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FINAL REPORT

THERMAL MANAGEMENT
OF SPACE-BASED, HIGH-POWER,
SOLID-STATE RF AMPLIFIERS

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M. F. Rose	Auburn University
L. C. Chow	University of Kentucky
J. H. Johnson	Microwave Modules and Devices, Inc.

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EXECUTIVE SUMMARY

GENERAL COMMENTS

In the NPB/FEL weapons concepts, high power RF devices will be used to provide energy for advanced accelerators. It is presently envisioned that the operating power level of these weapons will be on the order of gigawatts and will be composed of many elements with varying efficiencies. To provide the RF power two options exist, each having distinct advantages and disadvantages. The first, system concepts employing microwave tubes to provide the requisite RF energy, are high voltage systems with the section of the device producing RF distinct and separate from that section of the device which must dissipate the waste energy. These devices (klystrons and klystrodes) are in general on the order of 75-80% efficient. And secondly, at the other end of the scale, solid-state modules capable of powering the weapons concepts exist up to a frequency of 850 MHz. Solid-state sources are inherently low-voltage, high-current devices and have the unfortunate attribute that the RF and waste heat production are co-located in a semiconducting junction. While microwave tube collectors can be run at high temperature, the geometry is flexible enough to allow collector heat loading to be much less than 100 W/cm^2 for most of the scenarios studied. By contrast, the power density within the junction of a RF transistor may approach 2500 W/cm^2 . Further, for operation, the transistor junction temperature must not exceed some 500 K.

The options for handling waste heat in any case are to radiate directly to space, store the waste heat for later radiation, or heat exchange the waste heat into an effluent stream for subsequent ejection to space. Whichever way is

chosen, the thermal management system must not adversely impact total platform performance by adding significant weight/volume or by restricting the performance of other on-board devices.

SYSTEM ASSUMPTIONS

Power conditioning technology is capable of operating at efficiency levels in excess of 95%. They are, however, heavy with near term state-of-the-art being in the order of 0.2 kg/kW. One of the attractive features of using solid-state devices for powering these concepts is the possibility of eliminating much, if not all, of the mass associated with power conditioning. In general, solid-state modular systems, such as the Navy's SPS-40 radar, are low-voltage, high-current machines which make them ideal candidates for powering with fuel cells specifically tailored and matched to a given module size. Figure 1 is a block diagram of a candidate system as studied by the IEG. For this study, we assume that all of the RF amplifier stages could be powered by solid-state. The near-term state-of-the-art would allow f_0 and $2f_0$ to be powered by solid-state. The technology for $4f_0$ is uncertain, and, to date, suffers from lack of effort. At f_0 and $2f_0$, efficiencies of single chip devices are on the order of 70-80% with some apparent advantage to operating at low temperature. Current system studies indicate that the 1700 MHz stage may be eliminated in the near term.

It is assumed that the system will be powered by fuel cells which can be segmented, modularized, and tailored to provide appropriate V-I characteristics. In so doing, massive electrical conductors are eliminated and plumbing minimized since prime power, RF source, and one segment of the

Figure 1 Block diagram of candidate NPB/FEL system as studied by the IEG.

accelerator are essentially co-located. The power level for such a module is assumed to be 1 megawatt RF.

The maximum continuous run time for a space platform is assumed to be 500 seconds. However, the total system would periodically be tested to assess state-of-readiness. It is assumed that these tests would last for at least 30 seconds. In this study, we have examined the feasibility of several methods for removing waste thermal energy from solid-state RF modules subject to the following assumptions:

- On-board supercritical hydrogen is available at a temperature of 35 K, 30 bars, and at a flow rate consistent with cooling the cryogenic cavity of the accelerator.
- All of the waste energy to be dealt with is in the solid-state RF module.
- The maximum continuous run time is on the order of 500 seconds.
- The single element efficiency is on the order of 75%. Module efficiency is in the 60-70% range.
- The solid-state element junction temperatures are confined to ± 200 C.

SCOPE OF THE STUDY

The following were investigated as part of this work:

- Direct radiation of waste energy to space
- Use of thermal storage media to provide a storage capability for 500 seconds
- Secondary coolant loop heat exchange to hydrogen bus
- Use of hydrogen to directly cool the modules
 - Effect of hydrogen diffusion/permeation
 - Dynamic stresses
 - Thermal shock

The following team was assembled to conduct the study:

<u>Team Member</u>	<u>Affiliation</u>	<u>Technical Area</u>
Prof. M. F. Rose (project coordinator)	Auburn University	Systems analysis Direct energy conversion
Prof. L. C. Chow	University of Kentucky	Experimental thermodynamics
Mr. J. Johnson	MM Devices	Experimental device fabrication/design
IEG Panel	NASA/DOD	Systems analysis
LASNL Staff	DOE	Liquid cooling Thermodynamics modeling

A synopsis of the study results appears in the following charts:

Technique	Level of Understanding	Major Systems Implications	Comments
Hydrogen cooling	1. Poorly understood 2. Lack of demonstration	1. Everybody wants to use hydrogen since it is charged to the accelerator mass budget. 2. Pressure and flow rate compatible with regulation rather than pumping. 3. Convenient topology possible. 4. Restrictions on temperature swings due to other user requirements. 5. Possible to build "microchannel" into chip base to eliminate massive heat sink. 6. Single point failures possible. Complex plumbing necessary since other systems need hydrogen after RF sources. 7. Minimum mass. 8. May have to add extra hydrogen. 9. Potential thermally induced mechanical stress incompatibility. 10. Start-up sequence may be influenced by cooldown time of cryogen distribution system.	1. Techniques utilizing "liquid" loops must "heat exchange" into hydrogen. Why not build single heat exchanger into chips rather than have two? 2. Allows chips to run at lower junction temperatures. This may or may not be advantageous. Chip is more efficient but higher hydrogen flow rates necessary to remove a given unit of waste energy. 3. Possible problem with hydrogen diffusing into junctions. Major literature search indicates effect may be beneficial rather than detrimental. 4. <u>Technique appears feasible.</u> 5. Major materials impact (diamond, HOPG, etc.) 6. Thermally induced stresses and distribution cooldown can be engineered but have system implications. 7. Hydrogen permeation is not a problem for the temperature range assumed.

Synopsis of Study Results (continued)

Technique	Level of Understanding	Major Systems Implications	Comments
Direct radiation/ radiation	Excellent	<ol style="list-style-type: none"> 1. Specialized topology. 2. Enormous mass penalty (>50% of S/C). 3. Operating temperature too low to effectively utilize. 4. Enormous surface area necessary. 5. Surface area of radiator large enough to effect maneuverability and station keeping. 	<ol style="list-style-type: none"> 1. Technique well understood and is currently employed in all S/C coupled to secondary coolant loops or heat pipes. 2. Technique governed by absolute temperature and surface emissivity. Integrated emissivity greater than 0.95 has been achieved. 3. <u>Technique not feasible due to low temperature of operation.</u> 4. Technique would become viable at about 1000 K. 5. No solid state device technology on horizon at that temperature.
Phase change (melting)	Excellent	<ol style="list-style-type: none"> 1. Must carry on-board sufficient material to store in sensible and phase change all waste energy for max run time. 	<ol style="list-style-type: none"> 1. Extensive literature search conducted. Paraffins and water best choices. Most phase change materials with large latent heat of fusion are outside allowable temperature swing.
Exotic phase change (mixable liquids, metal oxide decomposition, boiling)	Poor	<ol style="list-style-type: none"> 2. Due to low thermal conductivity, it is difficult to "load" energy into storage media while maintaining constant junction temperature. 3. Massive fins or flowing system necessary to maintain constant junction temperature. <u>Pumps required.</u> 4. Necessitates complex topology especially for finned structure. 5. Many single point failure modes. 6. Requires storage reservoir. 	<ol style="list-style-type: none"> 2. Over 200 phase change materials investigated. 3. Thermal storage materials usually have low thermal conductivity. 4. If flow is necessary, trade-off exists between liquid cooling-heat exchange system and pumps-reservoir for storage. 5. Exotics too poorly understood within systems to judge.

Synopsis of Study Results (continued)

Technique	Level of Understanding	Major Systems Implications	Comments
Liquid cooling	Excellent	1. Added mass due to coolant, pumps, plumbing, and secondary heat exchanger.	1. Major literature searches conducted, over 50 technical papers reviewed.
Liquid coolant with microencapsulated phase change materials	"Slurry" coolants not well developed	2. Waste energy transferred to coolant only. Must be transferred to radiator or heat exchange to hydrogen bus. 3. Due to temperature of hydrogen bus, freeze up may occur in exchanger. Could be avoided by auxiliary heater added to exchanger. 4. Amount of coolant and operating temperature may produce incompatible thermal requirements wrt other users of on-board coolant. 5. Many catastrophic single point failure modes. 6. Use of microchannel plate technology reduces system mass. 7. Extra hydrogen may have to be added to implement.	2. Bennet's research gives excellent treatment. 3. If systems implication are acceptable, technique is viable. 4. Enormous mass penalty if energy must be radiated due to low temperature. 5. Heat exchange to hydrogen bus is not an established technology in the range of interest. 6. Microchannel cooling in the range of interest (kW/cm^2) demonstrated but not well developed. 7. Microchannel cooling technique absolutely necessary to reduce mass. 8. Two phase flow possible. Incomplete understanding.

Feasibility of the Different Cooling Techniques

Technique	Feasibility	Comments
Hydrogen Cooling	FEASIBLE	- minimum mass - untested technology - major link with aerospace plane technology
Direct Radiation/ Radiation	NOT FEASIBLE at current operating temperatures	- requires incompatible system topology - enormous mass required
Phase Change	MAY BE FEASIBLE in some form	- enormous mass penalty - requires flowing system - special topology
Liquid Cooling	FEASIBLE	- substantial mass penalty - must exchange to hydrogen bus - considerable complexity

From the above charts, it appears that the following are justified:

- The direct radiation to space and thermal storage techniques are not engineering feasible, and no further research is necessary at this time.
- The liquid coolant loop technique is engineering feasible, but it is more massive and has more redundancy issues than cooling directly by hydrogen.
- The direct cooling by hydrogen is the most promising concept, and it should be pursued with further studies and experimentation.

INTRODUCTION

The advanced weapons concepts envisioned by the SDIO employed a wide array of highly energetic devices, which due to inefficiencies, generate large quantities of waste heat. Generally, they are composed as shown schematically in Figure 2. Power and thermal management are integrally related. In the vacuum of space, disposing of waste energy is a major problem which can contribute as much as 50% to the overall spacecraft mass and volume. The problem becomes more acute as the temperature at which the energy must be rejected is lowered. In an earlier study¹, thermal management issues associated with megawatt class RF microwave tubes were explored to determine if there were simple, approximately mass neutral schemes which might be adapted to dispose of the waste energy generated within a tube collector operating in space. The assumptions for that study were:

- Tubes were in the megawatt class-70% efficient for single simple collector and 90% efficient for depressed collectors.
- On-board, super critical hydrogen was available at a pressure of 35 bars and a temperature of 35 K.
- The largest single event run time was 500 seconds.
- The device would be dormant for long periods of time, be required to become active in tens of seconds followed by long periods of dormancy.
- The only allowable effluent is hydrogen.
- System impact must be minimal.

Figure 2 Block diagram showing interrelation between various components of the power system.

A cursory examination of the problem quickly reveals that there are only three possibilities for accomplishing the task, i.e. radiate the energy to space, a commonly accepted practice, store the energy on-board, and discard the waste energy in the kinetic energy and temperature of an acceptable effluent. That study produced several "acceptable" schemes which could be used because their system impact, at first glance, was acceptable, and suitable experiments for "proof-of-principle" are progressing.

Since solid-state RF sources are a viable technology for applications similar to those envisioned for microwave tubes, a similar study was needed to identify the techniques which might be employed to remove waste heat from multi-component modules made up of solid-state devices.

It is important to establish some of the differences between solid-state and vacuum tube RF sources since these differences play heavily on the technology which might be employed for thermal management. First, single unit vacuum tubes are capable of megawatt output with efficiencies between 70 and 90%. Solid-state units would employ an array of some 2000 individual transistors with a collective efficiency of 60-75%. Secondly, the waste energy produced by the vacuum tube is clearly separable from the RF conversion section of the device. The waste energy and RF production are essentially co-located in the junction of the transistor. Thirdly, the maximum temperature at which the waste energy can be rejected for the vacuum tubes is some factor of 4 greater than that of the solid-state device. Finally, the vacuum tube technology tends to demand high-voltage, low-current power conditioning while solid-state devices need high-current, low-voltage sources which may not need power conditioning at all. The apparent lack of the necessity for complicated power conditioning and operation at low voltage are very

attractive features with major system implications. One of the most interesting aspects is the apparent opportunity to segment the power supply.

The assumptions for this study were again similar to those for the microwave tube study.

- The junction temperature must not exceed ± 200 C.
- On board hydrogen is available at whatever flow rate, temperature, and pressure that is consistent with cooling the accelerator.
- The longest continuous run time is 500 seconds.
- Technology employed must have minimal system impact.

Individual transistor units in the module are capable of power levels on the order of 500 watts at efficiencies from 65-80%. At that level 125-270 watts of waste power must be dissipated. Note that the area in which the RF is produced is only a few millimeters wide, and power densities greater than 2000 W/cm^2 must be handled by the thermal management scheme. Figure 3 places in context the magnitude of this problem with respect to other widely recognized thermal events.

The contradictory requirements of high heat dissipation and "low" temperature rise limit the technologies which can be employed and force tradeoffs which add mass to the system. Since cost-to-orbit is a major part of any spacecraft system study, innovative techniques which might be able to handle the high thermal flux with minimal mass penalty are indeed a priority item.

In this study, we have examined direct radiation concepts, thermal storage concepts, liquid coolant loops, and direct cooling by using on-board hydrogen. Each of these approaches is evaluated in terms of feasibility, systems impact,

Figure 3 Comparative heat flux for energetic events.

and level of technological understanding. The remainder of this report details our findings.

METHODOLOGY

Due to significant variations in the packaging/construction details of individual solid-state devices, the thermal characteristics of an individual unit is described in terms of overall thermal resistance, θ . This quantity is described as:

$$\theta = (T_j - T_r)/Q \quad \text{K/W-m} \quad (1)$$

where T_j is the operating device junction temperature, T_r is the rejection temperature of the waste energy, and Q is the thermal energy flux which must be removed. Since failure rate is highly sensitive to temperature, θ is usually kept as small as possible, and because the transistor construction involves a number of materials with differing thermal properties, the thermal resistance as defined in equation 1 may have a number of terms characteristic of the substrate used, thermal spreader, bonding agent, coolant properties, etc. To make the problem tractable, without the extensive use of computers, the problem is usually simplified to one dimension. While not as accurate, this approach allows an easy calculation of the relative merits of each technique and suffices to yield "first order" calculations of necessary parameters such as flow rates, radiator sizes, etc.

Conductive thermal transport in one dimension is governed by the Fourier relation:

$$Q = k A \frac{\Delta T}{\Delta x} \quad (2)$$

where Q is the heat flow, k is the thermal conductivity of the media in which thermal flux exists, A is the cross sectional area and $\Delta T/\Delta x$ is the thermal gradient in the direction of heat flow. As noted earlier, there is structure in the junction so that the equation 2 can be written as:

$$Q = \frac{(T_j - T_r)}{\sum_c (\Delta x / k A)} \quad (3)$$

where the sum is to indicate that several materials might be involved. Substituting into equation 1,

$$\theta_{jr} = \sum_c \Delta x / kA \quad (4)$$

Equation 4 clearly shows that the thermal resistance associated with the path from the junction to the rejection point can be drastically affected by choice of materials, number of materials (layers of solder, adhesions, thermal spreaders, etc.) and their thermal conductivity. The external resistance, i.e. the explicit thermal resistance of the remainder of the thermal management suite, is technique specific and will be discussed in the appropriate appendices.

For each task/method explored, the open literature was extensively reviewed and interpreted in terms of systems concepts as described in the CARDS, SPAS, Proceedings of the RF sources workshops, and the NPB/FEL symposium. In this way, each technique explored always had a "system focus" insofar as the systems were defined in the above referred material.

Finally, several discussions were held with members of the Independent Evaluation Group for the Strategic Defense Initiative (IEG) both at SANDIA and NASA Lewis on various system aspects and the state-of-the-art of some of the component technology. In selected areas such as hydrogen permeation, low temperature operation, and packaging, individual experts from a number of laboratories were actively consulted, and their publications were extensively researched through open literature sources.

RESULTS BY TASK

TASK I: RF THERMAL REQUIREMENTS

The establishment of thermal requirements is a very complicated task due to the difficulty of determining the temperature at which the junction of a solid state device is operating. In the course of this work, we have followed simple one dimensional models, consulting wherever available, more sophisticated two dimensional treatments.^{2, 3} These models were augmented by the experimental work of Bennett who used an Infra-red thermography unit to determine the actual operating temperature of a transistor junction.⁴ In general, the temperatures measured showed that junctions could operate at a temperature of 350 K and might operate at a maximum temperature of some 500 K. Work discussed in Appendix C shows that some of these same devices work quite well at temperatures on the order of 77 K.

The results described in Appendix A, clearly show that direct radiation and thermal storage concepts are impractical operating within these temperature extremes. Therefore the thermal requirements called for in this task tend to apply to "fluid cooling." Two options exist - use liquids such as water, Freon, etc. and to use the supercritical hydrogen available after it has been used to cool the accelerator structure. The use of liquids such as water to cool high density integrated circuits is standard practice and was used to cool the SPS-40 radar. A comprehensive review of the literature yielded some 300 readily available technical articles which describe this technique. The single most valuable article, and references therein, describing the state-of-the-art is a major review article by Bar-Cohen which details the results of cooling several

major chip types from a series of manufacturers.⁵ Since the application was terrestrial, there was little concern for mass and volume. Consequently, heat spreaders built into heat sinks with macroscopic flow channels were in general employed. For space applications, mass and volume are at a premium and there is far more interest in higher power levels with the associated higher heat flux to be removed from the junction. As a result, a number of investigators have considered the application of microchannels with and without heat spreaders to more effectively handle the large heat flux associated with high power devices.^{6, 7, 8, 9} For this study, we have assumed that microchannel technology will be employed to cool the RF structures independent of the cooling fluid. This technique is briefly described in the appropriate appendix and in detail in the references.

In order to specify a design, it is necessary to assign an operating junction temperature, a ΔT swing allowable within the coolant, and the coolant itself. Several cases are considered in detail in the appendices and some typical results are quoted to illustrate the wide range of possibilities. Table 1 lists coolant flow rates and "head pressure" for a variety of coolants, which are necessary to remove some 3.5 kW of waste thermal energy from an 8 kW RF module.

Assuming "normal hydrogen," if the temperature is allowed to swing by only 5 K, the pressure drop and flow rates do not appear to be remotely practical. If the temperature swing is allowed to be on the order of 100 K, the pressures and flow rates still do not appear practical. As shown in Appendix B, cooling appears possible with supercritical hydrogen. It is fair to say that a ΔT on the order of 50-150 K will be necessary. The final driving pressure will be determined by friction losses, etc. in the connecting plumbing. Until a detailed design of the system is complete, it is only possible

Table 1 Coolant, coolant flow rate, and head pressure for chip with microchannel cooling scheme.

Coolant (5°CΔT)	Flow Rate (Gal/Min)	Pressure (psi)
Water	1.34	55.5
Liquid Nitrogen (70°K)	3.44	42.3
Hydrogen Gas (35°K)	• 5675	12509
• 32 gr/sec.		
Coolant (100°CΔT)	Flow Rate (Gal/Min)	Pressure (psi)
Hydrogen Gas (35°K)	** 284	625
** 1.6 gr/sec.		

to estimate the necessary pressure to sustain adequate flow through the microchannel plates.

