are used in series in the pilot scale system.



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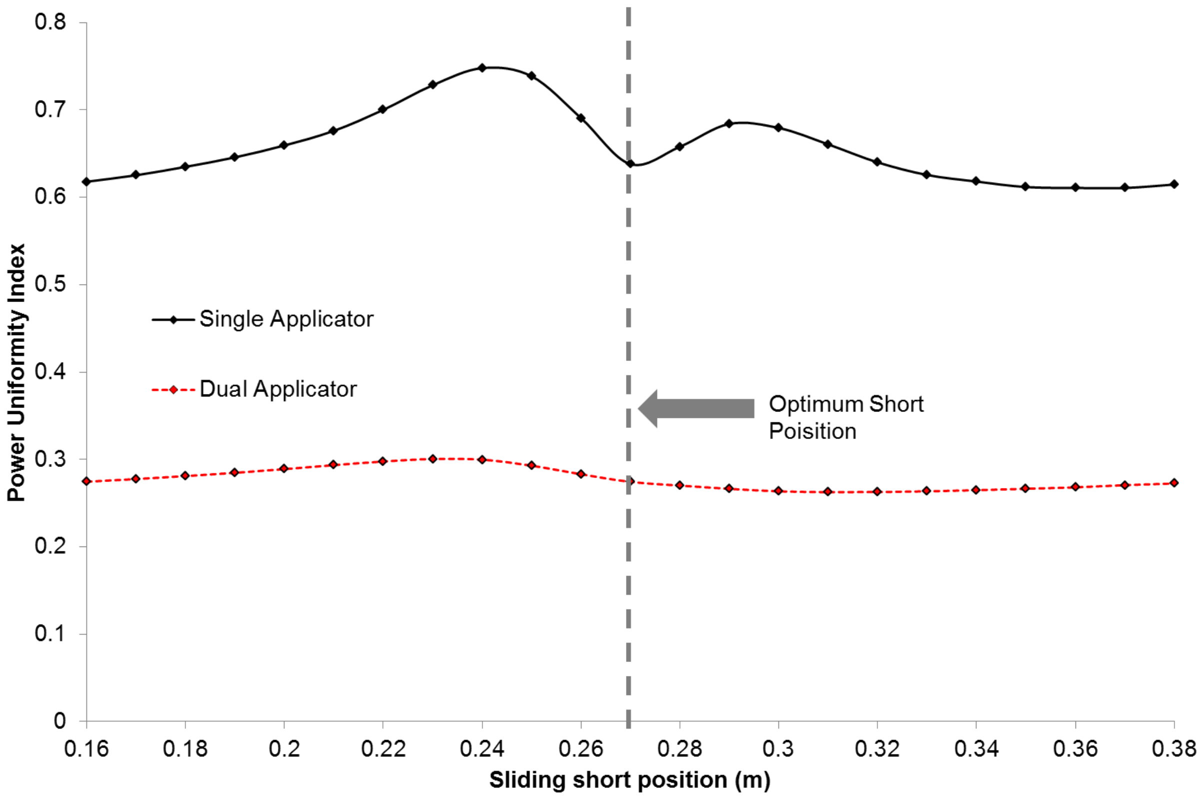


**Figure 17:** PUI as a function of sliding short position in the dual applicator configuration for the quartzite Ore 1 -50.8+25.4mm. PUI for single applicator shown for comparison

## 7 Operational Stability

During the commissioning process and sample production under the Phase I (single applicator) and Phase II (dual applicator) test programmes, the pilot scale plant has processed around 900 tonnes of ore, of which approximately 300 tonnes was under microwave power. A typical run is shown in Figure 18 which is derived from the data acquisition system. It shows the mass of material flowing through the applicator and the forward and reflected power during the run, as measured by each of the in-line 3-stub tuning units.

The material processed in the run is flowing at a throughput of 150tph and the microwave power from both generators set at 100kW each. It can be seen that the microwave power is applied almost instantaneously. The power does take a number of seconds to stabilise and is an artefact of the so called ‘fast start’ process inherent to the microwave generators. Once the generators have stabilised, the reflected power is typically below 2 - 3 kW for the duration of the run, thereby ensuring that the power is efficiently and stability transferred to the ore during processing.



