'Clean technology for a thriving planet'

Tetronics International

The Destruction of CW Agents and their Precursors Using Plasma Arc Technology

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Presentation Content

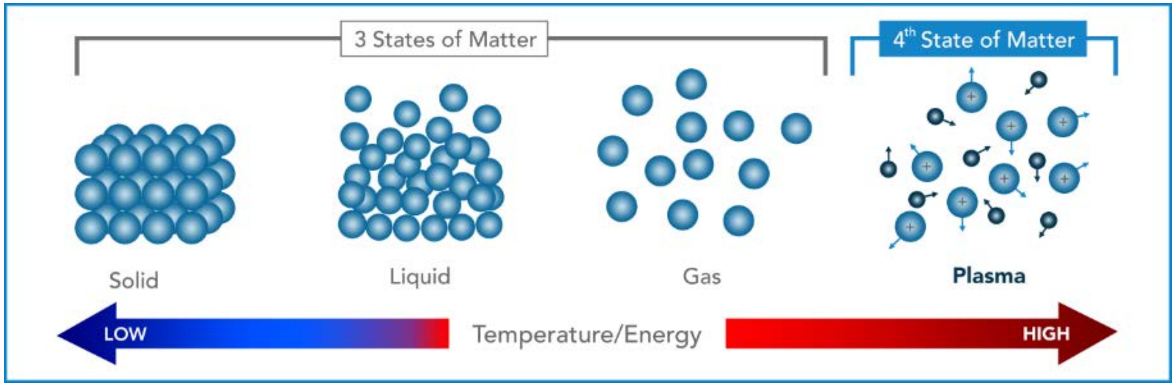
- Tetronics – History, Current Profile and Example Reference
- Introduction to Plasma
- Project Requirements – Phases 1 and 2
- Phase 1 CW Agent Summary
- Phase 1 – Summary and Conclusions
- Phase 2 – Summary Scope and Equipment Layout
- Q and A.

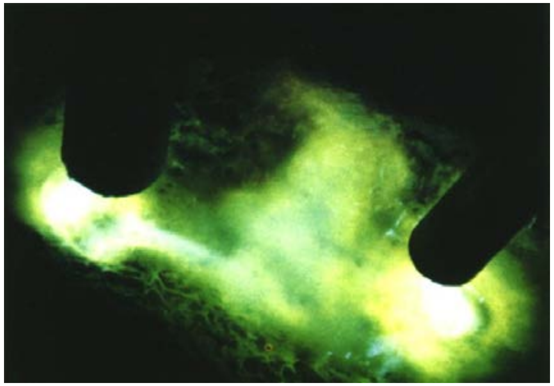
Tetronics Background

- Market leader in the application of DC Plasma Arc technology on a global basis
- Established 1964 in Oxfordshire, UK with a R&D focus
- Acquisition by InvestSelect in 2004 triggered significant investment, move to new bespoke facilities at Marston Gate and strategic repositioning of the company into new areas of application
- Comprehensive and sophisticated R&D trial facilities – Technology qualification and reduced barrier to entry
- Mature technology platform with a securely protected IP that continues to be developed
- 109 patents granted or pending across 12 families
- Experienced process design, engineering and manufacturing staff complemented by project management, commercial and environmental regulatory expertise
- 80+ installations globally