There are definite efficiency-temperature tradeoffs which can be made in the choice of what temperature to use when designing a system. In order to obtain an estimate of the amount of the supercritical hydrogen needed to cool a module, it is necessary to estimate both the enthalpy available in the hydrogen as a function of the temperature rise, and the efficiency of DC to RF energy conversion. Figure 4 is a calculation of the enthalpy as a function of temperature swing starting from the approximate conditions for the supercritical hydrogen as it exits the accelerator. The calculation assumes that the specific heat of the supercritical hydrogen C_p is constant at 25 kJ/kg-K. Obviously, the ability to cool using the supercritical hydrogen is strongly dependent upon system imposed constraints for the allowable temperature swing. The constraint in task I is concerned with the junction temperature. If the thermal resistance can be kept quite low, coolant swing can be as high as 150 K. In that case, each kilogram of hydrogen could absorb 3.75 megajoules of waste thermal energy.

Figure 5, taken from Appendix C shows the efficiency of conversion for bipolar transistors over the temperature range 30 C to -180 C. Clearly, operating at lower temperatures can increase the efficiency by as much as 20%. At the Prospector I workshop, it was shown that similar increases in efficiency could also be achieved using Static Induction Transistors (SITS).¹⁰ From a systems point of view, several factors will determine the choice of operating temperature:

Figure 4 Supercritical hydrogen enthalpy as a function of change in temperature.

Figure 5 Bipolar transistor efficiency and power output versus cold plate temperature. Refer to Appendix C for further details.

- The allowable delta T swing must provide sufficient enthalpy for the waste heat load.
- The delta T swing must be compatible with other system cooling requirements such as the conductors, conditioning and fuel cells.
- Decreased conversion efficiency translates immediately to added fuel load.

These and other issues will be discussed in detail in the discussion of the results of task III.

TASK II: RF MODULE REQUIREMENTS

This subject is considered in detail in the Appendix C. The factors which govern choice of a module size depend upon many system issues. Some of the most important are:

- Single unit transistor power
- Operating voltage and current desired
- Thermal management technique employed
- Power conditioning required
- Output configuration
- Module specific power
- Absolute module power

The state-of-the-art in single device RF transistors is in the range of 200-500 W with device efficiency in the 70-80% range.

If sufficient funds are available, that number may increase and approach 1000 watts in a single device. If there is not a simultaneous increase in efficiency, the thermal load per transistor will also double, thereby complicating the thermal management problem even though the total waste energy which must be disposed of is essentially the same.

In most of the designs of large space based weapons concepts, the basic module seems to be on the order of 1 MW RF as a building block. This block is associated with a specific section of the accelerator and feed point such that the accelerator can be made modular with a specific accelerator gradient as one moves down the machine. From the point of view of this study, it is necessary to choose a module which will minimize the plumbing necessary to distribute coolant to the components of the module, provide a convenient

exit so that the coolant can be routed to a heat exchanger or further distributed to other users, be compatible with the RF feed system to the accelerator and easily connected to the DC power system. Further the module operating voltage must be compatible with estimates of the capability of contemplated power supplies.

As discussed in Appendix C, based upon prior work for the USAF at the Wright Patterson Air Force Base, single transistors with efficiencies of 85% at 425 MHz, 75% at 850 MHz and 500 W output are near term state-of-the-art. Further, these transistors have been shown to be capable of operating over the temperature range as specified in task I. There are a number of configurations which could be used to package individual transistors into an acceptable building block for a total unit. Figure 6 illustrates several which were considered in this study. Note that it is possible to use many materials in the construction of the package. Table 2 in Appendix C clearly shows factors of two reduction in the thermal resistance are possible over readily available technology if diamond thin films could be used in the module construction. Artificial diamond thin film production capability is far from ready to be used in a manufacturing process even though laboratory prototypes of suitable thin films have been made by a number of laboratories. A concerted effort with appropriate funding could make this technology available in 10 years or less. As a compromise between producability, cost, and performance, a silicon/BeO pill package directly mounted to a microchannel plate as shown in packaging design f in figure 6 was chosen for the fundamental unit. It is unclear at the moment whether or not thermal-induced mechanical stresses would limit this design. The results of our calculations indicate that this design in its preliminary form is marginal for use at 35 K inlet temperature but should perform acceptably at higher temperatures.

Figure 6 Options for packaging RF transistors.

A 500 W transistor package using design f is approximately 1.02 cm (0.4") x 1.27 cm (0.5"). Four of these units in a linear array provides 2000 W in a package approximately 6.35 cm (2.5") x 7.62 cm (3.0"). This is considered as demonstrated laboratory technology and successfully operated at 77 K. Two units mounted back-to-back as shown in design f, figure 6 with a microchannel plate with fin dimensions on the order of 0.127 cm (0.05") forms a basic 4 kW unit. As discussed in Appendix C, this module would have the following characteristics:

Output Power	4 kW, CW
Gain	12 dB
Frequency	425 MHz
Efficiency	80%
Base temperature	35-90 K
Mass	170 grams (6 oz.)
Volume	90 cm ³ (5.5 in ³)

All individual transistors will be cooled in parallel from a central plenum to minimize both the temperature gradient across the module and the amount of plumbing necessary to distribute the coolant. As discussed in Appendix C, four of these modules can be combined to provide 20 kW. Adding an RF input/driver stage, and protection network produces a package with the following approximate dimensions: Length, 22.86 cm (9.0"); Width, 10.16 cm (6.0"); Height 12.70 cm (5.0"). The weight of the package is approximately 1.8 kg (64 oz.), and operates at a projected efficiency of 71%. The projected input parameters for this module operating at 20 kW RF is 250 volts and 112 amperes. If the unit is operated at 20 kW input, the nominal RF output would be on the order of 16 kW with the current necessary dropping to approximately 90 amperes. These levels are compatible

with projected output parameters for both rotating machinery (homopolar generators) and electrochemical (fuel cells) prime power sources.

Assuming that it is desirable to feed the RF to the accelerator symmetrically from two points, a 500 kW module becomes the RF unit associated with an accelerator basic building block. Combining the above into a possible 500 kW module gives the following projected parameters:

32, 20-kW amplifiers	721.12 kW
Loss in output combiner	12.05 kW
Loss in input splitter	0.03 kW
Total power into control amplifier	1.4 kW
Total input power	722.52 kW
RF power output	500.00 kW
Control amplifier output	0.70 kW
Total power dissipation	222.52 kW
Efficiency	69.2%

In order to estimate mass of the unit, it is necessary to specify materials used in such parts as the cabinet, control structures, power distribution, etc. Consequently any estimate of total mass for a finished 500 kW amplifier unit is based upon a terrestrial version and not on a space rated version. As noted in Appendix C, the amplifier module would weigh in packaged form:

Cabinet structure	22.72 kg (50 lbs)
Output combiner	18.17 kg (40 lbs)
32, 20-kW amplifiers	58.16 kg (128 lbs)
Control amplifier	2.27 kg (5 lbs)
Coolant distribution	27.26 kg (60 lbs)
DC distribution and controls	18.17 kg (40 lbs)
Miscellaneous	0.91 kg (2 lbs)
Total	149.93 kg (330 lbs)

The above masses can be used to provide engineering system indices which can be used to estimate the contribution of the RF power to the total spacecraft weight and volume:

500 kW module volume	$2.51 \times 10^5 \text{ cm}^3$
Volume power density	1.99 W/cm^3
Mass power density	0.3 kg/kW

In calculating the above parameters, it is somewhat suspect to use a cabinet structure typical of a ground installation for the estimates of weight and volume. In addition, the 32 basic amplifiers constitute the largest contribution to the mass of the 500 kW module. If thin film diamond or BeO alone could be used both to form the substrate for the chip and also the microchannel plate, the basic unit mass would be decreased substantially. This would ripple throughout the other component mass estimates and at present cannot be given with any confidence. Our best guess is that it might decrease the total mass of the 500 kW module by 15-20%.

The same analysis can be done on a basic module operating at 850 MHz. The primary difference is the decreased efficiency. Table 2 in Appendix C is a summary of module requirements as called for in task II.

TASK III: SPACE PLATFORM REQUIREMENTS

The results of task IV clearly indicate that any coolant scheme which can hope to keep the total spacecraft mass within bounds is based upon "fluid" coolants. It is within that framework that the effect of the coolant scheme on the space platform is evaluated. In keeping with the assumptions mentioned in the introduction, the only allowable effluent assumed is hydrogen. Further for this section, it is assumed that the hydrogen will be used to directly cool the solid state modules without the need for an intermediate coolant loop. The basic rationale justifying this assumption is that first and foremost, we must dispose of the waste heat in the hydrogen effluent. Secondly, a secondary coolant loop will require heat exchange twice, with the requisite pumps to maintain coolant flow. Thirdly, secondary coolant loops require constant feedback to keep the coolant liquid from freezing in the heat exchanger and finally, the added complexity of the secondly loop will require some form of redundancy to eliminate single point failure in a number of the components of the secondary loop. As discussed in task IV, this technique can not compete with the direct cooling by hydrogen in terms of mass due to the added mass of the coolant fluid, the associated plumbing, and the necessary heat exchanger.

Figure 7 is a block diagram of a possible version of a neutral particle beam (NPB) weapon system consistent with today's planning. The highest frequency contemplated today is 850 MHz which is within the capability of solid state RF sources. Referring to figure 7, cryogenics are delivered to the thermal management system and prime power source depending upon the specific scheme employed. The cryogenics employed are hydrogen and oxygen. The oxygen, of course, is used only as an oxidizer in whatever scheme is used

Figure 7 Neutral particle beam (NPB) schematic.

to power the platform. The hydrogen however is used to cool the accelerator/beam management system, RF sources, any coolant needs associated with the power distribution system, and as fuel in the prime power unit. This diverse use of the hydrogen requires that special attention be paid to the thermodynamic state of the hydrogen as a function of "where it is in the system." As a result, there is a hierarchical scheme for utilization. In order to keep the total amount of hydrogen in bounds, and to avoid unacceptable flow velocity, it is utilized (after storage) in the supercritical state.

In storage, the hydrogen is kept at approximately 20 K. It is first sent by the distribution system to cool the accelerator components as shown in figure 8. The pressure is boosted to some 30 bars and the temperature is allowed to rise to 35 K. The flow rate from the accelerator is about 18 kg/s. At 35 K, there is still enormous enthalpy available to be used for cooling. The next major thermal requirement is obviously the RF source modules as discussed in the previous section. The input thermal parameters to the RF section are the output thermal parameters from the accelerator. It is obvious that care must be taken at the output from the RF section to allow cooling of "whatever else" needs the hydrogen. There are several possibilities. The prime power source, the ion source, the beam neutralizer, the power conditioning/distribution system, and the effluent management scheme will certainly have some cooling requirements. For the study, we assumed that the system would be powered by fuel cells. Figure 9 is a more detailed schematic than that given for prime power shown in figure 7. Also included in figure 9 is a state table which lists flow rates and temperatures at various parts of the prime power/effluent management system. If as indicated in this report and from the results of Prospector I, a temperature swing of about 100-150 K is necessary to cool effectively the solid state RF section, there could be serious conflict

Figure 8 Schematic of NPB components which must be continuously cooled.

Figure 9 Fuel cell diagram and state table for a 10 MW NPB power system.

with the requirements associated with the fuel cell and the heat exchanger necessary to remove the waste water produced in the fuel cell.¹⁰ The output temperature from the solid state devices is in the range of 135-185 K. The table in figure 9 lists four state points which fall within this range. These are all associated with the heat exchanger and if this method of providing RF power to the accelerator is chosen, the heat exchanger will have to be redesigned to take into account the higher inlet temperature. Further, since the temperature associated with the other state points are governed by the inlet temperature at state point 1, the whole system would have to be changed to take this increase into account. Conversations with power engineers working with the IEG indicate that this is not a particularly difficult task and is unlikely to be a major complication. Note that at state point 3, most of the hydrogen on board the craft is thrown overboard as effluent, indicating clearly that most of it was on board for cooling anyway. Ample hydrogen would certainly be available at state point 2 or 3 for cooling the other items mentioned above, providing they did not require the hydrogen to be at a temperature below that necessary at these points. At present there are no detailed "thermal maps" which would allow a clear resolution of the correct way to use the available cooling capacity of the supercritical hydrogen. The design of the fuel cell system, outlined in figure 9, is for a 10 megawatt NPB system. An explicit assumption is that a similar system would be applicable for a unit required to provide power to a 1 megawatt RF module.

Figure 10 is a block diagram which illustrates relative layout of components for an NPB system.¹⁰ In the figure, power conditioning and prime power are discrete with a distribution system to carry power to each of the RF modules. If the power system is fuel cells, it is reasonable to segment the power system and combine it with each of the RF amplifiers. In that

Figure 10 Block diagram of a NPB device with power and cryogen fuel source.

configuration, the distribution system is simply plumbing from the accelerator coolant output to the RF amplifiers and the fuel cell modules. The cryogenic tank holding the oxygen would have to have a distribution line along the edge of the RF amplifier units with a feed to the local fuel cell. Figure 11 is a drawing of a fuel cell-RF amplifier arrangement designed to encircle the accelerator module powered by it. It would be equally valid to use a single unit as shown in figure 10; however, the configuration in figure 11 minimizes both electrical conductor, tubing to carry hydrogen, and plumbing associated with removal of waste water that would have to be carried to state point 12. It is not clear whether or not a central heat exchanger would be necessary for water condensation or if each separate 1 megawatt module would need its own heat exchanger. The minimal plumbing required by this module design also minimizes the pressure drop associated with line length and "bends and turns" in the line.

At the Prospector I workshop, loading of the cryogen distribution system was determined to be a potential problem which must be considered before a basic system layout could be realized.¹⁰ Appendix B contains a preliminary treatment of that problem. In the appendix the relation between initial and final pipe temperature, pipe dimensions (both length and diameter), the pipe fill rate, and necessary venting are discussed. It is clear that by venting, the cryogen distribution system temperature can be brought to the appropriate temperature for distribution to the RF sections within acceptable stress limits. There are several factors which must be considered within an overall system context but cannot be evaluated until a specific design is available. The most serious of these factors are:

Figure 11 Conceptual power module combining 1 megawatt RF, 1500 kW fuel cells, and one accelerator section.

- Several additional valves will be necessary to control venting as lines cool.
- The mass of the hydrogen needed to cool the distribution system will depend on plumbing dimensions which are specific to a particular design.
- Acceptable cooldown rates may influence NPB start-up sequence.

As indicated in Appendix C, a 500-kW RF module needs some 721 kW DC power input. The size of that module was estimated to be some 91.4 cm x 43 cm x 63.5 cm, which is compatible with accelerator cavities on the order of 1 meter in diameter. The IEG field support team estimates that fuel cell specific power densities on the order of 0.182 kg/kW are near term state-of-the-art. Further, they estimate that the far term state of the art will yield units with power densities of 0.045 kg/kW. A near term fuel cell power module would then weigh on the order of 130 kg and a far term comparable unit on the order of 33 kg. The near term art adds mass comparable to the RF unit itself while the far term unit is much less than the RF unit mass. Early studies by Verga indicate that compact fuel cells can be arrayed to provide the appropriate V-I characteristics in packages comparable in dimensions with the RF module which lends credence to the basic power-RF package proposed in figure 11.¹¹

The RF feed system to the accelerator cavity is likely to be highly complex. Since the accelerator must be cooled in a state of dormancy, the feed system could represent a major "thermal leakage path." Since the dormant time is much longer than any active test time or weapons operating time, it is

probable that the RF feed/RF coolant line as shown in figure 11 will be a total "disconnect." The exact nature of a feed system is beyond the scope of this study. However, the proposed geometry is compatible with scaled dimensions from other studies. Referring to figure 9, the cryogenic oxygen must receive some preheat prior to entering the fuel cell. Simultaneously, water is available at state point 9 at 436 K. The heat exchanger shown in figure 9 necessary to preheat the oxygen could simply be intimate contact between the waste water line and the incoming oxygen line. The total mass of the 1 megawatt module minus the accelerator cavity is on the order of 281 kilograms in near term and 183 kilograms utilizing projected far term technology. There would however be little system penalty for making a single 1 megawatt unit with a single feed point system as shown in figure 10.

The modular approach described above has several advantages when compared with other methods of powering solid state RF sources. Some of these are:

- modular power easily segmented
- minimizes RF feed system
- minimizes DC distribution system
- minimizes plumbing necessary for coolant transport
- minimizes pressure losses in plumbing.

TASK IV: APPLICABILITY OF ALTERNATE COOLING TECHNIQUES

In this task, several coolant schemes which at first glance appeared capable of providing the requisite thermal management were considered.

Specifically, the following were considered:

- Direct radiation to space
- Thermal storage
- Liquid cooling
- Direct cooling with the on-board Supercritical Hydrogen

Each of these techniques are considered in sufficient detail in an appropriate appendix to assess practicality in light of systems studies such as SPAS, CARDS and the NPB/FEL workshop results. In addition, there were two aspects of cryocooling of the RF sources which deserved special attention. The problem of how to bring the cryogenic distribution system to the same temperature as the cryofluids in an acceptable time and the problem of permeation of hydrogen through the materials used in the construction of the modules. Both of these problems are considered in separate appendices in sufficient detail to allow their consideration in the next design phases.

The results of this task are as follows:

Both the direct radiation to space and thermal storage techniques, while not excluded on the basis of physics, are grossly impractical due to system impact in terms of weight and volume. Further, if they were "the only way," specific circuit topologies, power distribution systems, and accelerator geometries would have to be considered which are far beyond the scope of this study.

Cooling by liquids is quite feasible and had essentially been established due to the work of Bennett and others.^{2, 4, 5, 6} There are however several salient

points which must be considered in any decision to implement that technique. While it does not require the major mass penalties associated with direct radiation and thermal storage, there is a considerable penalty in the form of pumps, secondary coolant, distribution system and an extra heat exchanger. Further, complicated feedback controls would be necessary to ensure that the secondary coolant did not freeze up in the heat exchange to the hydrogen bus. It was also determined that the start up sequence would be influenced by the necessity to interface the cooldown of the hydrogen distribution system with the dynamics of the coolant loop. At the moment, that does not appear to be an insurmountable problem. Insufficient detail was available to evaluate that problem. It was decided to confine the study to single phase flow, although it was recognized fully that nucleate boiling/mist impingement techniques are capable of higher cooling rates than single phase techniques. That decision is based upon the following:

- Condensation and subsequent heat exchange into the hydrogen bus is still necessary.
- Pumps are necessary to circulate the coolant.
- Dynamics of two phase flow in 0-g are poorly understood.
- Unclear how to eliminate hot spots or implement without heat spreaders due to the unusual nature of the concentrated thermal waste.
- Only potential mass savings would be in the volume of the coolant which is insignificant in comparison with other components.
- Specialized circuit topology would be necessary to implement.

Direct cooling by hydrogen appears to be the most promising of the techniques to employ if mass, minimal system complexity and minimal "moving parts" are the dominant drivers. Appendices B and C establish first cut designs and tend to bound the parameter space in which the technique would appear feasible. Three major concerns were identified and subsequently scoped.

TASK V: SUPPORT OF PROSPECTOR I
(A Workshop on the Thermal Management of Space Based RF Sources)

Under the joint sponsorship of the Space Power Institute, Rome Air Development Center, Los Alamos National Laboratory, and the Wright Research and Development Center/WPAFB, a workshop to assess the problems of thermal management in the space environment was held at the Prospector Hotel and Conference Center in Park City, Utah. The meeting was four days long and had as its primary objectives the assessment of the state-of-the-art for the thermal management of space based high power RF sources, research issues which might allow further advances in the art, and experiments which could be implemented, with a minimum of funding, to provide proof-of-principle verification.

