PRESENT AND FUTURE TRENDS IN HIGH POWER GENERATION.

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1. SUMMARY

Modern warfare requires high levels of microwave power for various applications. Semiconductors are only suitable for low and medium power levels, for high power generation microwave tubes are still the most effective solution.

The feasibility of high power levels is mainly dependent on technology. The topics are given below:

- Tube type
- Tube design
    - Electron beam
    - Efficiency & cooling
    - Operating voltage.
- Energy storage

The reliability requirements are strongly related to the modes of operation.

Tube designs, production techniques and maintenance greatly determine tube reliability. Good power supply design can strongly increase tube reliability and hence system reliability. New power supply topologies also necessitate protection systems for the tube to run under high power conditions.

The procurement costs, the limited lifetime of the tube and the necessary maintenance are the main cost-drivers. Tube design and efficient maintenance procedures will increase the lifetime of the tube. The build-in test equipment of the power supply will reduce maintenance costs.

New cathodes and higher efficiencies will allow for higher output power. Reliability and lifetime will be increased by new technologies and "smart" power supplies, the latter also being responsible for decreasing maintenance costs.

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2. ABBREVIATIONS

The abbreviations used throughout the text are explained in this section.

BIST	Build-in Self Test
CFA	Cross Field Amplifier, a tube type family.
CW	Continuous Wave
EC	European Community
EMI	Electro Magnetic Interference
EOL	End Of Live
EW	Electronic Warfare
FEA	Finite Element Analysis
HV	High Voltage
HVPS	High Voltage Power Supply
MEOB	Naval Electronics and Optics Establishment
MPM	Microwave Power Module
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
OE	Operational Envelop
OP	Operation Point
RSG	Research Study Group
TNO	Netherlands Organization for applied scientific research
TNO-FEL	TNO Physics and Electronics Laboratory
TWT	Travelling Wave Tube, a tube type.

3. INTRODUCTION

Modern warfare requires high levels of microwave power for various applications. Semiconductors are only suitable for low and medium power levels, for high power generation microwave tubes are the most effective solution. The paper will give an overview of present and future trends in high power microwave systems, based on electron beam tubes.

Modern warfare requires high levels of microwave power, often in combination with wide bandwidth and high duty cycles. For many years, the generation of high power levels was the domain of microwave tubes, such as: Magnetrons, Klystrons, CFA's and TWTs.

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In the past years, the reliability of the microwave tubes and the related power supplies proved to be limited. High maintenance cost and the vulnerability to single point failures accelerated the design of solid state replacements in the 70's. The design of new tube technology and HVPSs (High Voltage Power Supply) ceased.

The development of high power solid state amplifiers in D, E and F band amplifiers started. The designers made use of medium power amplifiers, called books, the power of which was combined. This made the solid state amplifier very reliable and user friendly.

The design of solid state microwave amplifiers had to rely on:

- The development of the combiner.
  The design of combiners, specially the Wilkinson combiner proved to be very successful. The bandwidth, combining losses and power handling were well predictable and the production method well within the present technology.
- The availability of transistors.
  The development of high frequency high power transistors slowed down. The expected 200 to 400 W transistor was only met in the D-band. For the other bands the power stopped at 150 W (E/F band) to 5 W (J-band). The large quantities of transistors required in the high power amplifiers brought the price of the amplifiers out of the range of many users.

The interest in the use of microwave tubes returned. System designers took full advantage of:

- The development and studies in scandate cathodes;
- The use of dedicated cathode-types in specific tubes;
- Improved brazing technology and tube processing;
- Increased understanding of the operational use by the manufacturer;
- The fine tuning of the HVPS, the protection circuits and R.F. circuits to the tube.

Within NATO, RSG-19 is assigned to develop a new standard for the reliability of high power microwave tubes.

For the assessment of the various reliability aspects of tubes and their HVPS the concept of the OE (Operational Envelop) is a useful tool. It also helps to adept the feasibility of tube and HVPS concepts.

This paper will first address the concept of the OE. Feasibility, reliability and cost-effectiveness are the three aspects that will be covered next.

4. OPERATIONAL ENVELOP

To model all various aspects of tube reliability, RSG-19 introduced the "operational envelop" concept. Three definitions will clarify this concept:

- Operation point (OP):
  Any combination of voltages and currents (temperatures, shock, vibration etc. may also be included) that is applied to the tube or is present on the HVPS.
- Valid operation point:
  Any OP that the tube or HVPS can handle for prolonged time (the specified lifetime).
  Valid OPs are often subject to time constraints, their validity is restricted to a given pulse width and/or duty cycle.
- Operational envelop :
  The boundary of the set of all valid OPs.