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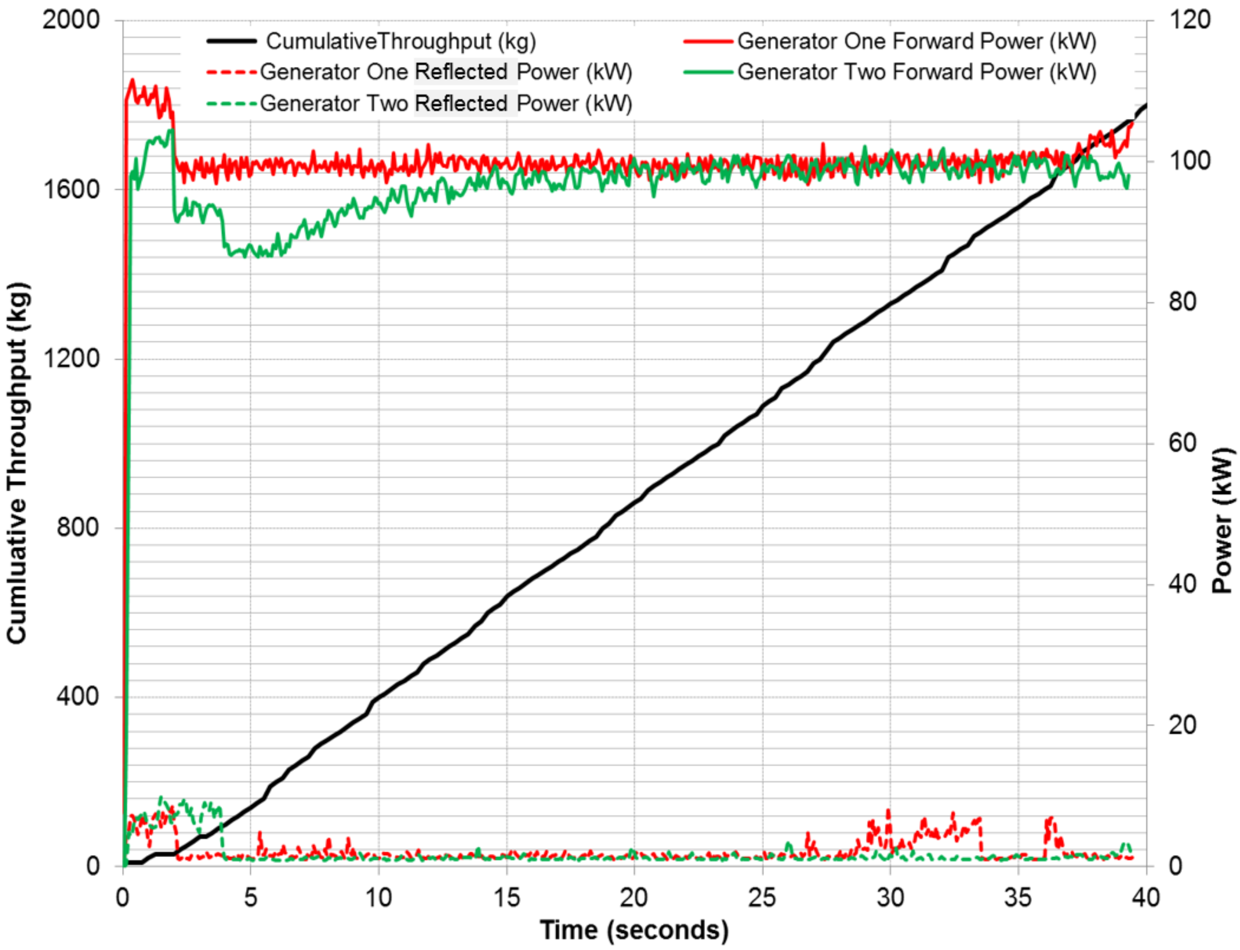


**Figure 18:** Exemplar process log for Ore 1 treated at 2 ×100kW and 150tph

## 8 Conclusions

By integrating electromagnetic design with a materials handling system, we were able to yield a pilot-scale microwave system capable of stably treating porphyry copper ores at throughputs of up to 150tph. The system is based on controllably flowing a blend of ore fragment sizes down though a vertically aligned tube as a packed bed. The mass flow hopper and applicator interfaces ensure the material is transferred through the $TE_{10n}$ single mode applicator, such that power from two 100kW generators operating at 896MHz can be delivered reliably without arcing.

The performance of the applicator was validated by evaluating scattering parameters measured experimentally of the as built system to FDTD simulations. Good correlation between the two was observed, particularly for Ore 1 ($S_{11}$ experiment -3.69 ±0.25, simulation -3.4). The use of a series of corrugated chokes around the applicator tube allowed the applied microwave field to be confined, such that the average power densities in the bulk ores are of the order 6.6× $10^6$W/m$^3$.

By adding a second applicator in series with the first, an increase in the cross-sectional area covered by the size of the areas of highest power density is significantly increased. This results in a decrease in PUI from 0.64 to 0.27. Combining this with an increase in throughput capacity from 100tph to 150tph by fluidising the ore in fine material resulted in a significant increase in system performance.


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