As authorized in task V, support was provided to the workshop organizers in the form of technical report preparation, technical editing and report typing, and report reproduction. This report will be published as a Space Power Institute technical document and distributed to the attendees in late August. The report will also be made available to interested researchers through recommendations by the sponsoring agencies. A brief summary of the principal conclusions of Prospector I are included in this report as Appendix D.

CONCLUSIONS AND RECOMMENDATIONS

Following the procedures established in reference 1, the techniques for cooling solid state RF sources in the megawatt range were evaluated. The results of that evaluation are presented in the executive summary.

Since direct radiation and thermal storage do not appear to be remotely viable techniques, the waste energy must be disposed of in the form of added energy to the cryogenic hydrogen initially stored and maintained with the platform. There does appear to be sufficient enthalpy in the hydrogen to handle the thermal management task. However, there does appear to be some conflicting requirements from a systems point of view, which may necessitate minor redesign and some weight penalty.

The secondary coolant loop approach to the problem will probably be considerably heavier than direct cooling by the hydrogen. The extra heat exchanger, the secondary coolant itself, the pumps and plumbing will necessitate complex controls with feedback and introduce the need for redundancy to prevent high probability single point failure modes. However, this technique is closer to standard operating practice and as such is well understood and within the current art if heat spreaders and cold plates are employed. Use of these components add unnecessary mass penalties which could be rectified by the proper design of microchannel plates and the use of advanced materials.

As a follow on to this study, it is recommended that further research be conducted to:

- Establish in as much detail as possible, thermal maps of selected NPB/FEL weapons concepts

- Continue research and exploratory development of microchannel cooling technology using advanced materials
- Continue exploratory development of solid state RF technology both to improve efficiency and single-unit capability
- Establish operating limits in both the high temperature and low temperature regime
- Continue system integration studies to minimize distribution networks for power and cryogens
- Construct detailed computer models to evaluate stresses induced by the temperature gradients
- Build "best design" modules with microchannel plates and operate with supercritical hydrogen coolant.

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APPENDIX A

ALTERNATE COOLING CONCEPTS

Direct Radiation to Space

Thermal Energy Storage

Liquid Coolant Loops

M. FRANK ROSE

APPENDIX A

ALTERNATE COOLING CONCEPTS

DIRECT RADIATION TO SPACE

In the microwave tube study, direct radiation to space proved to be an attractive concept for removing the waste heat from the collector structure of the tube. It is worth examining here to see if the same technique could be employed on a similar conceptual basis. Radiation via a suitable structure is the accepted method of long term thermal management of current spacecraft. There are two important differences in accepted practice and the situation envisioned for the NPB/FEL space weapons concepts. First, the amount of waste heat that must be rejected is enormous in comparison to the existing spacecraft needs. Second, the requirements for maneuverability make it highly undesirable to have large linear appendages attached to the main structure.

The radiation from a structure is governed by the Stefan-Boltzmann relationship which governs the radiated energy flux per unit area, E:

$$E = \sigma \epsilon \left(T^4 - T_b^4 \right) \quad (A1)$$

where σ is a constant and has the value $5.6697 \times 10^{-8} \text{ W/m}^2\text{-K}^4$, ϵ is the integrated emissivity, T is the radiator temperature and T_b is the temperature of the local background. Figure A1 is a plot of the above relationship for several emissivities. It has been shown experimentally that emissivity values greater than 0.9 can be obtained by suitable texturing for a variety of materials (See reference 1 in general text). In the section on tasks, the allowable

RADIATED POWER DENSITY VS TEMPERATURE AND EMISSIVITY

Figure A1 Power density which can be radiated from a planar structure as a function of temperature and emissivity.

temperature limit for the semiconductor were set at a maximum of approximately 500 K. Assuming that limit applies to the junction, the methodology applied in section two would require that whatever radiating structure was employed would have a substantially lower temperature than the junction itself. For the sake of illustration, assume a 500 kilowatt RF module which is 70% efficient. This will require the radiating structure to pass some 215 kilowatts of excess power. Assuming an emissivity of one, a background temperature of 0 K, a radiating temperature of 300 K yields a surface area of 4680 m² to radiate 215 kW. This ignores whether or not there exists materials with sufficient thermal conductivity to allow a temperature gradient of 200 degrees between the junction and the radiating structure. Consultation with members of the IEG field support team and other experts at the NASA LeRC, indicate that radiator structures complete with heat pipe feed systems will have a mass density on the order of 5 kg/m². At that density, the mass necessary for a radiating structure to dispose of the waste thermal energy is on the order of 2340 kilograms. Based upon data supplied by the IEG, the near term state-of-the-art in fuel cells is estimated to be 0.182 kg/kW. The fuel cells necessary to power the module would then weigh about 130 kg. Similarly, based upon the data in Appendix C, the mass of the RF module, employing near term state-of-the-art, is on the order of 150 kg. Clearly the radiating structure would dominate the mass of the module, as well as require a radiator which is 68 meters on an edge.

Weapons concepts based upon RF drives employ a nominal 50 MW of RF power. To achieve that power level, 100 of the modules described above would be needed. The total radiator surface area would be some 468,000 m² with a mass of 234,000 kg. Clearly this is an unacceptable mass penalty. The above system mass and area penalties vary as the fourth power of the

temperature. If the system were to run at lower temperature by a factor of two, the above numbers would escalate by a factor of 16. Conversely, increasing the operating temperature of the radiator by a factor of two would decrease the above parameters by a factor of 16. That would necessitate semiconducting RF power devices to run at temperatures near 1000 K. At present there are no technologies on the horizon which promise that capability.

An order of magnitude improvement of the mass density of the radiator would still necessitate a unit which is too heavy to implement. Even if the radiator weight could be drastically curtailed, the area of the radiator for a given temperature is fixed by equation A1 and therefore still poses a problem in spacecraft dynamics.

While there are no "physics reasons" why a direct radiation to space concept could not be reduced to practice, it is highly unlikely that it would be chosen because of spacecraft constraints in terms of weight and volume, and from our point of view does not warrant a detailed study of the nature of the materials/transport system which would be needed to extract the energy from the module thermal bus to the radiator structure. A detailed analysis would probably require materials with thermal properties far beyond known technology, totally unacceptable circuit topologies, and a massive conductor network.

THERMAL STORAGE CONCEPT

In the initial study of the techniques for cooling microwave tubes, thermal storage of the waste heat was shown to be a viable concept which needed further engineering studies in order to implement an acceptable storage collector (See general reference 1). There are two important factors which must be taken into account when considering the same technology for application to solid state devices. First, the temperature at which the devices must operate is low in comparison to that allowable for a microwave tube collector structure. Second, the power density in the junction of the solid state device is more than an order of magnitude higher than that incident on the surface of a microwave tube collector.

In order to even consider the use of storage techniques, massive thermal spreaders would have to be employed to remove the heat from the active junction and lower the power density to a level consistent with the thermal properties of the storage material. The use of thermal spreaders is not sufficient reason to dismiss the concept if mass is no object. However, due to the economics of space launching, a premium is placed upon low weight and volume. For that reason, it is instructive to see first if there are candidate materials which could store the requisite thermal energy and second, calculate the mass for comparison with the mass of the other system components. If the mass is significantly greater than the amplifier modules, the power supply, and the conditioning system, this alone is sufficient grounds to eliminate thermal storage from further consideration. Thermal spreaders, containers, and pump systems could only increase the mass of the system. Therefore a decision based on the storage material mass represents a "best case."

Figure A2 illustrates conceptually how the technique could be implemented. The geometry of the 750 kW module would have to be configured such that fins could be attached to a heat spreader to allow contact with the thermal storage media. The thermal conductivity and area of the fins would be picked to allow an acceptable value for the thermal resistance of the overall configuration which would keep the junction temperature below the allowed 500 K. Table A1 below lists a representative sampling of thermal storage materials collected from the literature. Several hundred sources were investigated. In general, the best materials, in terms of latent heat of fusion, had melting temperatures far in excess of any contemplated operating temperature for solid state devices. Since there is a limited temperature range over which the solid state devices will operate, it was assumed that the devices operated at a specific temperature and that the temperature swing allowable for the thermal storage material was no more than 200 K. Consequently, the energy stored in the sensible heat is assumed to be negligible.

Table A1
Representative Sampling of Phase Change Materials Which
Might Be Used for Thermal Storage

Compound	Melting Point K	Heat of Fusion kJ/kg
Succinic Anhydride	396	203
Succinic Acid	460	278
1,4 Dihydroxybenzene	449	246
Water	277	333
Glaubers Salt	300	243
Hexadecane	300	242
Paraffins	325	209

Figure A2 Conceptual cooling scheme utilizing thermal energy storage media.

Water, in the form of ice would appear to be the best choice for the purposes of illustration. From an engineering point of view, its properties are well characterized. Assuming the longest run to be 500 seconds, 646 kg of ice would be needed for each megawatt RF module, plus the associated high thermal conductivity fin structure. Recalling that the estimated weight of the megawatt module is on the order of 560 kg, the thermal storage technique would weigh at least 1.2 times the module weight. Using copper fins, a crude estimate of the mass associated with the thermal distribution system is 345 kg, making the mass fraction 1.8. Using these numbers, the thermal storage mass for a 50 MW system with a maximum continuous run time of 500 seconds is on the order of 3.2×10^4 to 9.9×10^4 kg. Further, if the weapon is to be used again, the waste thermal energy must be removed, and the liquid reconfigured around the module as it freezes. Intermittent testing would require cooling to remove minor traces of liquid formed in the multi-second runs. It is however possible that the water could be stored at a sufficiently low temperature to allow periodic testing without the necessity of a phase change. Clearly, the required mass penalty associated with this method is unacceptable. Calculations based upon any of the other media in the table above clearly yield heavier thermal storage requirements and do not warrant further consideration.

The necessity of using a fin structure if this technique of thermal management were considered is clearly evident in the range of thermal conductivities associated with these compounds. The thermal conductivities for all of the organic materials investigated in general fell into the range of 0.1 - 0.3 W/K-m. The thermal conductivity of water is on the order of 0.6 W/K-m. By contrast, the thermal conductivity of copper is some 400 W/K-m. In order to keep an acceptable value of the junction

temperature, an efficient means of transporting the waste heat to the appropriate storage media must be adopted. Copper or diamond would be obvious choices. Diamond in its present state of development is not ready for such applications.

Other phase change concepts.

Phase changes associated with chemical reactions were briefly considered in this study. An ideal choice for consideration is the thermochemical reactions which are endothermic and in which the reaction products are clearly separable. Decomposition reactions of the type $AB + \text{heat} \rightarrow A + B$ are candidates if the reaction can be reversed. Two compounds were considered. Table A2 lists the relevant reactions.

Table A2
Endothermic Reactions Potentially Usable
in Thermal Management

Reaction	Temperature K	Energy Absorbed MJ/kg	Mass Penalty kg
$4 \text{ KO}_2 \rightarrow 2 \text{ K}_2\text{O} + 3 \text{ O}_2$	500 -1000	2.1	10^4
$2 \text{ PbO}_2 \rightarrow 2 \text{ PbO} + \text{O}_2$	500	0.26	9×10^4

The above mass penalty is for a system which operates at 50 MW for a maximum of 500 seconds. If such a system were employed, the oxygen could be used to power the unit and the mass penalty would not be nearly as severe as that indicated in the table above. This technique was not considered further due to the following:

- The reaction temperature range is beyond the operating temperature of the solid state devices contemplated.
- Reaction rate kinetics were not available for this study.
- System implications were unclear, but would require complete redesign.

Thermal storage based upon liquid-gas transitions were also not considered in this study because of the a priori assumption that the gasses would not be allowed as effluents. In order to be a viable concept, the resultant gasses would have to be contained in a suitable container, some means would have to be used to separate the two phases in zero gravity and in the embodiment which might be possible, the gas could be condensed in a heat exchanger and pumped back through the system. In that scenario, this technique would be a special case of a liquid loop system.

LIQUID COOLANT LOOPS

The use of liquids to cool solid state modules is an established art and there is a well established literature (See general references 3, 4, 5, 6, 7, 9) detailing the limitations of the technique. In general, the module to be cooled is mounted on a thermal spreader material, which in turn is mounted on a ground plane. Connected to the ground plane is a coldplate through which the appropriate coolant liquid is circulated as shown in figure A3. If weight and volume are not prime constraints, this technique should be viable over a respectable range of thermal rejection requirements. As the trend to higher packing density increases, the need for more compact thermal management leads to the necessity of eliminating some of the components shown in the figure above. It is possible to remove the cold plate and integrate cooling directly into the ground plane as a first option. This would obviously increase the packing fraction of VLSI.

In their pioneering work, Tuckerman and Pease (general reference 9) showed that the liquid cooling technology described above and in the references cited, could be scaled down to micro-dimensions and applied directly to the back of an appropriate chip. In that work, they were able to remove 0.8 kW from a 1 cm² chip while allowing a temperature rise of 72 C. Using the same technique, a number of investigators (cited above) have been able to remove even greater amounts of waste heat from chips with comparable dimensions while allowing a smaller temperature rise. The basic idea is illustrated in figure A4. Fins with a large aspect ratio are constructed on the back of the chip and a suitable fluid is driven through the channels in the y direction as shown. This geometry obviously provides a rather large surface area for heat transfer from the solid to the liquid.

Figure A3 "Conventional" solid-state cooling scheme utilizing microchannel cooling.

Figure A4 Schematic of microchannel plate.

The performance of the thermal management scheme is characterized by its thermal resistance $\theta = \Delta T/Q$ where ΔT is the temperature rise from the junction of the component above the input coolant temperature and Q is the dissipated power as discussed previously. Since solid state devices are constrained to operate at maximum operating temperatures no greater than 500 K in this study, the thermal resistance plays an important part in the maximum power at which the module can operate. As discussed in the section on methodology, the thermal resistance is the sum of several components. θ_{CO} is due to conduction from the circuits through the chip fine structure and may itself have several parts. θ_{CV} is the contribution due to convection from the "heat sink" to the coolant. In this case the heat sink also serves as a microchannel plate. The last term of immediate interest is θ_{ht} and is due to the heating of the fluid as it absorbs energy while flowing through the heat exchanger.

In order to make θ_{CO} small, it is advantageous to reduce the number of components in the chip to an absolute minimum. In the chip concepts proposed in this document, the active chip is deposited directly on a silicon substrate or with a BeO layer between the silicon and the active semiconductor region. This contribution to the thermal resistance is obviously highly sensitive to the materials selected. Table A3 lists critical material parameters and their temperature variation taken from Bennet's work (general reference 2).

θ_{ht} can be minimized by using a coolant with a high heat capacity and at a suitably high flow rate. θ_{ht} is given by

$$\theta_{ht} = \frac{1}{\rho C_p f} \quad (A2)$$

Table A3

Temperature Dependent Material Properties

Materials	Coefficient of Linear Expansion $\times 10^{-6}/^{\circ}\text{C}$	Density kg/m^3	Heat Capacity $\text{J}/\text{kg}\cdot\text{K}$	Conductivity $\text{W}/\text{m}\cdot\text{K}$	Melting Point $^{\circ}\text{C}$
Beryllium Oxide	12.0	3,030.0	$906.3 \cdot \log(T) - 4141.$	$0.2750 \cdot T^{-1.217}$	1,278.0
Diamond	—	3,520.0	$-4.251 \cdot T + 2048.$	$0.5467 \cdot T^{-1.23}$	3,550.0
Pyrographite	—	1,670.0	$85.59 \cdot T^{0.4302}$	$0.1315 \cdot T^{-1.136}$ $0.5342 \cdot T^{-1.11}$	3,550.0
Graphite	—	1,730.0	$865.5 \cdot \log(T) + 4208$	$-0.0648 \cdot T + 112.5$ $-0.9201 \cdot T + 151.9$	3,550.0
Gold	14.2	19,320.0	$0.04197 \cdot T + 1116.3$	$597.6 \cdot T^{-0.1079}$	1,064.0
Silicon	3.0	2,330.0	$310.8 \cdot \log(T) - 1068$	$0.3409 \cdot T^{-1.355}$	1,410.0
Tungsten	4.5	19,300.0	$14.65 \cdot \log(T) + 47.23$	$-50.4647 \cdot \log(T) + 4$	3,410.0

where f is the flow rate, C_p is the specific heat, and ρ is the density of the coolant fluid. For the purposes of this study, water is the coolant of choice although the methodology applies to any fluid media. The specific heat of water is about 4.2 kJ/kg-K and with reasonable flow rates makes only modest contributions to the thermal resistance.

θ_{cv} is the dominant term in the thermal resistance and can be minimized by appropriate design of the microchannel plates. Referring to figure A4, a microchannel plate consisting of n parallel channels each of length L , height z , and width W must absorb a constant heat flux Q . Following Tuckerman and Pease, the appropriate expression for θ_{cv} is

$$\theta_{cv} = \frac{2}{k_f Nu_{\infty} L W} (W_c \alpha^{-1} \eta^{-1}) \quad (A3)$$

where k_f is the thermal conductivity, Nu_{∞} is the Nusselt number and depending upon the channel shape is between 3 and 9. L , W , and W_c are defined in figure A4. α is the area multiplication factor due to the channels and η is the fin efficiency factor.

θ_{ht} , since it is defined in terms of volume flow rate can easily be redefined in terms of head pressure which must be provided by the appropriate pump:

$$\theta_{ht} = \frac{1}{\rho C_p f} = \frac{24\mu L}{\rho C_p P W} (W_c^{-3} \alpha^{-1}) \quad (A4)$$

where μ is the coolant fluid viscosity, P is the head pressure, and all the other terms have been previously defined. It is obvious that there are many parameters which can be varied to affect a particular design. In order to keep the scope of this work in bounds, it is just as instructive for our purposes to

use Tuckerman and Pease's treatment to provide an acceptable example. An optimized expression for θ is:

$$\theta = \frac{8.01}{W L^{1/2}} \sqrt[4]{\frac{\mu_s}{k_f k_w^2 \rho C_p P Nu_\infty}} \quad (A5)$$

where k_w is the thermal conductivity of the wall material.

Since we have contemplated a microchannel plate made of silicon as a possible substrate in our study, it is again appropriate to use the data from general reference 9 and apply some of the study constraints. For a head pressure of 30 psi (2.07×10^6 dynes/cm²) and with $W_c = W_w = 57 \mu\text{m}$, an aspect ratio of 6.4, Nusselt number of 6 and laminar flow, the value for θ as calculated above is 0.086°C/W . Recalling that θ is also equal to $\Delta T/Q$, a 100 degree temperature rise from the junction to the coolant would allow a cooling rate of 1163 W/cm^2 . The assumed flow rate for this calculation is $11 \text{ cm}^3/\text{sec}$. If a junction rise of 200°C is allowed, the cooling rate is doubled and is on the order of 2.3 kW/cm^2 which is compatible with the estimated thermal flux which must be removed from the 500 kW modules. Note that for this optimization, increasing the pressure by a factor of 16 in equation A5 also yields 2.3 kW/cm^2 while maintaining a junction rise of 100°C . The head pressure is some 35 atmospheres and is comparable to the pressure assumed for the supercritical hydrogen used to cool the accelerator. No attempt was made to see if the structural design used in this section would be able to sustain the required stresses. In Appendix B, L. Chow has shown that the stresses induced at 35 bars in the hydrogen cooling scenario are probably sustainable.