As long as the tube is operated within the OE, the stress factors are within the limits and the (well designed) tube will exhibit a good reliability.

During switch-on, the tube will run under a number of OPs, varying from "all voltages zero" to the chosen OP. All OPs should be within the OE.

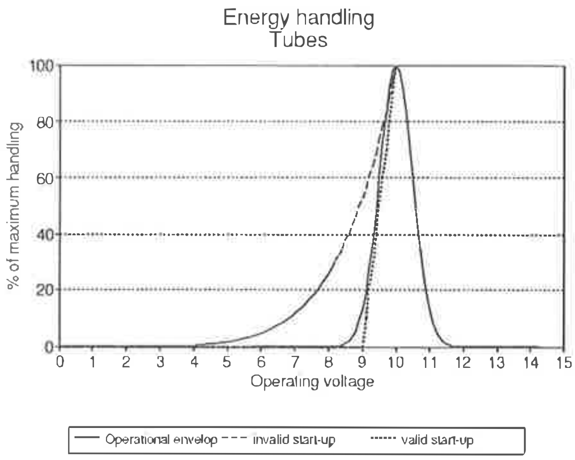

Fig. 1. Operational envelop with valid and invalid start-up curve.

An example is given in fig. 1. A given tube can handle 100 % energy at 10 kV, due to beam defocussing the energy handling capacity is decreased for other voltages. This leads to the shown OE. Two switch-on curves are given. One clearly has OPs outside the OE, so it is an invalid start-up curve. The other remains within the OE, giving a valid start-up.

5. FEASIBILITY

The feasibility of high power levels is mainly dependent on technology. The topics are given below:

- *Tube type*
  The requirements for coherency, stability and bandwidth mainly determine the most suitable tube type and hence the maximum obtainable peak power.
- *Tube design*
  New tube designs and production techniques allow for higher power levels. Three aspects require our special attention:
  - *Electron beam*
    The electron beam converts DC power to RF power. The ability to generate and focus high energy electron beams is of major influence on the power level that can be achieved. We will focus on modern cathode design and cathode materials to investigate how the beam current can be increased.
  - *Efficiency & cooling*
    Increasing system efficiency allows for more output power at the same level of dissipated heat. Better cooling implies a higher level of allowable dissipation and hence output power.
  - *Operating voltage.*
    Higher operating voltages increase output power, however they also increase the electron velocity and hence require a major change in tube design. This limits the operating voltage in being a tool to increase output power.
- *Energy storage*
  High peak power levels require large energy storage and cause, due to fast switching, high levels of Electro Magnetic Interference (EMI). Modern techniques to store and control energy, under both operational and error conditions, will be addressed.

The system specification is the technical translation of the operational requirement. This specification dictates the class of tube and the technology to be used in the tube. In this paragraph the tube type, design, power supply and interface will be discussed.

5.1 Tube type

The tube class is driven by:

1 Frequency and bandwidth;
This determines the use of a TWT, klystron or magnetron etc.. For a wide frequency band, up to 2 octaves, a TWT will be the best choice. For a limited bandwidth but tuneable over a 4 to 5 % bandwidth, a klystron is a good choice. A magnetron will be the best alternative for up to 3 % bandwidth.

2 Power output;
For the power output and the related duty cycle a TWT and klystron is capable of delivering medium peak powers (200 kW) with duty cycles up to 20%. The use of a magnetron will give high peak powers (1 MW) but low duty cycles up to 1%.

3 Stability;
Stability in a tube depends strongly on the power supply of the system. For stable, good AM and PM noise figures <-100dBc/Hz the TWT and klystron is the best choice. For a magnetron special measures have to be taken in a coherent system, -60 dBc/Hz can be reached.

4 Reliability;
The reliability of the three tube classes mentioned above depends on the stress that is applied to the tube. This will be discussed further in paragraph 6.

An overview is given in table 1.

	TWT	Klystron	Magnetron
Freq. tuning	External source	External source	Fixed/ tuned
Bandwidth	Octave(s)	Tuneable w.r.	Tuneable s.r.
Peak power	Medium	Medium	High
Duty cycle	Up to CW	Up to CW	1% max.
Coherency	Excellent	Excellent	Poor
AM/PM noise in dBc/Hz	<-100	<-110	<-60
Stability	Depending on external source	Depending on external source	0.2%
Reliability	20.000 hrs	20.000 hrs	3.000 hrs

Table 1, Overview tube types
w.r. = wide range, > 3 %.
s.r. = small range, < 3 %.