Plasma – Basic Theory

- Plasma: an ionised gas often referred to as the 4th state of matter

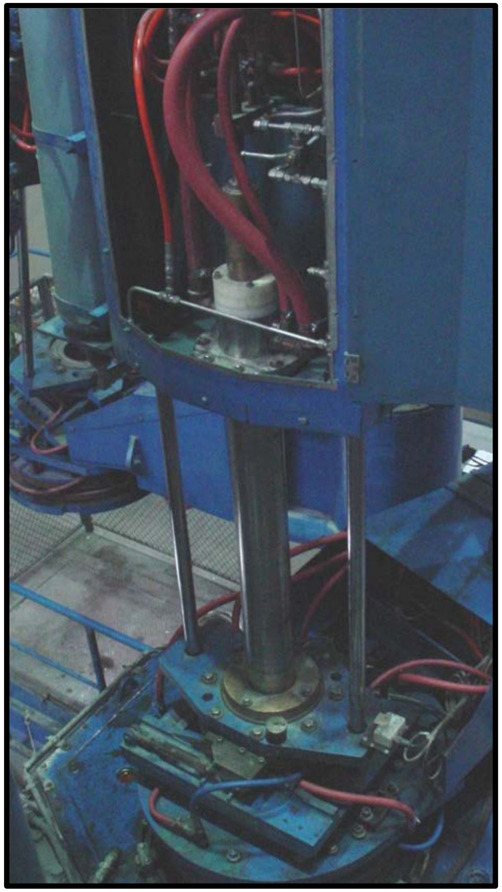


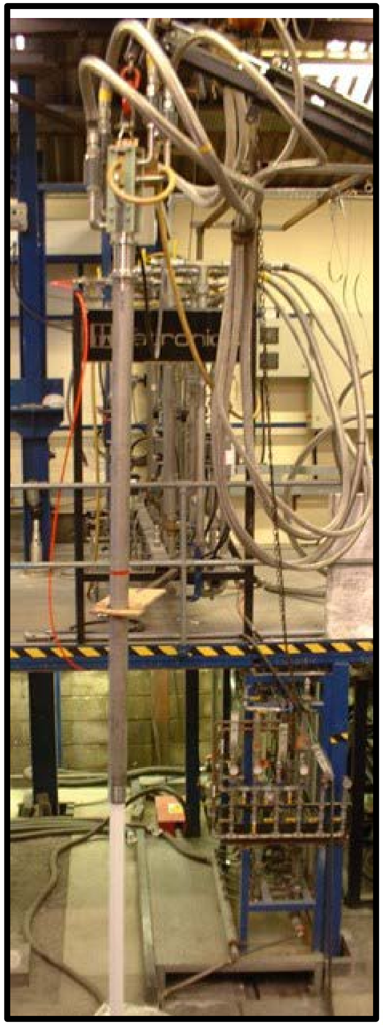


- Examples of plasma: lightening, auroras, stars & sun - plasmas constitute more than 99% of the universe
- Thermal plasma emits intense heat and Ultra Violet light
- Formed when a gas (e.g. nitrogen) is heated to >5,000K by an electric current
- Plasma cracks/reforms all organic matter and melts or vitrifies inorganic matter into an inert rock (Plasmarok®) with properties superior to granite

Tetronics' Plasma Technology Reference GEKA-Munster (Germany)

- In 2002 GEKA's plasma facility obtained full operational authorisation
- Tetronics plasma systems were retrofitted to improve reliability and process energy efficiency
- Application is mainly to do with land remediation and the destruction of Arsenic based contamination
- Tetronics installed customised 70 mm OD extended 4m multimodel plasma torches with interfacing seals.
- http://www.geka-munster.de





Benefits of Plasma

- Proximal solution-offering quicker establishment and treatment
- Flexible operational profile, good turndowns and agent tolerance
- Robust, reliable and easy to maintain technology, i.e. minimal resourcing
- Small physical foot-print and no unusual site requirements
- Low environment impacts – the hazards are eliminated and not just packaged
- Lowest capital and operation cost at 'small' operational scales
- Tolerance of feed compositional variations
- Proven patented technology

Project Requirements – Phase 1

- Phase 1. Concept Study - Objective was to theoretically validate the use of a transportable variant of Tetronics' DC Arc plasma technology to effectively destroy a given list of CW agents and precursors
- Project Steps:
  - Thermodynamic modelling of agents - Thermodynamic equilibrium model and heat/mass balance (Outotec HSC 7.11 = Gibbs free energy minimisation)
  - Operational modelling leading to the produce Furnace Operating Plans (FOP) for each agent at 50, 150 and 500 kg/hr
  - Sensitivity analysis (structured quantitative decision making process) - Determines how the system's transportability requirements impacts design philosophy whilst ensuring safe destruction of the agent compounds
  - Equipment options, trade space assessment
  - HAZOPS and ARM
  - Equipment specification, CAPEX and OPEX