Since the flow rate is directly proportional to pressure, increasing the pressure as indicated above will also increase the mass flow rate by the same fractional amount. The $11 \text{ cm}^3/\text{sec}$ would be $176 \text{ cm}^3/\text{sec}$ —some 10 liters/min. Physically realizable circuits cannot be packaged with the packing factors assumed above. Referring to figure 17 in Appendix C, the 4 kW module has a surface area of 47 cm^2 and generates about 1 kW of waste thermal energy. If the waste energy is concentrated over half that area, and the thermal resistance is maintained at the value given by the Tuckerman and Pease optimization, the flow rates drop to about a liter/sec, while still maintaining a comparable junction temperature. This is consistent with the example given by J. Johnson in Appendix C. In order to estimate the coolant flow needed for a 500 kW RF module, it is necessary to define a distribution system and do detailed thermal mapping of a major sub-module. To first order, it would appear that a mass flow rate on the order of 54 liters per minute would suffice to cool a 500 kW module. Allowing a junction temperature swing of 50 C would reduce that number to about 5 liters per minute --which should be an acceptable number.

Weight Optimization

The following is taken from the study on the cooling techniques for microwave tubes (general reference 1) and was written by Prof. A. Faghri.

The following method can be used to determine the pump power, line sizes, and total equivalent weight of one meter tube length as a function of tube I. D. for transferred heat. The weight penalty for the pump is assumed to be 0.159 kg/W .

The power for the fluid pump is determined by the equation:

$$P_e = \frac{\dot{m} \Delta P}{\rho \eta}$$

where
$$\Delta P = \frac{32f L \dot{m}^2}{\pi^2 \rho g_c D^5}$$

$$f = 0.25 [0.0056 + 0.5(Re)^{-0.32}]$$

$$Re = \frac{4 \dot{m}}{\pi \mu D}$$

$$\dot{m} = \frac{Q}{(C_p \Delta T)}$$

The total equivalent weight of one meter tube length as a function of the tube I. D. is given by the previous equations and the following equations:

$$W_{\text{pump}} = P_e (0.159 \text{ kg/W})$$

$$W_{\text{fluid}} = \frac{\pi}{4} D^2 \rho L$$

$$W_{\text{pipe}} = \frac{\pi}{4} (D_o^2 - D^2) \rho_p L$$

The dimensions of these quantities are as follows:

P_e = Pump power (W)

ΔP = Pressure drop (N/m²)

f = Fanning friction factor for turbulent flow (dimensionless)

Re = Reynolds number (dimensionless)

$\dot{m}$ = Mass flow rate (kg/s)

L = Length (m)

ρ = Fluid density (kg/m³)

ρ_p = Pipe density (kg/m³)

g_c = Gravitational constant (kg-m/N-s²)

η = Pump efficiency (dimensionless)

D = Inner diameter of tube (m)

D_o = Outer diameter of tube (m)

μ = Dynamic viscosity (N-s/m²)

Q = Total heat load (W)

C_p = Specific heat of fluid (J/kg-K)

ΔT = Change of fluid temperature (K)

W = Weight (kg)

Fluid Properties Evaluated at 20 C

Fluid	Specific heat (J/kg-K)	Dynamic viscosity (N-s/m ²)	Density (kg/m ³)
Freon-21	1061	3.7×10^{-4}	1365
Ammonia	4810	1.31×10^{-4}	600.7
Water	4182	9.93×10^{-4}	998.2

To determine an optimum weight design, the procedure is as follows:

- (1) Determine a module design.
- (2) Determine the mass flow rate based on the total heat load and the allowable ΔT of the working fluid.
- (3) Calculate the power equivalent weight for various tubing inside diameters for a unit length of tubing.
- (4) Obtain the weight of the tubing for a unit length.
- (5) Determine the fluid weight per unit length.

- (6) Add the weights of the tubing, fluid and the power equivalent weight to obtain the total equivalent weight per unit length of tubing.

In order to size a pump, it is necessary to determine the total system pressure drop. The major pressure drops occur in the lines and the heat exchanger. The equation for ΔP can be used to determine the pressure drops in straight lines. Various sources contain appropriate multiplying factors to account for bends in the lines, valves, and all other variations from a straight line. The characteristics of a pump are given by means of an experimentally generated curve which relates pump power, flow rate, and pumping pressure (or head).

Further investigations of one-phase loop technology have been rather limited since the completion of the Space Shuttle design and development programs. Most of the current interest in thermal buses resides in the development of two-phase technology. There are, however, development issues that require further effort if one-phase fluid loops are to be used on long-life military missions:

- (1) Fluid leaks
 - a) Redundancy
 - b) Contamination
- (2) Active components
 - a) Metering valves
 - b) Motor/pump assemblies.

The fluid leak issue exists on two-phase loops as well. The question that needs to be addressed is whether to implement a fully redundant fluid loop (which would double the weight for lines and their fluid inventory), or to

provide redundancy only at vulnerable components such as metering valves and motor/pump assemblies. The outcome of this question will have a major impact on the weight estimates for the thermal bus. Even if a loop is fully redundant, it is unlikely that a military spacecraft would survive the potential contamination from hundreds of kilograms of working fluid if there were a leak in the system.

Long-life motor and pump assemblies have been flight-certified for the needs of the Space Shuttle program with respect to mass flow rate, the pressure drop, and the working fluid. Military spacecraft will probably use a different working fluid to minimize the weight and will likely need specialized devices to account for the transient flow rates and the pressure drops. Therefore, it will be necessary to modify the successful Space Shuttle pump designs and to flight-certify them for use in military spacecraft. A large number of flow control valves will be needed to control the flow of coolant into each cold plate.

Since the study so far has dealt only with the removal of excess thermal energy from the solid state module itself, the remaining task is to assume the necessary plumbing to heat exchange into the hydrogen bus. The IEG field support team was consulted on the mass estimates for appropriate heat exchanger since the base line studies call for removing all water from the effluent stream. They estimate near term mass densities of appropriate heat exchangers to be 0.038 kg/kW and far term densities of 0.037 kg/kW. This implies that a 50 MW RF module operating at a total efficiency of 69% would need to weigh some 1850 kg. If subdivided and placed with each of the one megawatt modules, the individual heat exchangers would weigh on the order of 37 kilograms.

A conservative estimate for the mass associated with the coolant loop technique would be from 2-5 times the mass of the amplifiers. This would include pumps, coolant, tubing, heat exchangers and redundancy.

• • • . . More detailed designs can only be performed when a module specifically designed to be cooled by a secondary coolant loop is available.

APPENDIX B

DIRECT HYDROGEN COOLING

Cooling of Solid State Amplifiers with Supercritical Hydrogen

Hydrogen Permeation

Stress Calculations

Blowdown Study - Manifold Cooling

L. C. CHOW

M. FRANK ROSE

APPENDIX B

DIRECT HYDROGEN COOLING

INTRODUCTION

The subject of hydrogen permeation through potential substrate materials was of sufficient interest that two independent studies of the issue were done.

The first, conducted by M. F. Rose, concentrated upon potential deleterious effects due to hydrogen in the junctions, and the second, conducted by L. C. Chow, looked at the permeation rate and how to calculate it. These studies overlapped and fortunately reached the same conclusions. That is to say that hydrogen diffusion into the solid state junctions is not a problem.

Little, if any, occurs at temperatures below 300 K and, if it does, the effect is beneficial. In fact, it is sometimes used in commercial processing of solid state devices to neutralize impurity sites. In addition to the references cited by Prof. Chow, the following should be added:

S. J. Pearton, J. W. Corbett, and T. S. Shi, "Hydrogen in Crystalline Semiconductors," Appl. Phys. A, 43, 153-195 (1987).

A. Van Wieringen and N. Warmortz, "On the Permeation of Hydrogen and Helium in Single Crystal Silicon and Germanium at Elevated Temperature," Physica 22, 849-865, 1956.

The first of these is a major review article with 266 references and contains data on Si, GaAs, GaP, AlGaAs, CdHgTe, and Ge. The second reference is the only one found which investigated the effect of pressure. They found the

permeation rate to be proportional to the square root of the pressure.

Unfortunately, their work was above 1000 C and, therefore, not applicable to the current study. If the rate dependence cited in the above reference in

general holds, the added diffusion does not alter the basic conclusions of this study. Rather than summarize two studies, the remainder of this appendix is as submitted by Prof. Chow.

Cooling of Solid-State Amplifiers with Supercritical Hydrogen

This first progress report focuses on the heat removal capability of supercritical hydrogen (at 35 K and 35 bars) to cool a solid-state microwave chip. A one-centimeter square electronic chip generating 200 W ($= 2 \text{ MW/m}^2$) within the circuitry embedded on its surface is cooled using one hundred microchannels uniformly distributed over the chip width and running the length of the chip. A close-up view of one of the microchannels of width $50 \mu\text{m}$ and height $500 \mu\text{m}$ with a total chip thickness of $600 \mu\text{m}$ is shown in Figure 1. Hydrogen is pumped through the channel at a given inlet temperature and pressure, removing heat by forced convection as it flows through. Depending on the hydrogen inlet temperature and its flow rate, and chip heat generation rates, different chip temperature and stress configurations are expected. Preliminary studies indicate that the use of hydrogen as a microchannel coolant is feasible.

Energy Balance over Control Volume

Heat generated within the circuitry on the chip surface is conducted through the chip and convected at the microchannel walls into the flowing hydrogen. The chip is divided into a number of control volumes in the flow direction. If the area of the heat generating circuitry within the control volume is A_c and the heat generation rate is $Q'' \text{ W/m}^2$, then the energy input into the control volume is,

$$q = Q'' A_c \quad (1)$$

The hydrogen (coolant) is considered as a lumped system. It is pumped through the microchannel at a mass flow rate of $m \text{ kg/s}$. It enters the control volume at temperature T_{in} and exits at T_{out} . Therefore, energy taken up by hydrogen is,

$$q = m C_p (T_{out} - T_{in}) \quad (2)$$

The heat convected to the hydrogen from the chip at the walls of the microchannel can be expressed as,

$$q = h A_{\text{conv}} \left[T_{\text{wall}} - \frac{(T_{\text{out}} + T_{\text{in}})}{2} \right] \quad (3)$$

Here, T_{wall} is the average microchannel wall temperature over the control volume. The heat transfer coefficient which is dependent on the geometry, fluid properties and the flow field is given in the form of the Nusselt number (Kays & Crawford, Convective Heat Transfer, p. 103, 243, 2nd ed.),

$$\text{Nu} = \frac{h D_H}{k_{H_2}} \quad (4)$$

$$\text{Nu} = 5.62 \quad \text{Re} < 2300 \quad (5)$$

$$\text{Nu} = 0.022 \text{Pr}^{0.5} \text{Re}^{0.8} \quad \text{Re} > 2300 \quad (6)$$

where, k_{H_2} is the thermal conductivity, D_H the hydraulic diameter, Pr the Prandtl number, and Re the Reynolds number.

The heat conducted from the circuitry on the surface to the microchannel walls through the chip substrate (silicon in this study) is represented by,

$$q = k_{\text{Si}} A_{\text{cond}} \frac{T_{\text{chip}} - T_{\text{wall}}}{\Delta x} \quad (7)$$

where, T_{chip} is the temperature in the plane of the circuitry and Δx is the thickness of the chip.

Owing to the low operating temperatures of hydrogen considered in this study, its material properties are expected to change considerably as it takes up heat and increases in temperature. Consequently, the above equations are nonlinear with the material properties being a function of temperature, and must be solved iteratively to obtain the temperatures T_{H_2} , T_{wall} and T_{chip} within each section along the length of the channel.

Results

Heat generation rate is set at,

$$Q'' = 2 \text{ MW/m}^2$$

Hydrogen inlet velocity into the channel,

$$4 < V < 25 \text{ m/s}$$

Calculations were performed over a channel length of 1 cm, using 50 uniformly distributed nodes along the length (L). Maximum temperatures are observed in the exit region of the chip and are strongly dependent on the inlet hydrogen temperature and velocity. From Figures 2 to 4, the following trends are noted.

- 1) From Figures 2 & 3, the values of T_{chip} and T_{hydrogen} are very close. This is because the chip substrate has a very high thermal conductivity (the Biot number is small) and hence can maintain a low temperature gradient in the direction normal to the flow.
- 2) The lower the inlet temperature of hydrogen, the lower is the temperature variation within the chip. From Figures 3 & 4, we note that for $V = 4 \text{ m/s}$,

$$T_{\text{H}_2} \text{ inlet} = 35 \text{ K} \quad T_{\text{chip}} \text{ maximum} = 54 \text{ K}$$

$$T_{\text{H}_2} \text{ inlet} = 75 \text{ K} \quad T_{\text{chip}} \text{ maximum} = 174 \text{ K}$$

i.e., for a 40 K increase in inlet temperature, the maximum chip temperature increases by 120 K.

- 3) As the inlet velocity is increased, i.e., mass flow rate of hydrogen through the microchannel is increased, the maximum temperature within the chip falls steeply.
- 4) Pressure drop calculations in the flow through the chip indicate losses of the order of 0.05 to 1 bar as the velocity increases from 4 to 100 m/s.

CONCLUSIONS

- 1) Microchannel chip cooling with hydrogen available at low temperatures is feasible and promising from the thermal point of view.
- 2) Hydrogen is highly permeable. This issue needs further study. However, .. . : . . . the value of the permeation constant of H_2 through silicon as a function of temperature is not available in the literature at this time.

RECOMMENDATIONS

- 1) Further detailed calculations must be performed on a three dimensional chip model to determine:
 - a) The temperature gradients within the chip and channel, and confirm this feasibility study.
 - b) Effect of the temperature gradient on the chip internal stresses, surface stresses and imbedded circuitry.
 - c) Effect of fluid pressure and its changes as the fluid flows down the channel on the stresses within the chip.
- 2) Hydrogen permeation through the chip:
 - a) Leakage containment. One promising approach is to keep the chip at a temperature below 300 K.
 - b) Chemical stability of chip material and circuitry due the the presence of hydrogen.
- 3) Silicon behavior at low temperatures (approximately 50 to 100 K).

SILICON CHIP SECTION OF SINGLE MICROCHANNEL

FIGURE 1

HYDROGEN TEMPERATURE

$$Q'' = 2 \text{ MW/m}^2$$

$$T_{H_2} \text{ at inlet} = 35 \text{ K}$$

FIGURE 2

CHIP TEMPERATURE

$$Q'' = 2 \text{ MW/m}^2$$

$$T_{H_2} \text{ at Inlet} = 35 \text{ K}$$

FIGURE 3

CHIP TEMPERATURE

$$Q'' = 2 \text{ MW/m}^2$$

$$T_{H_2} \text{ at Inlet} = 75 \text{ K}$$

FIGURE 4

Cooling of Solid-State Amplifiers with Supercritical Hydrogen

The present report addresses the thermal management of microwave solid-state amplifiers which are potential candidates for power systems at 425 and 850 MHz. Researchers at Los Alamos National Laboratory have investigated the cooling of extremely high density packaging of rf amplifier modules with a heat removal requirement of about 200 W/cm^2 [1]. The technique uses water as a coolant which flows into the microchannels directly imbedded in the chips. The microchannel concept was first proposed by Tuckerman and Pease [2] in 1981, and is capable of removing up to 1 kW/cm^2 from silicon integrated circuits using water as the coolant. In the previous progress report [3], it was demonstrated that on-board supercritical hydrogen can be used to cool solid-state amplifiers. Even though the heat transfer coefficient is lower for hydrogen compared to water, this deficiency can be more than made up by having a colder heat sink which is hydrogen at cryogenic temperature.

In the cooling of microwave tubes and electronic components with hydrogen at cryogenic temperatures, one major concern is the diffusion and permeation of hydrogen through silicon components and the ensuing effects on the operation of these components. To date, an extensive literature search fails to reveal any information on the permeation of hydrogen through silicon. Only some hydrogen diffusion studies in silicon are found which have enabled us to estimate the permeability rate of hydrogen. However, this estimate is not reliable.

The hydrogen atom is the smallest of all elements (even though in molecular form it may be bigger than the helium atom). Hydrogen is shown to diffuse in atomic form, the molecule being stripped into its atomic form at electronic bonds within the material structure. Hence, it is the most likely to diffuse through even the densest materials. Also because of its ability to electronically bond within the material structure, its effects on material structural [4], chemical [5,6] and electrical [7] properties have been extensively studied.

A number of studies have been performed on the diffusion of hydrogen through different materials. Diffusion is a concentration driven process and is strongly governed by the electronic bond structure, and trapping within the pores and micropores of the material [8]. For example, Petrova-Koch et al.

[9] showed that for hydrogen diffusion through amorphous silicon deposited as thin films, using molecular beam deposition and glow discharge methods, microvoids and columnar structure defects are created. Such defects instigate faster diffusion and permeation.

The study of hydrogen diffusion through silicon ribbons [10,11], single crystals [12] and amorphous silicon [13] have also been studied. Hydrogenation of amorphous silicon has shown to change its thermal and optical properties [14]. Ginley and Hellmer [7] showed that hydrogen diffusion improves thin film and ribbon solar cell efficiencies. The electronic properties of silicon can be improved by the introduction of hydrogen (H), since, the hydrogen atoms interacting with the crystal lattice defects restore broken bonds and thus neutralize the defects, in particular, dislocations. It is suggested that hydrogen can actually improve the material properties of silicon chips by increasing their chemical and crystallographic stability [14-16].

Studies of standing sound waves on hydrogen diffusion in silicon were performed by Bakai et al. [15]. Romanovskii and Vinitskii [4], Nguyen and Kim [17] and Choyke et al. [18] have studied the effects of hydrogen diffusion on the strength of joints and annealing of buried damage layers. Also in the presence of hydrogen it has been shown that phosphorous [19] and boron [20] will diffuse into silicon.

The diffusion of hydrogen into materials such as silicon carbide [21,22], iron alloys [5] and copper [6] may provide valuable information into the sealing/protective capabilities of these materials on the outside of rf sources.

Hydrogen permeates very easily through most metallic [23] and non-metallic materials [24,25]. The permeation rate increases exponentially with increase in temperature. However, at cryogenic temperatures (using data extrapolated to lower temperatures), hydrogen permeation is infinitesimal in most materials [23-26]. If the permeation rates are indeed very low, then the rf tubes and the solid-state amplifiers can be directly cooled with hydrogen because the operation times of these tubes and amplifiers are short.

Hydrogen Permeation through Silicon

On a microscopic scale, atoms or molecules which make up materials occupy and maintain a finite intermolecular space. This interspace is characterized by the crystallographic or amorphous properties of the material, temperature and pressure of the system, and prior history/treatment of the material. The fact that a finite intermolecular distance exists, infers the existence of voids. The size of these voids, i.e., volume and face areas is further related to the intermolecular distribution. The introduction of a gaseous medium on one side of the diaphragm of the material (the diaphragm may be considered to mimic the electronic chip/rf wall), with a vacuum on the other side, introduces not only a concentration gradient but also a pressure gradient across the diaphragm. If the gas molecules are small enough to fit through the intermolecular spaces, and have sufficient kinetic energy to overcome the intermolecular electrical and Van der Waals forces, then they can pass through to the other side of the diaphragm. This process continues till equilibrium in pressure and concentration is reached. This transport of a gas through the diaphragm is called permeation. Hence, attributed to the process of permeation is an activation energy E of the gas molecule which is required to surmount the intermolecular spatial force fields [23]. From experiments performed [24-27] and from kinetic theory [23,26,28], the permeability can be represented by an Arrhenius form of relation,

$$K = \kappa_0 e^{-E/RT} \quad (1)$$

where, K is the permeability, κ_0 is the pre-exponential factor, E is the activation energy in cal/mole, and $R = 4.574$ cal/mole.K. The rate of permeation through a diaphragm of area A (cm²), thickness d (mm), with a partial pressure difference across the diaphragm of the particular gas component of ΔP , is given by,

$$q = K \Delta P^n / d \quad (2)$$

where, q is given in $\mu\text{l}/\text{cm}^2 \cdot \text{hr}$ measured at S.T.P. The exponent n generally takes the value $n = 1$ but for hydrogen with certain metals, $n = 0.5$.