5.2 Tube design

The system application plays a major role in the design of a high power tube. It dictates the materials and the constructions to be applied to the tube. Each application has its own specific design restrains. A search radar will be operational during a long period of time. A tracking and illumination radar will be used during a short period of time only. EW systems are active over short periods and are in a Standby mode for a long period. This is also the case with fire control and illumination radars whose reliability must be very high upon activation. Systems that are in standby for long periods, often exhibit arcing. Due to the long standby hours, ions may be collected around the cathode and the evaporation of barium oxide out of the cathode may pollute the ceramics and grid structure. Applying the HV (High Voltage) to the tube an arc may be induced by those effects. Failure will cause extreme danger to the platform on which the radar and/or EW is mounted.

In communication systems the operational use is different from the earlier mentioned systems. The tube is in the operational mode for long periods of time. The ions produced are collected by the beam and the evaporation of barium oxide is less due to the beam cooling of the cathode surface and the equal temperature over the gun parts. During the design of the cathode special measures on, cathode material, oxide, B or M type cathode, grid and thermal stress and stability have to be taken.

The platform that carries the system will dictate the mechanical stress applied to the tube. Land-based systems do not show high shock and vibration levels. Missile applications show high levels of shock, vibration and acceleration during the start. Fighter airplanes will shock and vibrate over a long period of time. Tubes on board ships will see low frequency vibrations over long periods of time. The three described situations all require special attention to the construction of the different parts in a tube. Restrictions apply to design also. In missile and fighter applications the weight of the tube and its power supply will be limited while for land-based and shipborne applications the weight is less stringent. This implicates that the tube designer has to be aware of the platform on which the tube will be used. Finite Element Analysis (FEA) proves a valuable instrument here. It allows the tube designer to predict the mechanical strength of his design and to simulate the impact of various stimulations.

The second part of this paragraph will focus on future strategies and techniques to cope with the above-mentioned problems.

5.2.1 Strategy

Future trends will focus on an increasing use of computer aided design. Libraries of tube parts (e.g. cathodes, RF-structures etc.) will be built up. A new tube will be designed by using the library-parts. More attention will be paid to the tube parts during their design, since they can be used in many tube designs. This will result in thorough FEA and thereby good mechanical strength, in good electric figures, in high reliability and in as simple as possible manufacturing. The manufacturer can easy adapt a given tube design to specific user requirements.

The users will tend to apply standard tube types and HVPS. The manufacturers can produce larger quantities of these standard products at lower costs. This allows for the application of many tubes, mini-tubes or MPMs (Microwave Power Module) in a high power amplifier to increase output power.

5.2.2 Cathode

Tube development will benefit from improved cathode design. Higher current densities and longer lifetimes are required. The development of coatings for the cathode, to lower the work function, are under investigation. Scandate proves to be very successful. Research is still required as the understanding of the physics is still not fully understood. A new development is the Field Emission Cathode Array (see fig. 2). High current densities can be reached in a medium vacuum environment. Figures of 40 to 400 A per square centimeter are attainable in a vacuum of 1.10-6 torr. Heaters are not required for this type of cathodes. $TaSi_2$ is a basic material for this type of cathodes. The limitation is the short life of the cathode. This is due to the relative fast deterioration of the tips in the $TaSi_2$ array. Further research using other materials and alloys are proceeding.

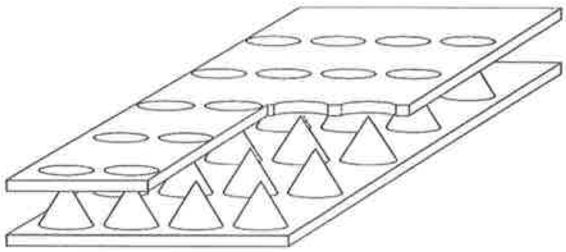

Fig. 2, Field Emission Cathode Array.

5.2.3 Cooling

The cooling of the tube has a major effect on the power handling of the tube. By efficient cooling of the R.F. structure, the power handling can be improved by at least 3 db. There are three distinctive groups of R.F. structure: Helix, Coupled Cavity and Ring Bar. In the coupled cavity and ring bar tubes the cooling of the structure is limited by the surface area of the structure. In the helix tube the heat transfer from the structure is limited by the heat resistance of the isolation material between the helix and the body. In general Beryllium Oxide or Aluminium Oxide is used. The use of diamond rods is under investigation, which promises a reduction of the heat resistance by a factor of 4. FEA proves a valuable instrument here. It allows the tube designer to predict the thermal behaviour of his design and to simulate the impact of various thermal stimuli.