Phase 1 – Thermodynamic Modelling Steps

- Thermodynamic modelling of all agents required – Thermodynamic equilibrium models and heat/mass balances developed for all compounds using the proprietary code of Outotec HSC 7.11 = Gibbs free energy minimisation methodology.
- Check HSC database for the chemical compound, if a listing was not present then a database record was created using "sister" compound, "child" compounds and data present in the scientific literature. Specific attention was paid to element balance and the molecular architecture of the substitute
- Due to the high specific process energy input to the plasma chamber compared to the theoretical amount needed to break the chemical bonds of the agent compounds, the approach is considered conservative
- Materials/agent specifications, and the equilibrium code outputs, were used as the basis of constructing normalised heat and mass balances.
- All materials were operationally modelled at 50, 150 and 500 kg/hr. This gave rise to process flow diagrams (steady state snap-shot) and furnace operating plans (working methodology and productivity)

Phase 1 - List of CW Agents Considered

Name	Pseudonym	Chemical formula	CAS	Category
Bis (2-chloroethyl) sulphide	HD/ sulfur mustard	$C_4H_8Cl_2S$	505-60-2	Agent
O-Isopropyl methylphosphonofluoridate	GB/ Sarin	$C_4H_{10}FO_2P$	107-44-8	
O-Ethyl S-(2-diisopropylaminoethyl) methylphosphonothioate	VX	$C_{11}H_{26}NO_2PS$	50782-69-9	
Methylphosphonyl difluoride	DF	CH_3POF_2	676-99-3	Precursor
Sodium-O-Ethyl methyl phosphonothiolate	EMPTA	$C_3H_8O_2PS$*Na	22307-81-9	
Phosphorus pentasulfide		P_2S_5	1314-80-3	
Phosphorus trichloride		PCl_3	7719-12-2	
Dimethyl phosphite	DMP	$C_2H_7O_3P$	868-85-9	
2-(Diisopropylamino)ethyl Chloride Hydrochloride	DIPAEC.HCl	$C_8H_{18}ClN \cdot HCl$	4261-68-1	
Monoisopropylamine	2-Propanamine	C_3H_9N	75-31-0	
2-Chlorethanol		C_2H_5ClO	107-07-3	
Dimethyl methylphosphonate	DMMP	$C_3H_9O_3P$	756-79-6	Surrogate
Thiodiglycol	TDG	$C_4H_{10}O_2S$	111-48-8	
Pesticide		tbc		
Dimethyl phosphite	DMP	$C_2H_7O_3P$	868-85-9	
Trimethyl phosphite	TMP	$C_3H_9O_3P$	121-45-9	
Triethylamine		$C_6H_{15}N$	121-44-8	

Phase 1 - Sensitivity Analysis

- Sensitivity analysis - Determined how the system's transportability requirements impacted on, and defined, the design
- Example of key DSTL defined constraints were as follows:
  - Regulatory compliance (IED* and best effort extremes)
  - Technical compliance
  - Plant transportability based on 20 ft ISO containers and associated footprints
  - Transfer Parameters (In/Out) of the known agents
  - High global (non-agent specific) DRE requirements
- The work resulted in a defined conceptual technical solution and understanding of the decision process (narratives). Results presented as a matrix inclusive of 'traffic light' based ranking

*Directive 2010/ 75/ EU on Industrial Emissions (sometimes referred to as the IED)

Phase 1 – Results of Key Sensitivity Analysis

- It was concluded that a plasma based inflight processing chamber, refractory lined with low thermal mass, with no slag retention scored highest against the criteria. This would be heated by DC electrode systems with favoured ARM credentials and chemical compatibility
- The plasma chamber would operate below atmospheric pressure by ≤1000 Pa (no egress).
- Favoured oxidant is oxygen enriched air to reactivity and working volume reduction
- Single facility line favoured and rated predominantly for the 150 kg/h agent throughput case, but with good turndown. Overall, a single facility has less component parts and is more space and energy efficient
- Input power, and therefore throughput of agent, limited for the scale of a 20ft. ISO container, i.e. ≤1 MWe allowing for environmental factors; e.g. anticipated climatic profiles
- These generators would supply insulated-gate bipolar transistor (IGBT) control based AC/DC convertors with good efficiency and multiple outputs for a given input
- Design for whole life operation
- Single fuel favoured with a high volume based energy density and favoured engineering support and safety credentials, i.e. diesel
- Feed identification and feed rate control required
- Sealed thermal heat sink and off-gas system required