As mentioned earlier, no permeation data for hydrogen through silicon exist. To estimate the time for a given quantity of hydrogen to permeate, an analogy was drawn between the diffusion constant D and permeability K of H_2 - SiO_2 [23] and H_2 -Si [29]. It is assumed that the mechanisms are similar, i.e., the proportionality of the diffusion constant D (cm^2/s) to the permeability K for H_2 - SiO_2 is similar to that for H_2 -Si. From Table 33 (pg. 534) of [23] and [29], we arrive at estimates of K for the H_2 -Si case. It . . . should be noted that these estimates may not be reliable.

Table 1 Diffusion constant and permeability

Temp. K	H_2 - SiO_2		H_2 -Si	
	D	K	D	K
281	5.72E-9	1.30E-5	3.E-11	6.84E-8
322	1.13E-8	8.34E-5	3.5E-10	2.6E-6

Units: D (cm^2/s), K ($\mu l.mm/cm^2.hr.atm$)

The data can be fitted to the expression for the permeation rate ($n = 1$) and the log taken to give (q in $\mu l/cm^2.hr$, for $\Delta P = 1$ atm, $d = 1$ mm, $A = 1$ cm^2),

$$\log q = 5.237 - 3484/T \quad (3)$$

This equation can be used to predict the amount of hydrogen that can permeate through a silicon plate.

Hydrogen Permeation Estimate

Consider a vacuum chamber initially at a pressure p_i . The chamber is separated from a hydrogen source by a silicon diaphragm. After a permeation time τ (hr), the final pressure in the chamber increases to p_f . If the volume of the chamber is V (μl), the temperature of the entire system is maintained constant at T (K), the pressure difference across the silicon diaphragm is ΔP , the area and thickness of the diaphragm is A (cm^2) and d (mm), respectively, then the change in mass of hydrogen in the vacuum chamber due to permeation can be written as (assuming perfect gas laws which are valid under these low pressure conditions [30]),

$$m_f - m_i = (p_f - p_i) \frac{V}{RT} \quad (4)$$

At S.T.P. (state denoted by subscript ∞), the density of hydrogen can be written as,

$$\rho_\infty = p_\infty / RT_\infty \quad (5)$$

The permeation volume flux q at S.T.P. ($\mu\text{l}/\text{cm}^2/\text{hr}$) is given by,

$$q = \frac{m_f - m_i}{\rho_\infty A \tau} \quad (6)$$

This permeation volume flux q is also related to the permeability K by,

$$q = \frac{K \Delta P}{d} \quad (7)$$

where ΔP (atm) is the pressure difference across the silicon diaphragm, and d (mm) is the thickness of the diaphragm. Combining Eqs. 4 to 7, one can get,

$$qA = \frac{(p_f - p_i)V}{\rho_\infty \tau RT} = \frac{(p_f - p_i)V T_\infty}{p_\infty \tau T} = K A \Delta P / d \quad (8)$$

Assume $V = 5 \text{ cc}$, $A = 1 \text{ cm}^2$, $d = 1 \text{ mm}$, $\Delta P = 1 \text{ atm}$, in order to have a pressure increase from 10^{-4} to 10^{-3} torr, the time required at $T = 322 \text{ K}$ is 88 days. At a temperature of 400 K , the time required is only 0.5 day. It is interesting to note the dramatic dependence of hydrogen permeation on temperature.

Conclusion

If the silicon chip is kept below a temperature of 300 K , the amount of hydrogen permeated through silicon is insignificant. This is especially true when the operating time of the chip is on the order of a few hours.

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Cooling of Solid-State Amplifiers with Supercritical Hydrogen

The present report addresses the thermal management of microwave solid-state amplifiers which are potential candidates for power systems at 425 and 850 MHz. Researchers at Los Alamos National Laboratory have investigated the cooling of extremely high density packaging of RF amplifier modules with a heat removal requirement of about 220 W/cm^2 [1]. The technique uses water as a coolant which flows into the microchannels directly imbedded in the chips. The microchannel concept was first proposed by Tuckerman and Pease [2] in 1981 and is capable of removing up to 1 kW/cm^2 from silicon integrated circuits using water as the coolant. In the previous progress report [3], it was demonstrated that on-board supercritical hydrogen can be used to cool solid-state amplifiers. Even though the heat transfer coefficient is lower for hydrogen compared to water, this deficiency can be more than made up by having a colder heat sink which is hydrogen at cryogenic temperature. This study indicates that by using hydrogen as a coolant at an inlet temperature of 35 K and total heat dissipation of 220 W or over 5000 W/cm^2 heat flux densities, heat can be removed and still keep the transistor at a maximum of 126 K. A structural analysis has also been performed. However, the lack of mechanical strength data on the materials prevents a failure prediction to be made.

Transistor Design

The bipolar transistor chip proposed for the 425 MHz solid-state amplifiers has the dimensions shown in figure 1 [4]. Six chips, mounted side by side, are used to form a push-pull 500 W transistor. The central heat sink is made up of silicon ($1200 \text{ }\mu\text{m}$ thick) in which are imbedded microchannels of cross section $120 \text{ }\mu\text{m}$ wide x $1000 \text{ }\mu\text{m}$ high. The silicon microchannel is sandwiched between beryllium oxide plates of thickness 1 mm ($1000 \text{ }\mu\text{m}$). On top of the beryllium oxide plates are mounted silicon chips, six on each side, of individual dimension 1.5 mm ($1500 \text{ }\mu\text{m}$) by 1.28 mm ($1280 \text{ }\mu\text{m}$). Figure 2 is a blowup of a single chip showing the actual active base area in which the heat generation is expected. These active areas number four longitudinal bands of

width 120 μm and length 1500 μm . The rest of the chip is considered to be inactive. For a heat generation rate of 220 W per six chips, the heat flux density of the active area works out to be about than 5000 W/cm^2 . The microchannel bus is designed to have the same pattern as the active areas (makes numerical modelling simpler). Each microchannel is 120 μm wide and 1000 μm high. They run parallel and directly below the active areas of the chips. The walls of the microchannel are thus 160 μm in thickness and run below the inactive areas. In order to do a detailed thermal and structural analysis of the system (computational space and time being limited), the numerical model must only consider a portion of the transistor which exemplifies the processes within. This reduction in physical size allows a higher resolution analysis to be performed, because the control volume can be discretized into smaller elements. Hence, only one face (each face has six chips, as shown in figure 1) of the transistor is modelled, this being a mirror image of the face on the opposite side. Then, a section of the chip is selected (as shown in figure 2) such that the active and inactive areas and a part of the microchannel are modelled. This slice of the transistor can be noted to be symmetrical along the whole width of the transistor. As shown in figure 3, the modelled volume consists of half the width of the active area, plus half the width of the inactive area on a beryllium backing. This is cooled by a quarter of the microchannel directly below the active area. Note that a single microchannel cools two active area bands, one on each chip on either face of the transistor.

Numerical Modelling

The transistor section shown in figure 3 was numerically modelled using the 3-dimensional finite element ANSYS program. The section was discretized into elements. The temperature variation within the transistor is expected to be substantial enough to require the incorporation of temperature dependent material properties. At cryogenic temperatures, the thermal properties undergo large changes and are noted in earlier calculations [3] to be crucial. Hence, the temperature dependent properties of the materials were used if available and are provided in the following tables.

Properties of Silicon

Thermal Conductivity $k = -0.580 \cdot (T - 273) + 175$ W/m.K [5]

Coefficient of Thermal Expansion [6]

Temperature	Coeff. of Thermal Expansion
K	α K ⁻¹
30	-0.07E-6
50	-0.2 E-6
100	-0.4 E-6
150	0.5 E-6
200	1.5 E-6
250	2.2 E-6
300	2.65E-6
350	2.9 E-6
400	3.2 E-6
500	3.5 E-6

Young's Modulus $E = 1.09 \text{ E}+11$ N/m² [7]

Compressive Strength $= 9 \text{ E}+7$ N/m² [7]

Properties of Beryllium Oxide

Thermal Conductivity $k = 304580/T^{1.2425}$ W/m.K [8]

Coefficient of Thermal Expansion $\alpha = 7.1 \text{ E}-6$ K⁻¹ [8]

Young's Modulus $E = 3.04 \text{ E}+11$ N/m² [8]

Tensile Strength $= 1.44 \text{ E}+8$ N/m² [8]

Properties of Hydrogen

Temp.	Viscosity	Density	Specific Heat
K	N.s/m ²	kg/m ³	J/kg.K
30	711E-8	55	2.83E4
50	350E-8	21.4	1.95E4
100	432E-8	8.49	1.23E4
150	572E-8	5.3	1.31E4
200	692E-8	3.85	1.375E4
250		3.0	1.425E4
300		2.49	1.435E4
350		2.11	1.445E4
400		1.84	1.46E4
500		1.456	1.485E4

Heat Transfer Determination

Heat that is generated in the active area of the silicon chip is conducted through the silicon, then through the beryllium oxide and finally into the silicon microchannels where the flowing hydrogen removes the heat at the microchannel walls by forced convection. Depending on the flow rate of hydrogen, the flow can be laminar ($Re < 2300$ [9]), in which case the ability to transfer heat is represented by the Nusselt number as [9],

$$Nu_{D_H} = 6.49$$

or, if turbulent ($Re > 2300$) by [9],

$$Nu_{D_H} = 0.022 Pr^{0.5} Re_{D_H}^{0.8}$$

Boundary conditions

For the thermal analysis, heat losses from the top face of the transistor is assumed to be negligible. Owing to the thermal symmetry of the section selected, all surfaces are set to be adiabatic. Contact resistance at the silicon/beryllium oxide boundaries is minimal. The microchannel walls are set as convection boundaries. Inlet hydrogen temperature is set at 35 K. Heat generation is set at 5093 W/cm^2 on the active area.

For the stress analysis, displacement and rotation at the symmetry boundaries are set to zero. No slippage occurs at the beryllium oxide/silicon interfaces. It is assumed that the transistor is fabricated at 298 K. Due to the difference in thermal expansion between silicon and beryllium oxide, a stress can be induced at the interfaces if the transistor is maintained at a temperature other than 298 K. The surface pressure on the microchannel walls due the hydrogen is set at $35 \text{ E}+5 \text{ N/m}^2$.

Results and Discussion

The inlet hydrogen velocity is assumed to be at 5 m/s, i.e., the total mass flow rate of hydrogen through the transistor (with 12 chips) is 5.8 E-4 kg/s .

Thermal analysis

Figure 4 shows the increase in temperature of the hydrogen as it flows along the length of the transistor. The temperature increase is almost linear with distance. The exit temperature of the hydrogen is 74 K, the temperature rise being 39 K. This can be easily shown to be the case by solving the energy balance,

$$\int \dot{m} c_p dT = \text{energy input}$$

Transistor made of dual material: silicon-beryllium oxide.

Figure 5 shows the temperature variations within the transistor section. Hydrogen enters in at the right hand corner (origin of axis) and exits at the left corner. Note, that no temperature variations exist in the 'X' direction, i.e., perpendicular to the direction of flow. This implies that no temperature variation exists along the width of the transistor, and hence the chips are all at the same uniform temperature. The maximum transistor temperature occurs as expected within the chip region and has a value of 123 K. From this chip location the heat is fanned out to the flowing hydrogen in the microchannel, the temperature of the transistor decreasing away from the chip towards the microchannel in both directions. The temperature of the transistor at the inlet is 64 K, and in the exit region 84 K. It is also noted that temperature variations in the direction of heat flow within the transistor only exist in the vicinity below the chip where temperatures vary from a red 123 K to a yellow 93 K, a 30° temperature drop. In other locations, temperature variations in the thickness direction are minimal. In this temperature range, both silicon and beryllium oxide have comparable thermal conductivities (see property tables). Hence, no sharp temperature variations are noted to occur at the beryllium oxide/silicon boundaries.

Transistor made of a single material: silicon

Within the temperature range of 30 to 150 K, both silicon and beryllium oxide have comparable thermal properties. Conceptually, the beryllium oxide is supposed to serve as a heat spreader and insulator. In fact, at the cryogenic temperatures in question, silicon is as good a conductor of heat. This

implies that it can also serve as a heat spreader. Thus, if the whole transistor is made of silicon, the average temperature variations in the structure should be similar. To confirm this, numerical experiments were performed for the same geometry as for figure 5, but, replacing the beryllium oxide with silicon. Figure 6 illustrates the temperature variation. Even though the temperature of the chip is 4 K higher (127 K as opposed to 123 K in figure 5), a cursory scan of the color coding, confirms that the average temperature over the system is comparable.

Stress Analysis

Stresses arise because of three phenomena:

- a) The coolant hydrogen has an inlet pressure of $35 \text{ E}+5 \text{ N/m}^2$. This imposes stresses on the structure.
- b) A temperature variation exists in the structure. Also, materials undergo a change in dimension with temperature change. Hence, temperature variations within the structure, will cause uneven expansion or contraction within the structure. Such dimensional changes can induce stresses within the material because of induced strains.
- c) Different materials have different coefficients of thermal expansion and Young's moduli. Even though no temperature variation may exist within the material, because of the different expansions undergone by the materials, a stress is induced at the interfacial boundaries. This is based on the assumption that no slippage occurs between the two materials.

Transistor made of dual material: silicon-beryllium oxide.

Figure 7 is a plot of the maximum stresses that occur within the section. The negative stresses indicate compression and the positive values indicate tension. The existence of different thermal expansion rates between beryllium oxide and silicon causes the system to act as a bimetallic strip. If no slip occurs between the two materials and no rotation is allowed on the boundaries, (under such cryogenic conditions most materials are brittle and do not tolerate any flexure) then regions of stress concentration are induced at the junctions of these two materials. This is seen in the greenish tinge on the color scan. The region within the channel area (dark blue area of silicon)

is under compression, and the beryllium (light blue) under tension. From the values of the stresses on the figures and the properties of the materials given, it appears that the silicon within the channel can handle the compressive stress. However, at the right hand corner the tensile stress may induce failure. The tensile stresses within the beryllium oxide are greater than the allowable tensile stress of $1.44 \text{ E}+8 \text{ N/m}^2$, which may again lead to failure.

It must be stated here that:

- a) the available data on the mechanical strength properties for the two materials is valid under ambient temperature conditions and higher. No data is available for the cryogenic temperatures in question. Under such cryogenic temperatures, most materials have undergone temperature embrittlement and cannot withstand the higher tensile stresses possible under ambient conditions. Hence, this transistor configuration would not survive structurally.
- b) depending on the boundary conditions applied on the structure, (allowance for rotation and translation), certain stresses can be relieved. However, owing to the brittle nature of the material under such cryogenic temperatures, no rotational flexure was allowed in the modelling.
- c) the variation of the coefficient of thermal expansion with temperature was available only for silicon. No such data was available for beryllium oxide in the cryogenic temperature range. Hence, the predictions cannot be certified, but do convey information on effects of expansion variations.

Transistor made of a single material: silicon

Owing to the difference in the thermal expansion rates between beryllium oxide and silicon, stresses are induced at the junctions of the two materials. These can be eliminated if the structure is made up of one single material, silicon, or beryllium oxide. For this study silicon was studied it being the material with which the microchannels are made. Figure 8 is a color stress scan of the same transistor made only of silicon. The stresses encountered within the structure are mainly compressive. This is encouraging, since, brittle materials handle compression well. The region of tensile stress occurring on the left of the strip in red has a value of $2.76 \text{ E}+6 \text{ N/m}^2$. This is

much lower than the compressive stress data available, but, generally the tensile stress of brittle materials is lower. No data being available for the cryogenic conditions in question, a failure prediction is not ventured.

Conclusions

The above study confirms that hydrogen available under cryogenic conditions can easily remove heat efficiently from high-power transistor packages. The feasibility of performing structural analysis to predict failure has been developed. It has been shown that a transistor made of dual material (silicon-beryllium oxide) may yield unacceptably high stresses. If beryllium oxide is a necessity in the operation of the transistor, and if microchannels can be manufactured in it, then perhaps the central heat sink should be made with beryllium oxide. Further experiments and analyses are essential to determine the:

- a) flow conditions, i.e., hydrogen inlet temperature and pressure, and transistor structural design for optimum operation
- b) mechanical properties of the materials under cryogenic conditions so that safe and failure free operation can be predicted.

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Microchannel Cooled Dual Faced Transistor

Figure 1

All dimensions in μm

Single Chip Configuration

Figure 2

All dimensions in μm

Figure 3

Figure 4

microchannel with hydrogen

ANSYS : 4.4
 UNIV VERSION
 MAY 10 1990
 12:01:43
 POST1 STRESS
 STEP=1
 ITER=10
 TEMP
 SMN =35.
 SMX =123.045
 XV =1
 YV =1
 ZV =1
 DIST=0.004021
 XF =0.700E-04
 YF =0.850E-03
 ZF =0.0051
 35
 44.783
 54.565
 64.348
 74.131
 83.914
 93.696
 103.479
 113.262
 123.045

Figure 5

ANSYS 4.4
 UNIV VERSION
 MAY 9 1990
 17:34:17
 POST1 STRESS
 STEP=1
 ITER=10
 TEMP
 SMN =35
 SMX =126.801

XV =1
 YV =1
 ZV =1
 DIST=0.004021
 XF =0.700E-04
 YF =0.850E-03
 ZF =0.0051

35
45.2
55.4
65.6
75.8
86
96.2
106.401
116.601
126.801

Figure 6

1

microchannel with hydrogen

ANSYS 4.4
UNIV VERSION
MAY 10 1990
12:52:20
POST1 STRESS
STEP=1
ITER=10
SIG1 (AVG)
DMX =0.130E-04
SMN =-0.223E+08
SMX =0.168E+09

XV =-1
ZV =1
DIST =0.004021
XF =0.700E-04
YF =0.850E-03
ZF =0.0051

Figure 7

1

microchannel with hydrogen

ANSYS 4.4
UNIV VERSION
MAY 9 1990
18:06:51
POST1 STRESS
STEP=1
ITER=10
SIG1 :(AVG)
DMX =0.711E-06
SMN =-86487
SMX =0.276E+07

XV =-1
ZV =1
DIST=0.004021
XF =0.700E-04
YF =0.850E-03
ZF =0.0051
-86487
229852
546190
862529
0.118E+07
0.150E+07
0.181E+07
0.213E+07
0.244E+07
0.276E+07

Figure 8

Blowdown: A Thermal and Fluid Study of Manifold Cooling Using Supercritical Hydrogen

In a previous report [1], it was demonstrated that on-board supercritical hydrogen can be used to cool space-based high power microwave tubes for future space platforms. One of the conceptual designs for the high power RF source configuration is illustrated in figure 1. Supercritical hydrogen is supplied via a manifold to the RF sources which are fed off bleeder ports uniformly spaced along the length of the manifold.

Consider an 80-meter long manifold (pipe) of internal diameter D_i and external diameter D_o , with wall thickness τ (see figures 1,2). This pipe acts as a distributor, supplying supercritical hydrogen at temperature T_{h2} and pressure P_{h2} to high power RF sources equidistantly placed along its length. The supercritical hydrogen acts as a coolant, taking up the waste heat generated in the RF sources and maintaining their temperature within acceptable limits.

When the system is inoperative, i.e., the RF sources are not powered, no cooling of the system is necessary, hence, no hydrogen is flowing through the system. Under such conditions the manifold is stored at T_{wi} and pressure P_i , these values being determined by the ambient conditions. Under operation conditions, the hydrogen is required to flow at M_{h2} and temperature T_{h2} . Assuming the walls of the manifold to have negligible heat loss, the steady state temperature of the walls would be those of thermal equilibrium with the hydrogen, i.e.,

$$T_w = T_{h2}$$

This implies that on start-up — Blowdown, i.e., the transient state during which hydrogen flow is initiated through the system, the temperature of the walls of the manifold must be dropped from T_{wi} to T_{h2} . This is possible because the cooler hydrogen takes up heat from the walls as it flows through the system. The fact that the hydrogen is taking up heat from the walls of the manifold may lower its cooling capability at the RF sources during this transient wall cooling period. The present report addresses the thermal management of the manifold feeder under conditions of blowdown. Such a manifold is an essential component of the RF cooling system.