5.2.4 Focussing

Higher efficiency and improved focussing will reduce the energy absorbed in the RF-structure of the tube. Stronger and more reliable magnets, such as Samarium Cobalt magnets, are key elements. Due to the reduced thermal load of the RF-structure, the tube output power can be increased.

5.2.5 Structure

The use of special plastic mandrills for manufacturing the RF-structures are investigated. This technology make use of a mandrill on which material, such as copper, is electroformed thereby creating the RF-structure. The mandrill is etched out of the structure and the RF-structure remains. Due to the limited amount of brazing high accuracy and high yield can be reached by this technique. It will also reduce the RF-losses in the structure and improve the R.F. efficiency.

5.2.6 Microwave Power Module

Hybrid technology combines the best of two worlds, the high power of the microwave vacuum tube and the gain of the solid state amplifier. To increase power (gain) of a tube higher electron velocities are required. This implies an increase of the operating voltage of the tube. There are a number of disadvantages. Higher voltages will add extra difficulties to the design and reliability of the power supply and increase the complexity of the design and production of the tube. In solid state higher gains are available. By combining the gain of the solid state amplifier and the power output of the tube a cost effective solution can be found. The low gain of the tube will reduce the high voltages of the tube. When the HVPS is added to the combination of tube and solid state amplifier the MPM is obtained. The MPM has the advantage of no external HV connection and no complex wiring, only three connections have to be made: input, output and power (e.g. 28 or 270 Vdc).

So far this approach has been seen in medium power amplifiers of 200 W and frequencies up to 18 GHz. The AM/PM noise performance of the MPM is only fair due to the poor stabilization of the HVPS. The high power per cubic centimeter rating results in stringent cooling requirements. It can be foreseen that a further development to higher power levels is achievable. Future developments will focus on improvement of AM/PM noise performance and cooling.

MPMs are perfectly suited for active phased array applications, where each antenna element (or set of antenna elements) requires its power amplifier. The advantages and disadvantages of the MPM versus solid state amplifiers is given in table 2.

	MPM	Solid state
Power	50 W	5 W
Efficiency	40 %	15 %
AM/PM noise	fair	good

Table 2, Comparison of an average MPM versus solid state.

The increased power of the MPM can be used either to decrease the number of units or to increase output power, depending on system requirements. both MPM and solid state amplifier require extensive cooling systems.

5.2.7 Mini tube

A way of increasing the system power output is the use of multiple mini tubes. The voltage required with mini-tubes is reasonably low, about 4 kV. By combining the power in a Wilkinson combiner or Rothman lens and using multiple power supplies, a reliable high power amplifier will be designed.

5.2.8 Dual mode tube

The development of dual mode tubes started in the 80's. The difficulties with the design of the vacuum envelope and gun slowed it down. New interest, specially for the designs from the former eastern block countries, can be seen in this type of tubes.

5.2.9 Klystron

The limited instantaneous bandwidth has been a disadvantage of klystrons. New developments in the E.C. have been started on the design of inter active klystrons. This design will give the klystron a bandwidth comparable to that of a TWT.

5.2.10 Magnetron

One of the life shortening effects in the magnetron is the wear-out of the cathode and the secondary emission of the cathode stem area. The improvements of the cathode material follow the trends shown for TWT and klystron. The effect of secondary emission can greatly be reduced by adding an appropriate coating to the cathode stem and by decreasing the stem temperature.

5.3 Power supply

The feasibility of a microwave power generator is not limited by the voltage and current ratings of today's HVPS. More important however is the protection and control of the power supply. The power supply should be kept within its OE under all conditions. The OE of the HVPS should include that of the tube, so the power supply can never be damaged by any operation condition of the tube. Both control and protection greatly enlarge the HVPS OE.

Present HVPS developments benefit from resonant switching converter topologies, that have among others the following advantages:

- Low EMI.
  Due to the sinusoïdal current EMI is reduced;
- Low stored energy.
  The resonant converter allows for higher switching frequencies which, in combination with low EMI, leads to simple output filters with a low amount of stored energy;
- Tight control.
  The high operating frequency and simple filtering allow for high control bandwidth and tight converter control;

The low converter EMI allows for fast acting control and protection circuits without the disadvantage of erroneous operation. Semiconductor protection devices are available that can react in nanoseconds and can handle several hundreds of amperes. They can make the HVPS virtually insensitive to the most extreme tube OP: the HV-arc.