Phase 1 – Equipment Options

- This assessment was undertaken on a similar basis to the sensitivity analysis, however in this case specific technological or equipment options were considered
- The purpose of this assessment was to identify the equipment, or configuration, options for the key plant systems, and evaluate them against the appropriate PVDs
- The assessment allow Tetronics to specify, scale and value the required equipment, which feed into subsequent work
- Results presented with comparative scores and decision process narrative

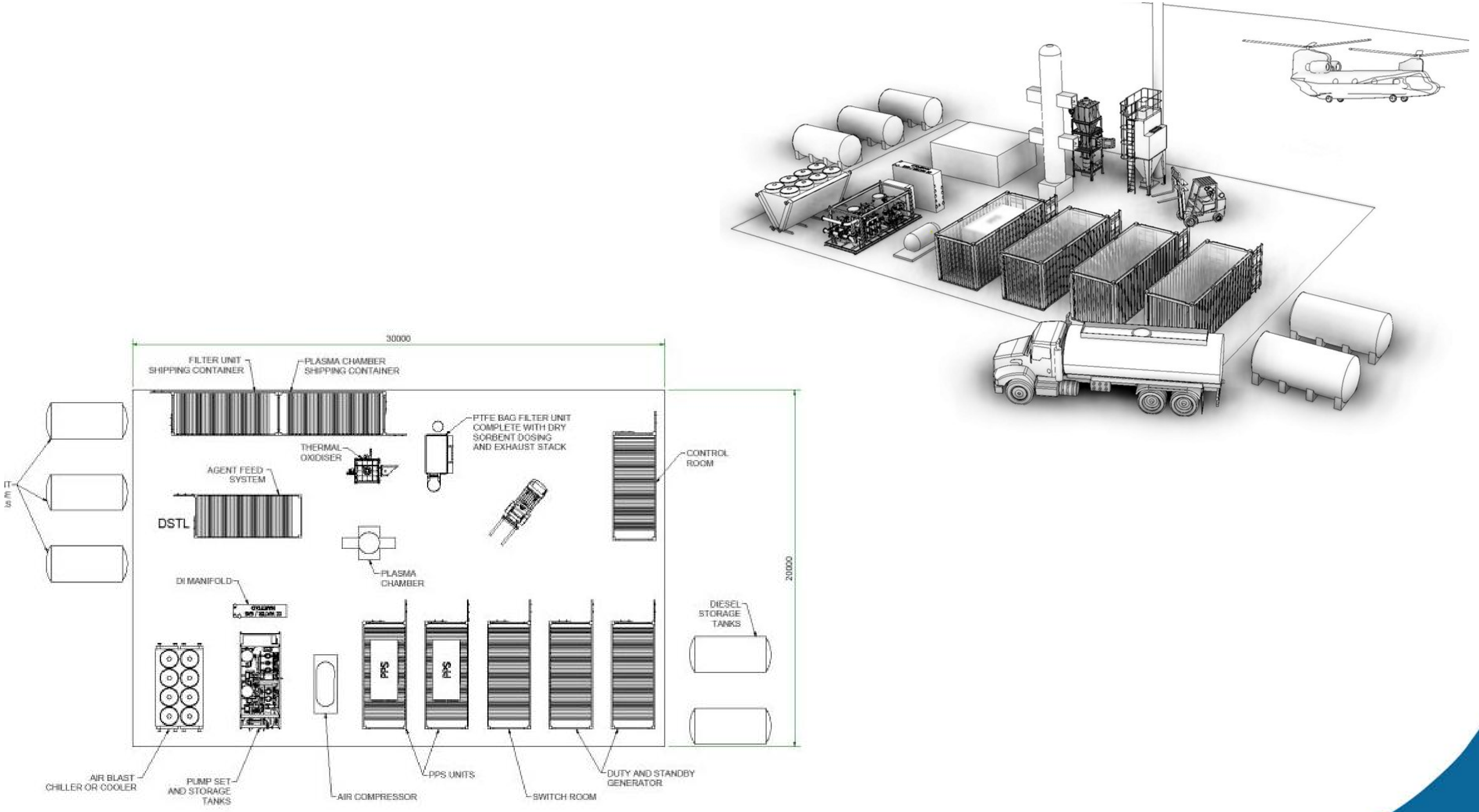
Phase 1 – Trade-Off Assessment

- Examined the impact of equipment options or configurations on plant transportability, and then "trade-offs" available between maximum transportability options
- In this context plant transportability is considered to be a measure of how quickly the plant can fulfil the following operating life stages:
  - Transport to site
  - Complete Set up
  - Complete Commissioning
  - Achieve design throughput
  - Complete Processing
  - Complete Decommissioning
  - Complete Disassembly
  - Removal from site
  - Disposal of by-products

Phase 1 - Layout

- Two extremes were considered at a plant engineering level; Industrial Emissions Directive (IED) compliance and a 'Best effort'. The latter case reflect the clear benefits of eliminating the primary hazards in an efficient way at the expense of the modest environmental impacts
- Plant footprint reduced from 30mx20m for the IED case with 11x 20 ft ISO containers to 20mx18m for the 'Best effort' case with 8x 20 ft ISO containers
- With regards to underlying site requirements there needs to be sufficient space for the facility, the ground conditions should be stable and offer the required level of structural support
- There is no specific requirement for a hard-standing, but the containers should sit level
- The equipment should be spaced to allow for normal operation activities
- Anchoring of the main process vessels is envisaged to be undertaken through the means of interconnection, however it will also be possible to tie these structural components into their transportation ISO containers; a concept to be further investigated and the FEED stage of project development

Phase 1 – Layout Drawing (dimensioned and annotated)