The use of supercritical hydrogen as a coolant, and its introduction into the manifold previously maintained at ambient conditions poses the question of:

- a) time constants involved in the cooling of the system.
- b) the magnitude of the
 - 1) thermal and
 - 2) fluid transientsoccurring within the system.
- c) the structural integrity of the system.
- d) the capability of the system to provide ample coolant flow rates.

Manifold Design

The schematic diagram of a 80 meter long manifold with uniform bleeding through 40 equally spaced feeders is illustrated in figure 1,2. The manifold has a uniform circular cross-section of internal diameter D_i and outer diameter D_o . The pipe is made of aluminum 6061 alloy. The manifold inlet receives its supply of hydrogen at 35 atmospheres and 35 K. The mass flow rate M_{h2} entering the manifold is bled off uniformly at successive feeder ports. This bled hydrogen is used in the cooling of the independent RF sources.

Energy/Heat Balance Over Control Volume:

The manifold is divided into a number of control volumes in the direction of flow. Figure 2 is a blow up of the control volume section of length l within the manifold. M_{h2in} kg/s of hydrogen at pressure P_{in} and temperature T_{h2in} flow into the control volume. Within a particular time interval Δt the walls of the manifold dissipate q Joules of heat to the hydrogen. Owing to the loss of heat the temperature of the walls fall from $T_w(t)$ to $T_w(t+1)$ during the same time interval. Simultaneously, since the hydrogen absorbs the heat its temperature rises from T_{h2in} to T_{h2out} . Owing to the friction between the flowing hydrogen and the walls of the control volume a pressure drop ΔP is incurred. Before exiting the control volume, $M_{h2bleed}$ of hydrogen is bled from the flow, and the balance of the hydrogen given by

$$M_{h2out} = M_{h2in} - M_{h2bleed} \quad (1)$$

flows into the next control volume. Heat dissipated by the manifold walls during its cooling down is conducted through the walls and convected at the inside

pipe walls into the flowing hydrogen.

The hydrogen (coolant) is considered as a lumped system. Within the control volume the hydrogen absorbs heat due to forced convection from the walls and exits at a higher temperature T_{h2out} . Therefore, energy taken up by hydrogen over the time interval Δt is,

$$q = M_{h2in} C_{ph2} [T_{h2out} - T_{h2in}] \Delta t \quad (2)$$

If the mass of the section of the wall within the control volume is M_w and its temperature at any instant t is $T_w(t)$, then the heat loss by this wall section must satisfy energy conservation and should equal the heat taken up by the hydrogen,

$$q = M_w C_{pw} [T_w(t) - T(t+\Delta t)] \quad (3)$$

The heat convected to the hydrogen from the walls of the manifold can be expressed as,

$$q = h A [T_{wcv} - T_{h2cv}] \Delta t \quad (4)$$

Here, T_{wcv} and T_{h2cv} are the average manifold wall temperature and hydrogen temperature within the control volume, respectively. The heat transfer coefficient h , which is dependent on the manifold geometry, fluid properties and the flow field, is given in the form of the Nusselt number Nu [2]. Depending on the flow rate of hydrogen, the flow can be laminar ($Re < 2100$ [2]), in which case the ability to transfer heat is represented by the Nusselt number as [2],

$$Nu = 5.62 \quad Re < 2100 \quad (5)$$

or, if turbulent ($Re > 2300$) by [2],

$$Nu = 0.021 Pr^{0.5} Re^{0.8} \quad Re > 2100 \quad (6)$$

where,

$$Nu = h D_i / k_{h2} \quad (7)$$

D_i is the internal diameter of the manifold, Re the Reynolds number, k_{h2} is the thermal conductivity and Pr the Prandtl number of hydrogen.

Pressure Distribution

Owing to the flow of hydrogen within the manifold, friction forces are set up due to the shear between the fluid and the wall surface. This shear force introduces a pressure drop in the flow field. Knowledge of the pressure field within the manifold determines whether sufficient flow of the hydrogen can be induced through the heat exchangers of the RF sources. Ideally, a near isobaric field is desired. This ensures that equal flow rates and pressures heads are available at the bleeder ports. The pressure drop within the control volume of length l is determined by,

$$\Delta P = f \frac{l}{D_i} \frac{U^2}{2} \rho_{h2} \quad (8)$$

where, U is the velocity of the flow, ρ_{h2} is the density of hydrogen and f is the friction factor [2],

$$f = 64 / \text{Re} \quad \text{Re} < 2100 \quad (9)$$

$$1/f = 2 \log_{10}[\text{Re} f] - 0.8 \quad \text{Re} > 2100 \quad (10)$$

Wall Thickness Determination

The determination of the wall thickness is an essential parameter of this study. It was noted earlier that the whole problem of transient cooling exists because of the fact that the walls of the manifold have a finite thermal inertia, which has to be cooled down before active cooling of the RF sources can be realized. This thermal capacity of the walls is determined by the mass of the walls. For space applications reduction of mass is paramount. The mass is determined by the geometry of the walls and the density of the material. However, the geometry of the structure is also determined by the stress considerations imposed by the pressure and temperature fields of the system. In this study aluminum 6061 alloy was selected to be used in a cylindrical geometry.

With reference to figure 3, the stresses occurring on the walls of a cylindrical container are given by the circumferential stress:

$$\sigma_r = P D_i / (2r) \quad (11)$$

and the axial stress

$$\sigma_1 = P D_i^2 / [D_o^2 - D_i^2] \quad (12)$$

The resultant principal stress is given by

$$\sigma_R = \sqrt{\sigma_r^2 + \sigma_1^2} \quad (13)$$

From design considerations, the principal stress must satisfy,

$$\sigma_R < \frac{\text{Yield Stress}}{\text{Factor of Safety}} \quad (14)$$

The yield stress is also a function of temperature. Hence, from design considerations the minimum value of the yield stress over the temperature range in question is chosen. The factor of safety is chosen equal to 4.

Owing to the low operating temperatures of hydrogen considered in this study, the material properties of aluminum and hydrogen are expected to change considerably as they dissipate and take up heat respectively. Consequently, the above equations are nonlinear with the material properties being a function of temperature, and must be solved iteratively to obtain the temperatures T_{h2cv} , T_{wcv} and P_{cv} within each section along the length of the channel.

Numerical Modeling

The 80-m manifold with 40 bleed ports was numerically modeled using a 1-dimensional lumped, transient scheme. The manifold was discretized into elements, a typical element is illustrated in figure 2. Using equations 1 through 14, the temperature and pressure fields are determined within the entire manifold system. Steady state is determined by the wall temperature reaching equilibrium with the inlet hydrogen temperature.

Results and Discussion

Boundary conditions

For the thermal analysis, the outer wall of the manifold are assumed to be well insulated (adiabatic). The internal walls of the manifold are set as convection boundaries. Inlet hydrogen temperature is set at 35 K and pressure is set at 35 bars. The initial temperature of the manifold walls is set at 300 K. The inlet hydrogen mass flow rate $M_{O_{H_2}}$ into the manifold is varied from 2 to 7 kg/s. This flow rate is equally distributed over the 40 bleeder ports. The internal diameter D_i of the manifold is varied from 3" to 6". Calculations were performed over a manifold length of 80 m, having 40 uniformly distributed bleeders/nodes along the length. At start up all bleeder ports are assumed to be open and have equal flow rates.

The temperature variation within the system is expected to be substantial enough to demand the incorporation of temperature-dependent material properties. At cryogenic temperatures the thermal properties undergo large changes and are noted in earlier calculations [1] to be crucial. Hence, the temperature-dependent properties of the materials were used and are provided in Tables 1 and 2.

Table 1: Properties of Hydrogen

Temp. K	Viscosity N.s/m ²	Density kg/m ³	Specific Heat J/kg.K
30	711.E-8	55	2.83E4
50	350E-8	21.4	1.95E4
100	432E-8	8.49	1.23E4
150	572E-8	5.3	1.31E4
200	692E-8	3.85	1.375E4
250		3.0	1.425E4
300		2.49	1.435E4
350		2.11	1.445E4
400		1.84	1.46E4
500		1.456	1.485E4

Manifold Dimensions and Weight

For a cylindrical manifold geometry of fixed length (80 m) the mass of the manifold is given by,

$$M_w = 80\pi (D_o^2 - D_i^2) \rho_{al}$$

where, ρ_{al} is the density of aluminum. As the diameter D_i is increased from 3" to 6", from equations (11-14) the thickness of the walls of the manifold and the mass increase is enumerated in Table 3 and figure 4.

Table 2: Properties of Aluminum [3]

Temp.	Specific Heat
K	J/kg.K
30	31.5
35	51.5
40	77.5
50	142
60	214
70	287
80	357
90	422
100	481
120	580
140	654
160	713
180	760
200	797
220	826
240	849
260	869
280	886
300	902

$\sigma_{yield} = 241$ MPa at $T = 300$ K [3]. This is the minimum yield stress over the temperature range of interest.

Table 3: Manifold Dimensions

D_i inches/cm	D_o cm	τ mm	M_w kg
3./ 7.62	8.08	2.3	123
4./10.16	10.76	3.0	218
5./12.70	13.46	3.8	340
6./15.24	16.15	4.6	490

Time to Fill System

Assume initially that the manifold is at a temperature of 35 K. If the hydrogen is flow is initiated, then depending on the size D_i of the manifold and the flow rates $M_{o_{H_2}}$ used, an estimate of the minimum time required to fill up the manifold before cooling of the RF sources can be realized is provided in figure 5. These calculations are based on the assumption that the manifold is initially empty

and all bleeder ports are shut. From figure 5 the time taken to fill up any system at a particular flow rate is proportional to the square of the diameter D_i . At $M_{O_{H_2}}=5$ kg/s, the time varies from $3.4 < t < 13.6$ secs for $3 < D_i < 6$ inches.

Transient Thermal and Fluid Behaviour

Time to Reach Steady State

Figure 6 illustrates the effect of diameter D_i on the thermal transient response of the system. The thermal transient comes into play in the case of the manifold being initially at a temperature other than that of the supply supercritical hydrogen. In this instance, the manifold will have to be cooled down. This estimate is necessary because even though the manifold may fill up earlier (as shown in figure 5), the fact that it is taking up heat from the manifold walls may reduce its thermal capacity for further cooling in the RF sources. Hence, a further increase in lead time over that for fill up is necessary before active cooling of the RF sources is feasible. These calculations are based on the fact that the hydrogen is continuously being bled through the ports during cooling of the manifold. This procedure greatly reduces the time taken for start up of the system, cool hydrogen being available for faster cooling of the manifold. For any particular diameter, the time to reach steady state increases with decrease in mass flow rate of hydrogen. For a flow rate of 5 kg/s, the time taken to cool the manifold to steady state conditions increases dramatically with the diameter D_i from 21 secs for a $D_i=3$ inches to 141 secs for $D_i=6$ inches. For a diameter of $D_i=5$ inches, the time taken to reach steady state varies from 182 secs for $M_{O_{H_2}}=2$ kg/s to 65 secs for $M_{O_{H_2}}=7$ kg/s.

Pressure Field

Figure 7 illustrates the pressure drop within the manifold at steady state. It is noted that as D_i is increased the pressure drop decreases rapidly. For $D_i > 5$ inches and flow rates < 5 kg/s, the pressure drop is approximately a bar or less over the length of the manifold. At any particular diameter, the pressure drop increases almost quadratically with mass flow rate.

The pressure drop ΔP is directly proportional to the square of the velocity (see equation (8)). Figures 8a-11a indicate that initially the velocity within the manifold reaches Mach numbers of the order of 0.4. It follows that within the same time period and region, the pressure drop should be correspondingly high. This is verified in figures 8b-11b which illustrate the transient behaviour of the pressure field within

the manifold during cooling. As time progresses, the manifold cools, velocities within the system subside, and the pressure drop takes up a steady state value. It is desirable to maintain isobaric conditions within the manifold so as to provide equilibrated flow rates through each of the RF sources. This is possible if the pressure drop is minimized.

Velocity Field

Figures 8a-11a, illustrate the trend of the velocity field represented by the Mach number. It is important to note that the maximum flow rate possible in a system is limited by choke flow conditions. For all cases in this study, during the transient and steady state regimes, the maximum Mach number occurring within any region of the manifold lies below 0.4. In the initial stages when the manifold is relatively hot, the hydrogen temperatures increases because it absorbs heat from the walls. Hence, the hydrogen density decreases (see Table (1)), causing an increase in the velocity of the flow while the mass flow remains constant. The rapid increase in the velocity in the initial few seconds is attributable to the rapid transfer of heat from the walls to the flow, causing large temperature and density changes. At the same time hydrogen is being bled off as it flows down the manifold, decreasing the velocity downstream. As time passes, the walls get cooler. The hydrogen is taking up less heat (the temperature difference between wall and hydrogen is lower, see equation (4)), hence, its density remains higher and the Mach number decreases with time at any location. Under conditions of thermal equilibrium, the Mach number shows an expected linear decrease as the flow progresses down the manifold. Hydrogen is uniformly bled along the length of the manifold, the cross sectional area of the manifold being held constant, the decrease in velocity is evident.

Temperature Profiles

Figures 8c,d-11c,d also illustrate the transient behaviour of the hydrogen temperature T_{h2} and the wall temperature T_w at any location along the manifold. Initially, the hydrogen has an immense cooling effect, its temperature rising to almost the initial wall temperature as it flows down the manifold. It is noted that the entry region of the manifold cools down much earlier than the downstream region. This is because as the flow proceeds downstream, the hydrogen is bled off gradually along the length, hence, reducing the thermal capacity of the flowfield as it flows downstream. The heat transfer capability of the flowfield is large enough to take full advantage of the thermal capacity of the flowing hydrogen. This is evident from the

fact that the temperature of the hydrogen at the different locations of the manifold are in equilibrium with the wall temperature at any time. Steady state conditions are attained when both the hydrogen and wall are at thermal equilibrium at 35 K.

Conclusions

The use of supercritical hydrogen as a coolant, and its introduction into the manifold previously maintained at ambient conditions has been studied. Estimates of:

- a) time constants required to fill up the system
- b) time constants involved in the cooling of the system before startup of RF power
- c) the magnitude of the
 - 1) temperature
 - 2) pressure
 - 3) Machtransients occurring within the system
- d) the mass and structural integrity of the system

were numerically obtained using a one-dimensional transient model. The model was set up so as to allow equal flow rates through each of the heat generating RF sources. However, owing to the existence of a pressure drop, it is recommended that the system design be such so as to allow isobaric (constant pressure) conditions within the manifold. This will not only provide equal flow rates through each bleeder, but also, provide equal pressure head for the flow. For $D_i \geq 5$ inches and flow rates $M_{O_{H_2}} \leq 5$ kg/s, the pressure drop is less than 1 bar over the length of the manifold.

References

1. Thermal Management of Space-Based High-Power Microwave Tubes, RADC-TR-89-187, October, 1989.
2. Kays, W.M., Crawford, M.E., 1980, 'Convective Heat Transfer', p. 103, 243, 2nd ed., McGraw Hill.
3. Cryogenic Materials Handbook, Vol. 1, Section A,B,C, AFML-TDR-64-280, NTIS# AD 713619, pg 4.132, July 1970.

M_{h2}^0 kg/s
 ① ② + X ◇ 4

Figure 5

Figure 7

Figure 4

Figure 6

$D_1 = 3$ inches

$M_{h2}^0 = 5$ kg/s

TIME second

1 2 3 5 7 9 13 21
 O Δ + X ◇ ◄ × Z

$D_1 = 4$ inches

$M_{h2} = 5$ kg/s

TIME sec

1 2 3 4 5 6 7 47
 O A + X $\diamond$ 4 X Z

Figure 10

B-50

$D_1 = 6$ inches
 $M_{h2} = 5$ kg/s
 TIME seconds
 ① 1
 △ 2
 + 4
 X 7
 ◇ 11
 ◊ 15
 X 25
 Z 141

APPENDIX C

SOLID STATE RF POWER AMPLIFIERS FOR SDI APPLICATIONS

Module Size

Efficiency

J. H. JOHNSON

Solid State RF Power Amplifiers for SDI Applications

Solid State Power Amplifiers have made dramatic progress over the last 10 years. Power output from a single UHF transistor has increased by a factor of 5. CW power output from an all solid state UHF amplifier has increased by a factor of 50. The cost of solid state UHF power (complete commercial system with power supply) has decreased by at least a factor of 10. Today, you can buy an all solid state, 60,000 watt, television transmitter or a 50,000 watt, CW instrumentation amplifier for close to \$10/Watt. Figure 1 illustrates these changes.

Another important improvement over the last ten years has been in amplifier cooling. Bulky convection cooled heatsinks with the transistors mounted some distance away were the norm in 1970. This gave way to densely packed fins with forced air by 1980. Today, one can envision direct water, liquid nitrogen or hydrogen cooling with microchannel cold plates. Total reduction in volume of the cooling apparatus has been at least 1,000.

In 1988, MMD developed a 2 KW, CW module for WPAFB that was cryogenically cooled with LN². This amplifier will be used as part of the baseline for further discussion. Figure 2 shows the 2 KW amplifier. Specifications are shown below:

Output Power	1800 Watts, CW
Frequency	425 MHz
Efficiency	70%
Supply Voltage	40 Volts
Base-Plate Temperature	-150 °C
Weight (aluminum base)	6 oz.

The other baseline amplifier for further discussion will be the 800 watt building block that MMD used in the 60 KW Grumman Amplifier. This building block is an adaptation of the cryogenically cooled 2 KW module. The power output is reduced to 800 watts and the base-plate temperature is increased to +35°C. Several critical components were found inadequate, even at the 800 watt level when the base-plate temperature was increased:

- Loss in the ceramic chip capacitors (the best that could be purchased) caused them to float in their own solder.
- Loss in the microstrip caused overheating.
- Once several modules were combined, some arcing was experienced.

Each problem has been solved resulting in a more efficient circuit.

- The ceramic chip capacitors were replaced with metal case mica units.
- Some of the microstrips were replaced with semi rigid coax.
- General construction practice was improved on the remaining microstrip.

Efficiency improved by 5 percentage points with these changes. It is very apparent that the components that make up the circuit need further study along with the transistors. Specifications for this baseline amplifier are:

Output Power	800 Watts, CW
Frequency	425 MHz
Efficiency	65%
Supply Voltage	32 Volts
Base-plate Temperature	+35°C
Weight (copper base-plate)	10.4 oz.

Four of the 800 watt modules were combined to achieve a 3,200 watt water cooled building block. Twenty (20) of the 3,200 watt building blocks are then combined for a full 50,000 watts of CW power. See Figures 3, 4 and 5.

It is interesting to note that MMD envisioned subminiature modules for high density RF amplifiers for space applications only 4 years ago. Today, MMD is building commercial amplifiers with them.

A general look at what has been learned over the last two years indicates:

- Running the transistors cooler improves efficiency by 10 percentage points.
- Allowing the junction to self heat to about -40 to -50°C provides optimum performance.
- Cooling helps the entire circuit, not only the transistor.
- There is a great deal of additional improvement that remains to be found in both the transistor and the circuit.