The sinusoïdal converter current reduces the electrical stress on the converter semiconductors which on the one hand increases reliability and on the other hand allows for an increased power handling. Also the switching losses are reduced resulting in a higher efficiency and, consequently, smaller heatsinks.

The high frequencies allow for small capacitors, transformers and, due to the sinusoïdal current, simple filtering.

Future trends will bring small and efficient power supplies. The main design effort will be on protection and control. The OE will be widened by adequate protection. The control electronics will be programmed to exactly monitor the OP and keep it within the OE unconditionally.

5.4 Interface

The power supply has two major tasks in relation with the tube, it should deliver enough power and it should keep the tube unconditionally within the tube OE.

Tight control of the OE will gradually allow for higher output power without over-stressing the sensitive parts of the tube. Tube design will be influenced by this trend, and gradually go towards tubes that allow for very high powers in return for a very narrow OE.

The OE will become more and more important in the future. It enlarges the possibilities of power tubes at the expense of increased risk to destroy tube or HVPS in case the OE is not properly maintained.

5.5 Energy storage

The energy, necessary to generate high power microwave levels, is drawn from the HVPS. The energy, supplied by power invertors, is temporarily stored in capacitors. In case of tube, the stored energy is uncontrollably released into the tube, which can be destroyed eventually. There are several techniques to avoid this energy release:

- Application of a crowbar.
- Limitation of energy storage.
- Application of HV switches.

These techniques are discussed more in detail below.

5.5.1 Crowbar

A crowbar is the conventional solution to avoid excessive energy release. It provides a low impedance pad for the energy source, thereby diverting the energy off the tube. Crowbars however show several drawbacks:

- Their reliability is limited due to sensitivity to wear;
- Their ability to "fire" is often not unconditional;
- Their reaction time is fair, a part of the stored energy is still released in the tube before the crowbar fires;
- The operation principle implies high currents compared to the operating current;
- The operation principle implies high current rise-times, the resulting EMI may easily cause damage to HVPS electronics.

5.5.2 Limited energy storage

The energy storage is limited to the maximum rating for the tube. This state of the art technique requires electronic circuits to compensate the effect of limited energy storage. Modern semiconductor technology provides high bandwidth components with sufficient voltage and current rating to enable these control circuits. The compensation electronics guarantee operation within the OE.

5.5.3 HV switch

HV-switches between energy storage and tube can block the energy release. Certain tube types (CFAs) require the switch also to switch the tube on and off. The conventional switches have drawbacks about equal to the already mentioned crowbar. To avoid these drawbacks, the HV-switch is often replaced by a low voltage, high current switch combined with a pulse transformer.

Future developments will bring the stacked transistor topologies. This emerging technology enables fast reacting reliable switches that can handle high voltages and high current levels. Today these switches still are bulky, in the near future they will be available in the same size as conventional switches. Stacked transistor topologies also enable control of rise- and fall-times, thereby reducing the amount of EMI. Moreover, operation within the OE, both under operating and error conditions, can be guaranteed by adequate control of the stacked transistor system.

6. RELIABILITY

The reliability requirements are strongly related to the modes of operation. The paper will address various aspects, including Mean Time Between Failure (MTBF) and the certainty that a tube will run upon switch-on.

Tube designs, production techniques and maintenance greatly determine tube reliability. Good power supply design can strongly increase tube reliability and hence system reliability. New power supply topologies also include the necessary protection systems for the tube to run under high power conditions.

This chapter will focus on reliability of power tubes and HVPS. The system reliability is not only determined by the sole reliability of the tube and HVPS but also by the tube-HVPS interaction. The concept of the OE is a useful tool to describe the various reliability aspects.

6.1 Tube

The TWT is taken as example, since it has all functions in physically separated areas:

- Electron generation in the cathode;
- Beam control in the grid;
- Beam focussing & acceleration;
- RF is generated/amplified in the RF structure;
- Electron collection in the collector.

Other tube types have some or all of these elements. The CFA family generally lacks beam control and focussing, electron collection is done by the RF structure. The klystron has the same outline as a TWT, however the RF structure is distinctive and they often lack a beam control grid.