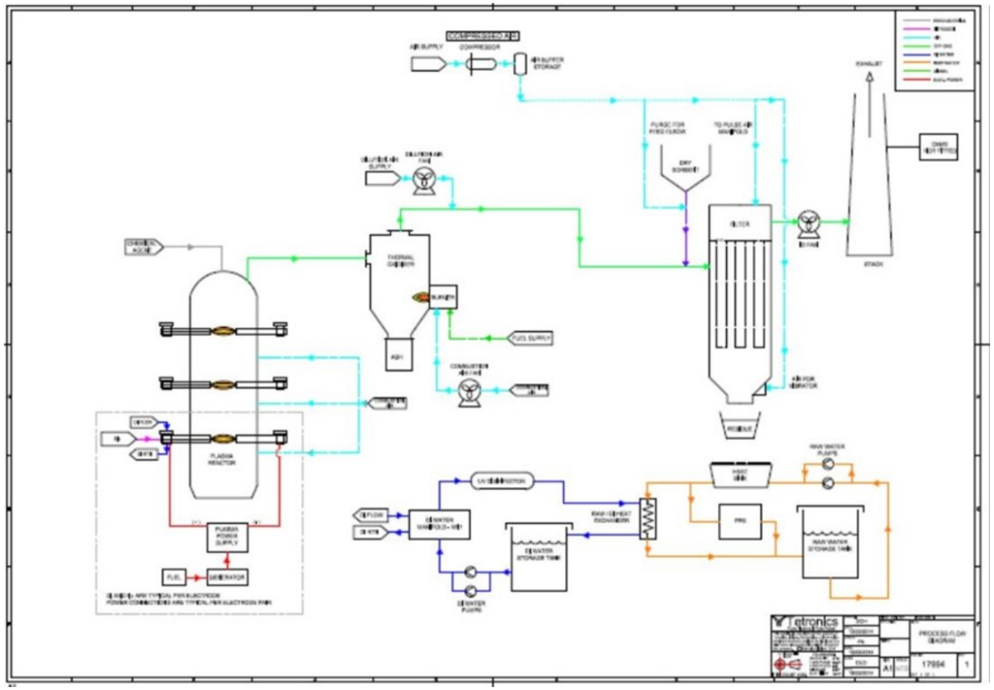


Phase 1 – Plant Specification, Capital and Operational Costings

- This section of Phase 1 was based on the fully IED compliant option for the plant so it can be taken as a "worst case" scenario
- It should be noted however that the equipment listed is to commercial and not military (or MILSPEC) standards
- Outline specification provided with tabulated responsibilities matrix.
- The indicative capital costs of the integrated system determined, inclusive of FEED work.
- A fully itemised operational cost schedule per kg CW agent was prepared for two model cases
- Front End Engineering Design (FEED) study recommended to improve commercial confidence / TRL levels

Phase 1 – HAZOPS

- The generic process design was the subject of an inter-departmental study into initial hazards and operability – HAZOPS
- This study was done after the equipment options had been assessed and layout discussed, but is deemed to be at level 0 in terms of detail
- The study took the form of dividing the conceptual design into nodes (P&ID defined) and then having a structured discussion around keywords and risk matrices.
- Each hazard or operability issue was scored according to expected frequency and severity of outcome; with score based action trigger levels
- The study was software driven by, HAZOP Manger 6.0 by Lihou Technical and Software Services



Phase 1 – ARM Assessment

- Availability, Reliability and Maintainability (ARM) is a methodology used to predict asset performance for a given configuration in terms of reliability, maintainability and availability
- This ARM analysis report was presented as tabulated information detailing:
    - Main plant items to be assessed
    - A statement of qualitative reliability, e.g. high (acceptable based on the application and continuous mode of operation for plasma) medium (acceptable but improvements are anticipated possible) or low (Not acceptable performance)
    - Explanation of how the qualitative reliability has been achieved e.g. operational experience of similar equipment in a similar environment
    - Generic failure modes of equipment
    - Engineering design principles which may be considered to eliminate/minimise generic equipment failures