Boundary Conditions for High Power Amplifiers

Very high power solid state amplifiers for SDI space applications present a unique set of problems:

- Small Size
- Light Weight
- Very High Power Density

The requirement of small size at minimum weight dictates that the basic RF "building block" use the highest power transistor that the state-of-the-art allows. Basic transistor limitations are:

- Yield limitations due to size of silicon chip
- Power distribution across the chip
- Ability to remove heat from chip
- Impedance of the transistor/circuit interface

As time has passed, the most significant limitation for 425 MHz has progressed from the first on the list to the last. If it is assumed that the thermal problem can be solved by using cryogenic cooling, the most significant limitation will be the interface impedance. Today, circuit designers can deliver repeatable designs that work with transistor input and output impedances in the 1.0 to 1.5 ohm range. This means the largest transistor is in the 400 to 600 watt range. Some impedance matching inside the transistor package is required to achieve the power and impedance level.

A simple model of the transistor output is shown in Figure 6. R_L is the load resistance that the transistor wants to see. C_O is the output capacitance associated with the transistor chip. L_P is the parasitic inductance associated with the transistor package and wire bonds. An impedance matching inductor, L_M , can be added inside the transistor package to partially compensate for C_O . L_M should be added as close to the transistor chip as possible in order to minimize L_P . In reality the real part of the load impedance can be just slightly smaller than R_L if the internal matching and parasitics are handled correctly.

A simple model of the transistor input is shown in Figure 7. The real part of the input impedance is dominated by R_E , the emitter ballast resistance that is added to a bipolar transistor to distribute the power evenly across the surface of the transistor chip and $W_T L_E$, a reflection of the emitter lead inductance. L_P is a parasitic inductance associated with the base wire bonds. Z_{IN} at the transistor chip is approximately 0.1 ohm. L_M , C_M , L_{M2} and C_{M2} may be added to the input to increase the impedance to the 1 to 1.5 ohm level at the package edge.

Figure 1

Solid State UHF Progress

Figure 2
2 KW CW Amplifier

1 KW module

S/N 1
32 V = Vcc 25 % Duty 02:17 PM 09/13/89

Pout dB	Pout W	Pin	I peak	Gain dB	Eff %	Temp
55.0	316	47.6	20.6	7.4	47.9	
56.0	398	48.2	22.1	7.8	56.4	
57.0	501	48.9	27.4	8.1	57.1	
58.0	631	49.7	30.6	8.3	64.4	
58.5	708	50.1	33.8	8.4	65.4	
59.0	794	50.7	35.6	8.3	69.7	
59.2	832	50.9	36.0	8.3	72.3	
59.4	871	51.3	36.7	8.1	74.2	

1 KW module

S/N 2
32 V = Vcc 50 % Duty 02:21 PM 09/13/89

Pout dB	Pout W	Pin	I peak	Gain dB	Eff %	Temp
55.0	316	47.5	21.2	7.5	46.6	
56.0	398	48.1	24.6	7.9	50.6	
57.0	501	48.8	27.9	8.2	56.0	
58.0	631	49.6	32.0	8.4	61.5	
58.5	708	50.1	33.8	8.4	65.4	
59.0	794	50.7	36.0	8.3	69.0	
59.2	832	51.0	37.4	8.2	69.5	
59.4	871	51.3	39.2	8.1	69.5	

1 KW module

S/N 2
32 V = Vcc 75 % Duty 02:48 PM 09/13/89

Pout dB	Pout W	Pin	I peak	Gain dB	Eff %	Temp
55.0	316	47.4	21.4	7.6	46.3	
56.0	398	48.0	24.2	8.0	51.4	
57.0	501	48.7	27.5	8.3	55.0	
58.0	631	49.7	32.5	8.4	60.8	
58.5	708	50.1	33.7	8.4	63.0	
59.0	794	50.7	36.0	8.3	66.2	
59.2	832	51.0	38.2	8.2	68.0	
59.4	871	51.3	40.1	8.1	67.9	

1 KW module

S/N 2
32 V = Vcc 100 % Duty 02:54 PM 09/13/89

Pout dB	Pout W	Pin	I peak	Gain dB	Eff %	Temp
55.0	316	47.3	21.8	7.7	45.3	
56.0	398	47.9	24.9	8.1	49.9	
57.0	501	48.7	28.5	8.3	55.0	
58.0	631	49.6	32.6	8.4	60.5	
58.5	708	50.0	35.4	8.5	62.5	
59.0	794	50.7	37.6	8.3	65.9	
59.2	832	51.0	39.2	8.2	66.4	
59.4	871	51.3	40.8	8.1	66.8	

Table 1

Data taken on the 800 Watt Amplifier operating at +35°C Base-plate. Junction temperature with 100% duty is 135°C and junction temperature with 25% duty is approximately 60°C. Note the difference in efficiency due to the lower junction temperature.

Figure 3

Adaption of the Cryogenically Cooled Amplifier for Operation at $+35^{\circ}\text{C}$. Maximum power output is 1,000 Watts. Amplifier is 2.25" x 3.9" and weight is only 10.4 oz. with a copper base-plate.

Figure 4

Four 800 Watt Amplifiers are used with a Driver in a 3.2 KW Building Block.

UHF 50,000 WATT (C.W.) AMPLIFIER

Figure 5

50,000 Watt, CW, UHF Amplifier Combines 20 3.2 KW Modules. Size is 4' x 5' x 7' and Weight is 4,000 lbs. Including a 2,000 lb. Power Supply.

R_L - Load required by the transistor for a particular power output
 $= (V_{cc} - V_{sat})^2 \div 2 \times \text{Power Output}$

C_0 - Transistor output capacitance

L_P - Package inductance

L_M - Inductive match

C - DC coupling capacitor

Figure 6

Simple Output Model

Figure 7

Simple Input Model

As frequency is increased, the low impedances become more difficult to handle and other factors such as yield, power distribution and thermal resistance pose additional limitations. Figure 8 shows maximum possible predicted transistor power vs. frequency. 500 watt transistors at 425 MHz have been demonstrated and development work is currently underway at 850 MHz that should also yield a 500 watt transistor.

Figure 8

Maximum Practical CW Power From A Single Push-Pull Transistor

There are also important boundary conditions for transistor junction temperatures. Steady state and transient limits are shown below:

- Maximum Rated Transistor Junction Temperature - 200°C
- Typical Maximum Operating Temperature - 150°C
- Tolerance For Over Temperature Spikes - Low
 - To 300°C Without Drive - 1 Hour Max
 - To 300°C With Drive - 1 Sec
 - Greater Than 300°C - 100 Micro Sec

Power dissipation must be dispersed evenly over the active area of the transistor in order to avoid hot spots.

- * Assumes other failure modes are not simultaneously present such as high VSWR or over voltage

Problem Areas Generic to High Power Design

By using very large transistors, the high power densities and RF currents create a unique set of problems. These are:

- Thermal Management
- Transistor Design
- High Current Capacitor
- Microstrip Lines
- Impedance Matching Transformers

Thermal Management is perhaps the most important as the maximum temperature of any of the various components is a basic limitation. The mounting technique and efficiency of the primary heat generating element, the transistor, are extremely critical.

To illustrate the importance of efficiency, consider two transistors that deliver 500 watts of output power:

	<u>Power Out</u>	<u>Collector Efficiency</u>	<u>Power Dissipated</u> (Including 50 W Drive)
Transistor A	500 Watts	70%	264 Watts
Transistor B	500 Watts	80%	175 Watts

An improvement in efficiency of only 10 percentage points reduces the power dissipated by 34% (89 watts reduction). Efficiency is discussed further in the transistor design section.

In order to discuss transistor packaging and the details of removing the heat, actual transistor chip designs must be considered. The bipolar transistor chip proposed for 425 MHz has the dimensions shown in Figure 9. Six of these chips mounted side by side are used to form a push-pull 500 watt transistor. Total silicon area is 0.07 inches by 0.330 inches or 0.023 square inches (0.149 square centimeters). If the 500 watt transistor were dissipating 220 watts (~ 75% collector efficiency plus 50 watts of drive power) and the heat source was distributed evenly over the entire surface of the silicon, the power density would be approximately 1,500 watts per square centimeter at the back side of the silicon. With the transistor capable of operating at 85% collector efficiency the 220 watts of dissipation should represent worst case. These efficiency levels assume that the

current chip design will be redesigned to use the new process now under development for the 850 MHz device (WPAFB development contract). However, the active base area as shown in Figure 9 is less than the total silicon area. The total active heat generating area is 0.0065 square inches or 0.042 square centimeters. Therefore, the power density through the silicon near the top surface of the chip is approximately 5,000 watts per square centimeter. The actual power density at the back side of the silicon will range somewhere between these extremes and will depend on the thickness of the silicon chip (0.03 to 0.05 inches is typical) and the heat spreading through the silicon. Figure 10 shows a photo of a typical 6 chip UHF transistor.

Figure 9

Single Chip Dimensions For 425 MHz Transistor
(500 Watt Transistor Requires Six Chips)

Figure 10

Typical UHF Transistor

The transistor chip proposed for 850 MHz is shown in Figure 11 (Currently under development for WPafb). Ten of the chips shown are required for 500 watts output. Power density extremes for the 850 MHz chip similar to that discussed above are 2,700 to 15,000 watts per square centimeter. 65% collector efficiency is used for a total power dissipation 320 watts (including 50 watts of drive power). The transistor should be capable of 75% collector efficiency; therefore, the 320 watt dissipation number should represent worst case.

Figure 11

Single Chip Dimensions For 850 MHz Transistor
(500 Watt Transistor Requires Ten Chips)

Figure 12 shows a curve of transistor efficiency vs. frequency using actual data taken on state-of-the-art transistors. The 12 micron pitch geometry (distance from center of one emitter to the center of the adjacent emitter) and process (Curve B) is the currently available MMD UHF transistor that was used in the LN² cooled CW amplifier developed for WPAFB. The 6 micron geometry and process (Curve A) is the new 2 layer metal device currently used for L and S band radar.

Figure 12
Bipolar Transistor Efficiency
Versus
Frequency For 12 and 6 Micron Pitch Geometries

The current 850 MHz transistor development that MMD is doing for WPAFB is a 6 micron device with improved processes for low temperature operation. It should follow the A Curve.

The efficiency drops off approximately 10% per octave in the frequency range that is $f_T/2$ to $f_T/5$. (f_T is the frequency where the transistor current gain is 1).

Average amplifier stage gain will be approximately the same at 425 and 850 MHz due to a change from common emitter at 425 to common base at 850 MHz. Currently available large transistors in this frequency range have approximately 10 dB power gain. The new process and 6 micron structure should provide 12 dB power gain.

MMD has taken data on efficiency and gain vs. cold plate temperature for a standard off-the-shelf UHF transistor mounted in a four transistor amplifier. A set of curves for peak power output with constant drive are shown in Figure 13 for different duty factors to show the effect of junction heating. The 1% curve shows how the transistor behaves with minimum self heating. The peak in gain (max. P_O) is at about -50°C and the peak in efficiency is at -130°C . When operated CW, the gain peaks with a cold plate temperature of -170°C (Junction is probably at approximately -50°C). It should be noted that the amplifier used was optimized for room temperature performance (using a low duty cycle pulse) and no adjustments were attempted to try and further improve the low temperature performance.

Power output vs. temperature
for 1600 Watt amplifier

Curves are for both CW and
pulse operation

$P_{IN} = 200 \text{ W}$

$f_{req.} = 435 \text{ MHz}$

$V_{CC} = 32 \text{ Volts}$

CW
1.0% Duty

10% Duty

Pulse - 100 USEC

Figure 13

Bipolar Transistor Efficiency and Power Output
Versus
Cold Plate Temperature

Since the h_{FE} (small signal current gain) of a transistor decreases as the junction temperature decreases, one would assume that performance would decrease as the temperature is reduced. However, one of the most significant problems with a large bipolar transistor is power sharing across the surface of the chip. Slight variations in surface temperature from one location on the chip to another cause significant variations in current flow (and power). At the very low temperatures the thermal conductivity of the various materials (silicon and BeO) improves by a factor of 4. Therefore, all areas of the chip are closely coupled thermally. I believe that improved surface temperature consistency is the key to the demonstrated performance improvement. This point can be further demonstrated by mounting the transistor chip directly on a 20 mil thick diamond. The diamond demonstrated excellent thermal conductivity at room temperature (approximately 4 times that of copper). Performance with the diamond heat spreader is very close to that obtained by using a -145°C cold plate. (See Figure 14)

Figure 14

250 Watt Single Transistor Performance with Standard Pill Package,
Diamond Insert Package and Standard Pill Package at Low Temperature

Several transistor packaging approaches have been demonstrated and others proposed. Figure 15 illustrates a variety of possibilities:

(a)
Standard Transistor
Package with
Mounting Flange

(b)
Pill Package
without Flange

(c)
Metal Pill Package

(d)
Ceramic Pill
Mounted on Micro-
Channel Heat Sink

(e)
Small Microchannel

(f)
Back to Back
Transistors with
Microchannel Between

Figure 15
Various Transistor
Packaging Approaches
C-17

In each package style the thermal resistance can be attributed to a series combination of values associated with layers of different material. The first layer being the silicon chip and then an insulating layer and finally a metal flange or carrier. Measurements have been made on a number of combinations with a room temperature cold plate as shown in Table 2. Values are normalized to standard package (a).

Table 2
Normalized Transistor Thermal Resistance
With Room Temperature Cold Plate

Structure. (Layer Thickness in Mils)	R _{TH} Die	R _{TH} Insulation	R _{TH} Carrier/Flange	R _{TH} Total
1. Si - BeO - Cu 6 - 60 - 100	0.33	0.5	0.17	1.0
2. Si - BeO 5 - 45	0.3	0.4	-	0.7
3. Si - Diamond - Cu 5 - 20 - 60	0.3	0.03	0.1	0.43

Table 2 clearly shows the value of replacing the BeO with a thinner and thermally superior diamond at room temperature. However, at very low temperatures both silicon and BeO become excellent thermal conductors (much better than copper). Therefore, the optimum compromise between producibility, cost and performance is probably the silicon/BeO pill package. By using the pill package, easy transistor assembly and test is assured. The pill package can then be mounted directly to a microchannel heatsink as shown in package design (f). Figure 16 shows material thermal conductivity versus temperature.

A 500 watt transistor design using package (f) is a ceramic (BeO) pill that is approximately 0.4" x 0.5" inches. Four of these transistors can be used to build a 2,000 watt module that is approximately 2.5" x 3" inches. Modules of this general type have been developed and power outputs of close to 2,000 watts have been demonstrated (LN² Coolant). The next generation of 2,000 watt modules will have:

- Improved Efficiency
- Efficient Cooling
- Improved Gain
- Lighter Weight

Two of the 2,000 watt modules can be mounted back to back with a microchannel heatsink sandwiched between. A microchannel heatsink size is selected that has long fins (0.050 inches) in order to provide sufficient cooling with super critical H₂. Some basic calculations are made assuming that the heatsink material is copper. Other materials can be scaled to the basic calculations. Figure 17 shows a possible back to back 4,000 watt module structure.

Temperature calculations are made in two steps for simplification purposes. First, the transistor junction temperature is modeled by mounting the transistor pills on a thick copper cold plate with the back side of the cold plate assumed to be a constant temperature. Figure 18 shows the model used for the 425 MHz transistor.

Figure 16

Material Thermal Conductivity
Versus
Temperature

Output Power	4,000 Watts, CW
Gain	12 dB
Frequency	425 MHz
Efficiency	80%
Supply Voltage	50 Volts, 100 Amps
Base-plate Temperature	35°K to 90°K
Weight	6 Oz. (170 Gms)
Size	5.5 in. ³ (90 cm ³)

Figure 17

Possible Structure For
4,000 Watt Module

Figure 18

425 MHz Thermal Model

Figure 13, 14 and 15 show the temperature profiles for 40 watts dissipated in each 425 MHz transistor chip for three basic plate temperatures. Forty (40) watts of power dissipation is a very conservative number used to represent worst case design. Table 3 shows data of thermal resistance versus temperature for both the 425 MHz transistor and the 850 MHz transistor.

The next step is to model a microchannel heatsink that is an appropriate size to replace the constant temperature surface. Both sides of the microchannel heatsink will be used to conduct heat from the transistors.

Table 3

Thermal Resistance Versus Temperature

425 MHz Transistor (6 Chip)			850 MHz Transistor (10 Chip)		
Temp (°C)	T (°C)	θ (°C/W)	Temp (°C)	T (°C)	θ (°C/W)
30	87	0.36	30	217	0.72
-100	53	0.22	-100	133	0.44
-200	26	0.11	-200	65	0.22

One form of microchannel heatsink suitable for cooling four 2 KW modules would be approximately 0.6" x 4.6" x 0.1". For purposes of calculation, the material will be assumed to be copper. Fins are 5 mils wide with 5 mils space and 50 mils high. Other material may be equally suitable.

Figure 19

Microchannel Heatsink

Some quick approximations will illustrate the capabilities of the microchannel heatsink. The first calculations will be made using water as the cooling fluid. The thermal resistance due to heating the water is θ_{Heat} . (See References by Goldberg as well as Tuckerman)

$$\theta_{\text{Heat}} = \frac{1}{2\rho cf}$$

Where:

ρ = Fluid Density
 C = Specific Heat
 f = Flow Rate

If a 5°C rise in water temperature is allowed and the heatsink must remove 3520 watts (four, 2,000 watt modules with 75% collector efficiency plus 800 watts of drive power). θ_{Heat} must be:

$$\theta_{\text{Heat}} = \frac{5^{\circ}\text{C}}{3520 \text{ Watts}} = 0.00142^{\circ}\text{C/W}$$

Therefore:

$$f = \frac{1}{23 \cdot \theta_{\text{Heat}}} = \frac{1}{2 \cdot 4.164 \cdot 0.00142}$$

$$f = \frac{1}{0.01183} = 84.5 \text{ cm}^3/\text{sec}$$

$$f = 5.06 \text{ l /min or } 1.34 \text{ Gal/min}$$

The optimum necessary pressure to attain this flow and minimize θ_{Conv} (the thermal resistance between the heatsink wall and fluid flow). See Reference 1 and 2.

$$p = \frac{12 \mu f}{W^3 N_o n} \left(\frac{K_f N_{\mu oo}}{K_w} \right)^{1/2}$$

$$\mu = \text{Viscosity} - 0.85 \times 10^{-2} \text{ poise}$$

$$W = \text{Chamber Thickness} - 5 \text{ mils or } 0.015 \text{ cm}$$

$$n = \text{Number of Fins} - 50$$

$$N_{\mu oo} = \text{Nusselt Number} - 8.2$$

$$N_o = \text{Correction Factor for Finite Fin Length} - 1.5$$

$$f = \text{Flow Rate} - 84.5 \text{ cm}^3/\text{sec}$$

$$K_f = \text{Thermal Conductivity of Fluid} - 0.0061 \text{ W/cm}^{\circ}\text{C}$$

$$K_w = \text{Thermal Conductivity of Heatsink Wall} - 3.91 \text{ W/cm}^{\circ}\text{C}$$

$$P = \frac{12 \cdot 0.85 \times 10^{-2} \cdot 84.5}{(0.015)^3 \cdot 1.5 \cdot 50} \left(\frac{0.0061 \cdot 8.2}{3.91} \right)^{1/2}$$

$$P = \frac{8.62}{2.53 \times 10^{-4}} (0.113) = 3854 \text{ gm/cm}^2$$

$$P = 55.5 \text{ psi}$$

Using the same heatsink with LN² (70°K) and H² gas (35°K) similar results can be obtained. Table 4 summarizes the results:

Coolant (5° C ΔT)	Flow Rate (Gal/Min)	Pressure (psi)
Water	1.34	55.5
Liquid Nitrogen (70°K)	3.44	42.3
Hydrogen Gas (35°K)	* 5675	12509
* 32 gr/sec.		
Coolant (100° C ΔT)	Flow Rate (Gal/Min)	Pressure (psi)
Hydrogen Gas (35°K)	** 284	625
** 1.6 gr/sec.		