In relation to general tubes, the MTBF of high power tubes is more related to:

1 Cathode stress.
High output power requires high current densities in the electron beam and thus at the cathode surface. This asks for new cathode (micro-) structures and materials. It can be necessary to operate the cathode at elevated temperatures. The latter will decrease cathode life and increase the out-gassing process.

2 Electrical stress.
High power tubes generally run under high voltages. This makes the tube sensitive to flash-overs due to gas in the vacuum envelope or contamination of the ceramics. Eventually this will lead to the inability of the tube to withstand the HV.

3 Thermal stress of the helix.
Due to imperfections in beam focussing a part of the electron beam is intercepted by the RF structure. The high speed of the electrons causes high heat dissipation in the RF structure.

4 Thermal stress of the collector(s).
All energy supplied to the tube is either converted to RF-energy or to heat. Almost all heat is, under normal conditions, dissipated in the collector. Overheating may cause the collector to melt or to evaporate metal (copper) which will form conductive layers on isolating ceramics. Collector cooling therefore is an crucial factor in tube reliability.

5 Vacuum.
Due to (thermal) stress in the brazing and/or hot spots anywhere in the tube, micro-leaks can develop, thereby causing loss of vacuum. High surface temperatures of parts inside the vacuum envelop can cause out-gassing, thereby destroying the vacuum. Also the evaporation of barium out of the cathode can have this effect.

Under certain circumstances, a "quick-start" is applied to the tube. The OE is "widened" to include the OPs with high inrush currents which can be done with special cathode and heater design. Special grids can keep the tube from operating thereby allowing for a fast switch-on of the HV.

The certainty that a tube will run upon a "quick-start" can be checked by the BIST (Build-in Self Test) of the HVPS. The heater can be tested upon resistance, where the quality of the vacuum can be proved with a static HV test. Tubes, equipped with an ion pump, can maintain their vacuum and allow for an easy check of the quality of the vacuum.

Tube technology nowadays moves to a "narrowing" of the OE in favour of an increased reliability. Better knowledge of thermal cathode behaviour can result in an OE that, under strict control of the OP locus, will allow for quick-start.

6.2 HVPS

HVPS reliability is, of course, subject to general reliability aspects that apply for all electronic devices. Due to its high power and voltage handling some specific aspects are noteworthy:

1 Electrical stress.
Semiconductors are used as close as possible to their maximum ratings, which requires adequate derating to meet the reliability specifications. The sinusoïdal currents of resonant converters lack high dV/dt and dI/dt which reduces the electrical stresses.

2 Thermal stress.
Most of the components are operated close to their maximum operating temperature, once more requiring derating. Resonant converters, running with sinusoïdal currents however exhibit greatly reduced switching losses that allow for reduced operating temperatures and enhanced reliability.

3 Switching
The high voltage levels implicate high levels of stored energy in parasitic capacitances. This energy is released upon switching and can destroy semiconductors. Resonant converter topologies can reduce rise-times, thereby reducing the current through the parasitic capacitors. This also can compensate certain parasitic capacitances.

4 EMI
The high pulsed output power causes high levels of EMI, which can destroy other parts of the HVPS. Once again rise-time reduction can reduce EMI.

BIST equipment does not increase reliability in statistical terms. A failure cannot be avoided by BIST. The certainty that both tube and HVPS will run upon switch-on however can greatly be increased by proper BIST procedures. This reliability aspect is especially important for missile systems, fire control and EW systems, since they are (only) switched on when life-threatening situation occurs.

6.3 Tube-HVPS control.

Tubes and HVPS strongly interact. As far as reliability is concerned, malfunction of either one can destroy the other. The increase of reliability depends on the HVPS that has to fulfil four requirements:

- It has to keep the tube within the tube OE;
- It has to keep itself within the HVPS OE;
- It has to be able to withstand all the tube's possible operating points, including arcing (=short circuit of the HVPS!). The HVPS OE itself should be wide enough to enclose all the tube's operating points;
- It has to be fail-safe: never should the tube be put in an invalid OP due to power supply failure.

The above-mentioned requirements can be met by new power supply technology. The power supply control has, apart from regular HVPS functions, four major tasks in tube & HVPS control:

- Monitor the OP of the tube;
- Compare the OP with the internally stored OE;
- Take corrective actions to keep the OP within the OE;
- Shut-down the power supply in case the OP is near the edge of the OE. At shut-down, the OP should remain within the OE.