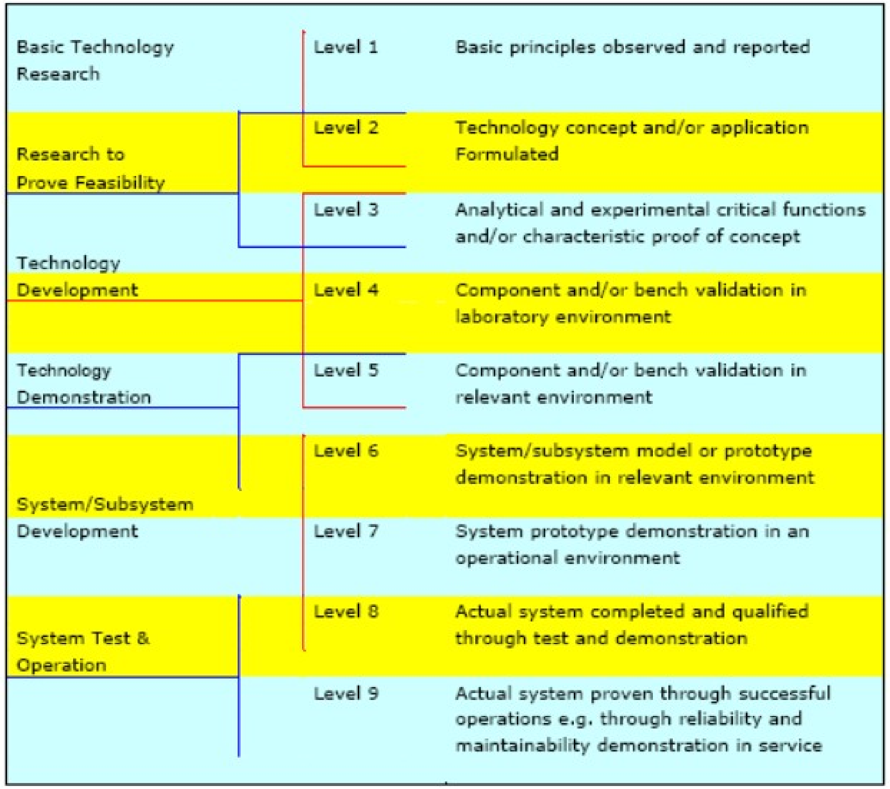
Phase 1 - Conclusions

- An operable transportable CW agent destruction system based on Tetronics' plasma technology is conceptually and scientifically feasible
- The 500 kg/hr agent option has been discounted due to the limited practical likelihood of the requirement being realised and the disproportionate impact on the design requirement
- The thermodynamic models show total compound destruction, the secondary chamber and acid gas off-gas system are capable of coping and the overall power generation requirement is possible using readily available equipment
- Tetronics believes that the work done so far has increased the TRL from the original level 1 to 3 (*Analytical and experimental critical functions and/or characteristic proof of concept*) where it is ready to progress to level 4 (*Component and/or bench validation in laboratory environment*)
- It is recommended that Phase 2 of the project be carried out at Tetronics' test facility in Swindon using suitable simulant materials to move the design of the Plasma destruction system beyond proof of concept and thus increase the Technology Reediness Level (TRL) of the envisage facility and also to empirically confirm the requirement for a Thermal Oxidiser
- It is estimated that up to 9 containers will be required, exclusive of diesel and agent storage ISO containers, for the facility
- The mode of operation proposed for this application is atypical for Tetronics and this illustrates how Tetronics has been guided by the scientific and engineering facts as opposed to having a pre-determined concept for the process
- Phase 1 has provided technical, commercial and engineering definition of the proposed process

Technology Readiness Level

- Technology Readiness Level (TRL) scale was pioneered by NASA in the 1980s.
- The TRL scale ranges from 1 (basic principles observed) through 9 (total system used successfully in project operations).
- At the end of Phase 1 Tetronics determined the TRL for the technology to be 3
- Phase 2 is anticipated to take the TRL level to ≥ 4.

Technology Readiness Levels Table (TRL)