Table 4

Coolant Flow and Pressure

Table 4 also shows that flow rates required with H² gas are excessive even when a ΔT of 100°C is allowed. The available hydrogen on a space platform will be at a pressure of 35 Bar. Therefore, super critical hydrogen (dense gas/liquid at any temperature with pressure above 13 Bar) may be a better choice for cooling.

Detail of UHF Amplifier Design For Future SDI Systems

The next generation amplifier will be a design with two modules mounted back to back with coolant pumped through the center frame as shown in Figure 17. Power output will be 4 KW. A new two layer metal transistor technology developed by MMD for L and S band radar will be adapted to the 500 watt UHF transistors for improved efficiency and gain. MMD is currently developing an 850 MHz transistor for WPAFB using the two layer metal technology. Transistor processes will also be optimized for low temperature operation.

Five 4 KW modules can be combined to deliver 20 KW. The mechanical arrangement is shown in Figure 20.

Figure 20

Figure 21

The efficiency of a 20 KW amplifier is calculated as follows:

DC Power - PA @ 80%	21.0 KW
DC Power - Driver @ 80%	1.387 KW
DC Power - Pre-Driver @ 80%	.125 KW
Combiner Loss Output	.80 KW
Divider Loss	.050 KW
Input Power	.02 KW
Output Power	16.000 KW
Total Power Input	22.535 KW
Power Dissipated	6.535 KW
Efficiency = Output Power	x 100% = 71%

Total Power In

The 4 KW amplifiers will have an output impedance of 10 ohms. Five of these amplifiers will be combined in series as shown in Figure 22.

Combining transformers of this type are commonly used. The phase of each amplifier with its output 10 ohm line will be adjusted for perfect in phase combination. The length of each 10 ohm line will also reflect a short circuit to the combining point when the transistor fails open. The input combiner will be similar except isolation resistors will be added to insure good power sharing.

Amplifier DC will also be connected in series with each amplifier isolated from ground. Each amplifier will have a zener diode sense circuit that will switch in an equivalent load in the event of amplifier failure.

Total current required when the amplifier is delivering 16.0 KW is 90 Amps (250 volts).

Figure 22

One 500 KW amplifier can be constructed by combining 32 of the 20 KW units as shown in the system diagram of Figure 21. The mechanical arrangement is shown in Figure 23. The system has comfortable power margin to allow each amplifier to operate with just enough power output to provide the overall 500 KW. Each 20 KW amplifier will have a nominal output of 16 KW.

The block diagram of the 500 KW amplifier is shown in Figure 9. A possible mechanical arrangement is shown in Figure 10 to demonstrate approximate size and weight.

Efficiency for the total 500 KW amplifier is:

Total Power in 20 KW Amps x 32	721.12 KW
Loss In Output Combiner	12.05 KW
Loss in Input Splitter	0.03 KW
Total Power Into Control Amplifier	1.4 KW
Power Output	500.00 KW
Control Amplifier Output	0.70 KW
Total Power Input	722.52 KW
Total Power Dissipation	222.52 KW
Efficiency =	69.2%

Amplifier Weight is as follows:

Cabinet Structure	50 Pounds
Output Combiner	40 Pounds
32, 20 KW Amplifiers	128 Pounds
Control Amplifier	5 Pounds
Control System	5 Pounds
Coolant Distribution	60 Pounds
DC Distribution & Control Cables	40 Pounds
Misc.	2 Pounds
	<hr/>
	330 Pounds

FREQUENCY: 425 MHz
 WEIGHT: 330 lbs.
 VOLUME: 8.9 ft.³

20 KW AMPLIFIER
 8 AMPLIFIERS EACH QUADRANT
 32 AMPLIFIERS TOTAL

30 dB GAIN
 64 oz.

500 KW CW AMPLIFIER

Figure 23

$$\text{Total Volume } 17 \times 36 \times 25 = 15,300 \text{ in.}^3$$

$$= 8.9 \text{ FL}^3$$

$$\text{Volume Ratio} = 32.7 \text{ Watts/in.}^3$$

$$\text{Weight Ratio} = .0106 \text{ oz./Watt} = .301 \text{ Gm/Watt}$$

The above ratios and the efficiency can be scaled to 850 MHz. Figure 12 shows actual efficiency data taken on state-of-the-art transistors. The 12 micron geometry and process (B) is the current device used in the CW amplifier developed for WPAFB. The 6 micron geometry and process (A) is the new two layer metal device currently used for L and S band radar applications. Dotted lines are projections beyond actual tests. The efficiency drops off 10% per octave. If the best available transistors are used at each frequency, this will continue to be true. Average amplifier stage gain will continue to be the same at 800 MHz due to a change from common emitter (at 425 MHz) to common base.

MMD current thinking suggest that a 500 watt transistor is now possible at 850 MHz. Therefore, the total number of output modules will increase only enough to cover increased losses in system components. The combiners and module impedance networks are slightly smaller and lighter. Total system weight should be approximately the same as the 425 MHz weight. Table 5 summarizes MMD's best estimates for each frequency range.

Key areas where substantial development is required to meet MMD estimates.

- Cooling with low temperature liquids.
- Transistor device development for low temperature optimization.
- Combining large numbers of amplifiers efficiently.
- Improved circuit components.

(A) BEST POSSIBLE
EFFICIENCY USING
6 JJ PITCH
GEOMETRY

(B) EFFICIENCY FOR
12 JJ PITCH
GEOMETRY

Table 2

ESTIMATED PERFORMANCE SUMMARY

Parameter	425 MHz	800 MHz
Largest Transistor	500 W	500 W
Transistor Collector Eff.	85%	75%
Transistor Gain	12 dB Common Emitter	12 dB Common Base
500 KW Amplifier		
Weight	330 Lbs.	330 Lbs.
Size	8.9 Ft.³	8.9 Ft.³
Efficiency	69%	60%

REFERENCES

1. N. Goldberg, "Narrow Channel Forced Air Heatsink," IEEE Trans. on Components, Hybrids, and Manufacturing Technology, Vol. CHMT-7, No. 1, March 1984
2. D. Tuckerman, "Heat-Transfer Microstructures for Integrated Circuits", Dissertation submitted to Stanford University, Feb. 1984, (only selected portions included).

APPENDIX D

SUMMARY OF PROSPECTOR I
KEY ISSUES IN SPACE TECHNOLOGY

THERMAL MANAGEMENT OF SPACE BASED HIGH POWER RF
SOURCES

M. FRANK ROSE

APPENDIX D

SUMMARY OF PROSPECTOR I

RATIONALE

The multitude of tasks envisioned by space planners for the coming space programs are all power intensive and will require drastic changes in the way we power future spacecraft. As the power requirements approach those of terrestrial demands, designers are faced with a series of options none of which lead to a spacecraft with minimum weight and volume. On the one hand, high voltage-low current systems minimize the mass of conductors used in transmission/distribution systems but quickly become useless without heavy insulation. This is due to the limits imposed by the local plasma/gas conditions around the spacecraft. In general it is not presently practical to run transmission lines at voltages exceeding one hundred volts. The alternate is to lower the voltage and raise the current, since power is simply the product of these two parameters. Multi-megawatts of power now demand megamp currents. These current levels translate immediately to massive conductors. If the conductors are not properly sized, thermal runaway occurs and the system is catastrophically destroyed. The highest powered system actively flying is the space shuttle. It has 36 kW on board and stays in orbit only a few days. The shuttle is a man-rated structure in which the power system is treated much as it would be in a terrestrial application. The most demanding of the futuristic applications need multi-megawatts. The obvious discrepancy between state-of-the-art and anticipated future needs points clearly to the objectives of the Prospector series of workshops--To explore key issues in space technology.

Obviously there are tradeoffs which will involve thermal management of the waste energy produced throughout any space system. The thermal management of the spacecraft is intimately associated with all aspects of the spacecraft from the power source to the load. There are only three options for controlling and disposing of waste energy on board a spacecraft. The waste will be stored on board for later disposal, radiated to space through a suitable structure, or "thrown overboard" in the internal energy of a suitable effluent.

Against this backdrop, the Space Power Institute, Los Alamos National Laboratory, the Wright Research and Development Center, and the Rome Air Development Center sponsored the first of the Prospector series of seminars and workshops on key issues in space technology. The subject of this first workshop is the Thermal Management of High Power Sources and Radio Frequency Devices to be found in Space-Based Systems.

Objectives

The objectives of Prospector I were designed to focus attention to technological impediments, clarify the issue sufficiently to suggest research, and try to envision the impact to future systems designs. The following are the primary objectives as given in the charge to the workshop participants:

- Characterize innovative thermal management concepts and their applicability to space power components
- Assess the state-of-the-art of generic thermal management techniques
- Identify the key research issues pacing the development of efficient, high-power, space-based RF sources

- Clarify the thermal system issues which must be addressed as part of overall spacecraft design
- Distinguish the limitations imposed by technology from those imposed by nature
- Establish guidelines for the consistent evaluation of thermal management techniques within an overall system concept
- Evaluate the available power sources appropriate for driving RF converters within the constraints of overall thermal management, weight and volume
- Evaluate the power conditioning technologies appropriate for matching RF converters with power sources, again within the constraints of overall thermal management, weight and volume.

WORKSHOP ORGANIZATION

The conference was four days long and was patterned after the highly successful Gordon Conferences. Sessions lasted from 8 AM to 12 Noon and from 7 PM until 10 PM, thereby allowing the participants to relax, break into smaller groups, or enjoy the local surroundings.

After a series of tutorials, the workshop was divided into the following working sessions:

Prime power and power conditioning for RF sources
Chairman: A. S. Gilmour, Jr. SUNY

Thermal management of microwave linear and crossfield tubes
Chairman: N. J. Wilson Private Consultant

Thermal management of microwave solid-state devices

Chairman: J. H. Johnson MMD Inc.

RF source-accelerator interactions

Chairman: D. W. Reid LANE

Attendance in each group was assigned, based upon expressed interest with the option to move to another group after the second day. Since many of the technologists in attendance were multidisciplinary, this rotation was highly valuable to the workshop output.

CHARGE TO THE WORKING GROUPS

The workshop organizers, in conjunction with key technologists assembled a list of key questions to be used as guidance by each of the working groups:

Prime Power and Conditioning

What is the SOA in PP and PC?

What are the key components requiring thermal control?

What are the allowed temperature swings and the maximum temperature?

Are there clear and ready technologies for thermal management?

How does thermal management contribute to power density? Was it included in SPAS, CARDS assessments?

How long can PP and PC operate adiabatically?

What is the minimum TM that the overall system will allow in the PP and PC subsystems?

How do other system components influence PP and PC issues?

What are some innovative/unproven concepts that might come into play in TM for PP and PC?

What are the key figures-of-merit for comparison of TM concepts? How does PP and PC TM influence *total spacecraft design*?

- Do PP and PC require certain S/C orientation?
- To what extent are vibration and effluent issues key to S/C design?
- How does TM affect radiator-sensor interactions, mass, volume, safety, redundancy, reliability?

Linear and Crossfield RF Tubes

What is the SOA in linear and crossfield tubes?

What are the key components requiring thermal control?

What are the allowed temperature swings and the maximum temperature?

Are there clear and ready technologies for thermal management?

How does thermal management contribute to power density? Was it included in SPAS, CARDS assessments?

How long can linear and crossfield RF tubes operate adiabatically?

What is the minimum TM that the overall system will allow in the Linear and crossfield RF tubes subsystems?

How do other system components influence linear and crossfield RF tubes issues?

What are some innovative/unproven concepts that might play in TM for linear and crossfield RF tubes?

What are the key research issues for linear and crossfield RF tubes?

What are the limitations imposed by nature on the TM aspects?

What are the key figures-of-merit for comparison of TM concepts?

How does Linear and crossfield RF tubes TM influence *total spacecraft design* ?

- Do linear and crossfield RF tubes require certain S/C orientation?
- To what extent are vibration and effluent issues key to S/C design?
- How does TM affect radiator-sensor interactions, mass, volume, safety, redundancy, reliability?

Solid State RF Devices

What is the SOA in solid state RF devices?

What are the key components requiring thermal control?

What are the allowed temperature swings and the maximum temperature?

Are there clear and ready technologies for thermal management? How does thermal management contribute to power density? Was it included in SPAS, CARDS assessments?

How long can solid state RF devices operate adiabatically?

What is the minimum TM that the overall system will allow in the solid state RF devices subsystems?

How do other system components influence solid state RF devices issues?

What are some innovative/unproven concepts that might play in TM for solid state RF devices?

What are the key research issues for solid state RF devices?

What are the limitations imposed by nature on the TM aspects?

What are the key figures-of-merit for comparison of TM concepts?

How does solid state RF devices TM influence *total spacecraft design* ?

- Do solid state RF devices require certain S/C orientation?
- To what extent are vibration and effluent issues key to S/C design?
- How does TM affect radiator-sensor interactions, mass, volume, safety, redundancy, reliability?

RF-Accelerator Interactions

What is the SOA in accelerator design, and what does this mean for the RF source?

To what extent are RF coupling and TM isolation mutually exclusive issues?

What are the allowed temperature swings and the maximum temperature for the accelerator?

What are the cryogenic parameters for the coolant at the exit from the accelerator?

Is there a preferred feed geometry? What are the pros and cons of multiple feeds?

What is the SOA in RF accelerators?

What are the key components requiring thermal control?

Are there clear and ready technologies for thermal management of the accelerator?

How does thermal management contribute to total system mass and volume? How was it addressed in SPAS, CARDS assessments?

To what extent can the system operate adiabatically?

What is the minimum TM that the overall system will allow in the accelerator subsystems?

How do other system components influence accelerator TM issues?

What are some innovative/unproven concepts that might come into play in TM for accelerators?

What are the key research issues for RF accelerators?

What are the limitations imposed by nature on the TM aspects?

What are the key figures-of-merit for comparison of TM concepts?

How do accelerator TM issues influence the total S/C design?

- Do accelerators require certain S/C orientation?
- To what extent are vibration and effluent issues key to S/C design?
- How does TM affect radiation-sensor interactions, mass, volume, safety, redundancy, reliability?

SUMMARY RESULTS

In the interest of space, the reader is referred to the proceedings of the workshop for the detailed output of the various working groups. In this report, only the future needs, critical developments, etc. will be reported.

Prime Power and Power Conditioning

The Prime Power and Power Conditioning group recommended the following:

- Detailed systems trade-off studies
- Studies of alternator transient conditions/energies/fault energy with load interruption
- Maximum temperature and maximum temperature swing for candidate switches.
- State and impact of high temperature electronics.
- Establish a data bank on both cryogenic and high temperature electronics
- Potential for use of phase change materials in converters.
- Exploration of advanced transformer designs for both adiabatic and cryogenic applications
- Advanced regulators for cross-field tubes.

Thermal management of Linear and Cross-Field RF Tube Amplifiers

In addition to a detailed account of the state-of-the-art, this group offered the following summary remarks and the accompanying table:

- RF tubes do not appear to be limited by any fundamental principles:
- Performance levels at 500 kW have been demonstrated on a pulse basis.
- Computations support the feasibility of cooling with hydrogen.
- New materials and heat pipe improvements offer trade off options.
- Confirmation data is required for:
 - performance of RF tubes into high VSWR cavity loads
 - consistency of phase and amplitude control values with LINAC time constraints
 - cooling of RF tubes with supercritical hydrogen at temperatures of 35 K and 30 bars pressure
- Cross-Field amplifiers:
 - Data needed to determine effectiveness of H₂ cooling at vane heat flux densities of 1.2-2.0 kW/cm²
 - verification of amplitude control at 0.25 dB level using voltage, magnetic field, or RF control
- Klystrodes:
 - Data needed using H₂ as the collector coolant
 - Impact of redesign with new materials must be assessed.

The following table is a technology assessment of the various cooling schemes investigated in general reference 1.

Summary of Cooling Techniques

TECHNIQUE	MOST DESIRABLE CHARACTERISTIC	LEAST DESIRABLE CHARACTERISTIC	RANKING
Direct hydrogen cooling	<ul style="list-style-type: none"> •Collector remains at 'low' temperature •Uses existing onboard hydrogen •Capable of cooling both collector types •Low collector mass 	<ul style="list-style-type: none"> •Requires extensive plumbing •Potential hydrogen diffusion problem •Complex valves to eliminate single point failure modes 	HIGH
Direct radiation to space	<ul style="list-style-type: none"> •Totally passive •Proof-of-principle demonstrated •Low collector mass •Capable of cooling both collector types 	<ul style="list-style-type: none"> •Collector must run hot •Potential thermal coupling to accelerator •Thermal assisted voltage flashover •External appendages to S/C 	MIDDLE
Thermal storage	<ul style="list-style-type: none"> •Totally passive •Low collector mass •No external appendages •Capable of cooling both collector types 	<ul style="list-style-type: none"> •Collector must run hot •Potential thermal coupling to accelerator •Potential hydrogen diffusion problem •Complex fabrication necessary 	MIDDLE
Heat pipes/Coolant pipes	<ul style="list-style-type: none"> •Established technology •Adaptable to complex geometries •Capable of cooling both collector types 	<ul style="list-style-type: none"> •Auxiliaries required •High mass •Needs heat exchanger to hydrogen or radiator •Must keep coolants from freezing 	LOW
Beam exit to space	<ul style="list-style-type: none"> •Simple design •Low mass •Special case of direct radiation to space concept 	<ul style="list-style-type: none"> •Perturbs local plasma •Possible S/C charging •Requires complex valving •Opens tube to uncertain environment 	LOW

Thermal management of solid state devices

As in the other groups, this group investigated a number of innovative ideas which might be useful in a systems context if further studies could be done to evaluate their effectiveness. Among the most promising are:

- Use a high temperature superconductor as a fuse element in a transistor to turn off the current if overheating occurs.
- Use sub-cooled boiling to cool transistors.
- Use spray impingement cooling for both back and front sides of silicon chips.
- Further integrate the amplifier circuit and active device.
- Introduce turbulent flow in the microchannels to further increase cooling.

This group also had concerns for system interface issues such as:

- Temperature differential between the amplifier and accelerator through the short RF connector/feed system.
- Ramp up time of the H₂ as it cools the RF system.
- High VSWR of accelerator during turn on and beam turn off may influence design of RF amplifier.
- Low voltage DC requirements is 50-250 volts and is a design decision. How much overvoltage can be tolerated and for how long.
- Loss of coolant cannot be tolerated for more than 1 second.

The group summary conclusions tend to put in focus the art with respect to the alternate method of producing high power RF in advanced space systems:

- Solid state amplifiers are a valid alternative to vacuum tubes.
- Cooling must be accomplished by using the supercritical H₂ stream.
- The best method for cooling the transistors is to use microchannel heatsinks immediately beneath the transistor.
- Cooling may be accomplished by allowing the H₂ a temperature increase of 135 K, a mean velocity around 1 m/s, and a pressure drop of 1 to 2 bars.
- The amplifier should be maintained at a temperature of 100 to 200 K during dormant periods.
- The amplifier will operate at a junction temperature from 100 to 200 K.
- Silicon is the only choice of material for the transistors at present.
- Moving the high pressure H₂ around the system is not a major problem and is not excessively heavy (probably less than a 10% weight penalty).

RF Accelerator Interaction

The RF accelerator interactions group had the following list of specific recommendations:

- A specific test/start-up sequence needs to be verified by an appropriate authority and available as baseline.
- Specific platform components need to be chosen such that a detailed hydrogen flow diagram can be produced.
- An experimental transmission line, complete with connectors, needs to be constructed for research.
- The concept of lengthening RF transmission paths in order to shorten prime power paths such that overall efficiency is increased needs to be investigated.
- Specific reliability and redundancy criterion need to be established.
- The concept of recuperating hydrogen needs reinvestigating.

The above is a brief summary of the principal conclusions and recommendations from the Prospector I. The reader is referred to the proceedings of the workshop which are available through the sponsors and the Space Power Institute.