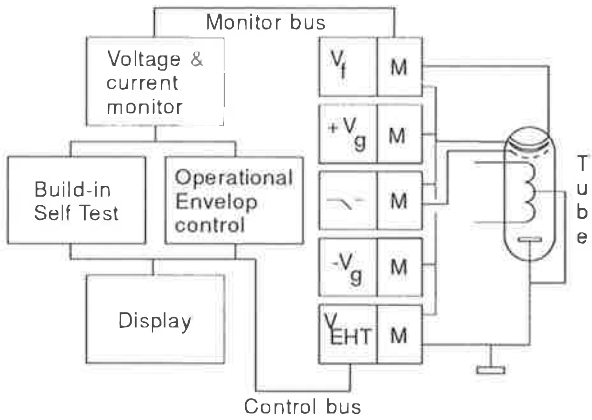

Fig. 3, Power supply with full OE control and BIST.

Given the above mentioned guide-lines concerning reliability of tube, HVPS and their interaction, a power supply was designed at FEL-TNO in the Netherlands. This power supply has extensive control electronics to guard the OE and BIST to check the power supply and the TWT. It has a display panel indicating which part of the TWT or HVPS is malfunctioning. The prototype still meets all reliability requirements after a more than four year test period. The lay-out of the HVPS is given in fig. 3.

6.4 Mini-tube

At a first glance, the choice between a "mini" and a "normal" tube has no impact on reliability. The mini-tube however works with lower electron speeds and hence lower voltages. This factor enables a significant increase in reliability of both tube and HVPS.

The major drawback of the mini is its relatively low peak output power. The mini is easier to produce, especially in series production, which allows for a lower price and a strict quality program. The mini has the potential to run at a significant lower dollar per watt rating than its bigger opponent. Even with the extra costs of combiners, large amounts of power can be generated cost-effectively by using a sufficient number of minis.

The mini will be the future solution in many RF power generators.

6.5 Microwave power module

The consists of a solid-state pre-amplifier, a (mini) TWT and a HVPS, all combined in one housing, see fig. 4.

The MPM further increases the reliability that is obtained by the use of mini-tubes:

- The gain is obtained by the solid state amplifier so the gain requirement for the tube is minimal. The tube designer can concentrate on reliability instead of on gain.
- The MPM runs at lower voltage than the mini tube.
- The tube and the HVPS can be perfectly matched with respect to their OE.
- Maintenance personnel does not have to handle HV-parts, which both increases reliability and safety.

The MPM has, as already stated, a lower power rating than the mini. For the same reasons however, their dollar to watt rating can be reasonable. The main application for MPM is the phased array antenna that benefits from the multiple amplifier concept and from the power combination that is done "in free space".

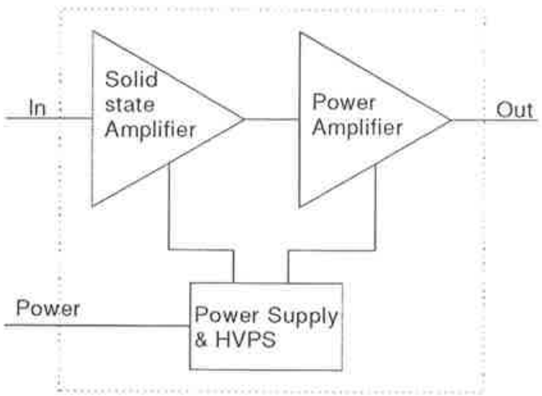

Fig. 4. The Microwave Power Module.

7. COST-EFFECTIVENESS

The procurement costs, the limited lifetime of the tube and the necessary maintenance are the main cost-drivers. Tubes also require maintenance when they are non-operating or in storage.

Production technology is in an on-going process of decreasing production costs, however tubes are labour-intensive to produce which strongly limits the effect of production technology on tube procurement costs.

Tube design and efficient maintenance procedures will increase the lifetime of the tube. The build-in test equipment of the power supply will reduce maintenance costs.

The maintenance cost of a system is not only the cost of repair and periodic maintenance, but also the cost of the logistic system.
The repair of the microwave tube is complicated and can in general only be done by the manufacturer at high expenses. The microwave tube has to be returned to the tube manufacturer for analysis and repair. This causes long turn-around times, meaning extra investments in spares tubes.
Repair of the defective HVPS may be performed by the maintenance organization of the system owner or may be contracted to the system manufacturer, requiring spare HVPSs due to long turn around times.

Maintenance personnel can only perform a limited fault analysis. A key factor is the limited time available for repair. A system has to be operational within the specified MTTR, often less than 1 hour. The maintenance engineer however has to determine whether tube or HVPS is defect. Effective HVPS BIST however can give a quick, good and well specified analysis of the fault.