Basic Technology Research	Level 1	Basic principles observed and reported
Research to Prove Feasibility	Level 2	Technology concept and/or application Formulated
Technology Development	Level 3	Analytical and experimental critical functions and/or characteristic proof of concept
	Level 4	Component and/or bench validation in laboratory environment
Technology Demonstration	Level 5	Component and/or bench validation in relevant environment
System/Subsystem Development	Level 6	System/subsystem model or prototype demonstration in relevant environment
	Level 7	System prototype demonstration in an operational environment
System Test & Operation	Level 8	Actual system completed and qualified through test and demonstration
	Level 9	Actual system proven through successful operations e.g. through reliability and maintainability demonstration in service

Phase 2 – Summary Description

- Aim – To design, fabricate, construct and operate a plasma chamber in line with the Phase 1 concept
- Demonstration will increase the TRL of a transportable plasma based thermal destruction unit
- Scaled testing ≤ 10 kg/hr CW agent in a spatially representative manner
- Experimental planned, in addition to standard process considerations, will cover a range of liquid feed materials, requirement for an SCC, graphite tolerance to fluorine under plasma conditions and also the spatial configuration and extent of the modular plasma chamber

Phase 2 – Materials to be Tested

- Six days of plasma treatment processing
- Trials and analytical measurements configured with the prime objective to maximise DREs over the plasma chamber and tolerance of the technology to power input turndown and cessation for finite periods
- Material Streams:

Dimethyl Phosphite (DMP) - $C_2H_7O_3P$
Thiodiglycol (TDG) - $C_4H_{10}O_2S$
Diethylene Glycol (DEG) - $C_4H_{10}O_3$
Trifluoroethanol (TFE) - $C_2H_3F_3O$
Sodium dihydrogen phosphate (SDP) – NaH_2PO_4 40wt% in H_2O

Phase 2 – Current Validation Plant Layout

- The support of Defence Science & Technology Laboratory (DSTL), Porton Down team, is gratefully acknowledged.

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Thank you