Periodic maintenance can greatly be reduced by BIST. As long as tube and HVPS are operated within the OE, there is no objection to use the tube as a test load for the HVPS and/or the HVPS as a test device for the tube. This however requires auto-calibrating facilities, fail-safe BIST and fail-safe OE control. Human interference, if necessary, then is limited to maintenance that requires specific equipment.

Periodic maintenance can also be reduced by training of the maintenance engineer in fault diagnostics on microwave tubes and HVPS. The basic principles on microwave tube theory and tube maintenance has to be part of his education.

Tubes do change their OE over lifetime. Maintenance engineers often report increased lifetime due to slightly changed voltage settings. When aging is included in the OE programmed in the HVPS, this can increase tube lifetime. The operation within the OE itself also increases lifetime.

Failure data comprise a great amount of information regarding reliability and MTTF. With data, obtained from BIST, maintenance engineers (following a well defined procedure) and factory repair engineers, an in-depth analysis of the failures can be made. Here the use of HV and STANDBY hours is of major importance and a real MTBF can be calculated. Special circumstances such as land-based and ship- or airborne, type of system fire control, illumination, search radar or jammer, have to be taken into account. The results of the analysis have to be available to the system user, tube manufacturer and/or the system designer. Depending on the results of the analysis operational procedures, system modifications or tube modifications have to be discussed.

8. CONCLUSIVE REMARKS

New cathodes and higher efficiencies will allow for higher output power. Reliability and lifetime will be increased by new technologies and "smart" power supplies, the latter also being responsible for decreasing maintenance costs.

After a decreasing interest in the use of high power vacuum tubes in the 70's and 80's, new developments started in the field of cathode technology, efficiency, power supplies and tube-HVPS interfaces. This brought the tube back into the newly developed systems as a reliable microwave power source.

The combining of power, as is common practice for high power solid state amplifiers, showed its benefits at the introduction of the mini tube. The marriage of the low power solid state amplifier and the mini tube resulted in the MPM, a versatile and easy to use power amplifier.

The development of new tube technologies will depend on the performance requirements of systems. The active phased array antenna act as a technology push into the development of MPMs.

The OE will be increasingly important for tube and HVPS design and development. Future developments will benefit from tight OE control. Close corporation between the designers of tube, HVPS and system is necessary to formulate the OE.

New technologies as scandate cathodes will allow for higher output power. Tube designers will take advantage from OE control to further increase output power.

Effective BIST will reduce maintenance costs.

The power amplifier of the future will consist of a number of (cheap) standard tubes, in most cases mini tubes or MPMs. The system will be virtually maintenance free, indicating the defective tube or HVPS part in case of a failure. The latter results in repair by replacement.

DISCUSSION

E. SCHWEICHER
Do the cooling problems you mentioned about HEMT's or MESFET's explain the cooling difficulties encoutered by TI and Westinghouse in the development of the active phased array antenna of the radar of the ATF F-22 ?

AUTHOR'S REPLY
I am not in a position to discuss the problems that are encountered during the development of the F-22 radar system. However TNO-FEL has a vast experience with the development of active phased array antennas, as for example used in the PHARUS universal SAR radar. Cooling of active phased arrays is difficult due to :
- the low efficiency of the semiconductor power amplifier
- the high power density involved
- the (virtual) absence of conduction cooling in two-dimensional array's. A medium (e.g. air, water or freon) is used to transport heat. This leads to an elaborate cooling system.

The higher efficiency of MPM's give them a strong advantage as far as cooling is concerned. The required cooling capacity for MPM can be down to 50 % when compared to a solid state amplifier with the same RF output power.

E. SCHWEICHER
What do you think about the power capability and the reliability of HEMT's and especially pseudomorphic HEMT's ?

AUTHOR'S REPLY
The amount of heat that can be dissipated by a HEMT (or any other transistor) is limited by its chip surface. The efficiency and chip surface determine the power capability of the HEMT. In relation to other semiconductors the efficiency is the main factor. However in relation with MPM's the chip surface becomes a main factor, since it cannot be increased beyond a given limit.
As my presentation indicates, almost any reliability can be achieved, as long as operation is limited to a given operational envelop. For HEMT's this will in general mean that high reliability is achieved for a limited temperature range, input voltage range and supply voltage range. When the device is "pushed to its limits" the reliability will decrease.