TM no. M62-78-01

TECHNICAL MEMORANDUM

title: Investigation of the State-of-the-Art in Power Handling Capability of Solid State Devices

author: James L. Brooks

date: January 1978

sponsor: Naval Facilities Engineering Command

program nos: YF53.534.091.01.104

CIVIL ENGINEERING LABORATORY
NAVAL CONSTRUCTION BATTALION CENTER
Port Hueneme, California 93043

Approved For Public Release; Distribution Unlimited

CONTENTS

INTRODUCTION

The need for power conditioning for increasing utilization of critical electronic loads has been a prime factor in creating a technology revolution in solid state power devices. There are numerous potential applications of these devices to Navy electrical systems, but the new technological capabilities must be thoroughly understood before applications can be formulated and developed. Naval Facilities Engineering Command has tasked the Civil Engineering Laboratory (CEL) with an investigation of the state-of-the-art capabilities of solid state power devices as they apply to Navy electrical systems. The results of the literature and industry search into solid state component limits, which was the first phase of the investigation, were reported in reference 1. As a result of this first phase, further investigation was found to be necessary in the areas of solid state component design techniques and the latest techniques for removing heat from solid state components. These studies were conducted by contract for CEL and are reported in references 2 and 3 respectively.

~~This memorandum was prepared as an internal working document, therefore, its distribution is limited to U.S. Government agencies only, and disclosure of all or part of its contents outside the Government must have prior approval of the Civil Engineering Laboratory or the sponsor of the work reported.~~

BACKGROUND

Both within the Navy and in the private sector, near-capacity conditions are common in electrical power systems, and it is unlikely that relief will come in the future as non-electrical loads are converted to utilize electricity produced from sources other than fossil fuels. In addition, the electronic loads are becoming more susceptible to electrical power anomalies which result from surge effects elsewhere in the distribution system as well as from the electronic loads themselves.

The need for power conditioning to assure the reliable flow of quality electrical power has opened up a whole new marketplace for solid state device manufacturers. Power handling capability of off-the-shelf components has increased profoundly in the last five years, and the ability to utilize these devices has been enhanced with the development of inexpensive, small-scale electronic control circuits.

There has been a dramatic increase in Navy requirements for no-break power and improved transient suppression. Alternate energy sources are receiving considerable attention for application to remote bases. The cost of energy is making it economically feasible to shift loads to station-generated electricity during peak usage. All these are potential applications of solid state power conditioning.

ACCOMPLISHMENTS

Solid State Component Characteristics

Probably the most significant results of the literature and industry search is the knowledge that state-of-the-art power handling capabilities of solid state devices are changing rapidly. The market is continually expanding and requiring higher voltage and current ratings with faster switching speeds. Thus it is not possible to say that the literature search has been completed; rather, it must be continuously updated to follow new advances in device capability.

Silicon controlled rectifiers (SCR's) have been utilized as power handling devices for some time, but recent developments have given them the ability to handle bulk power. Currently, devices are commercially available which can block 2,500 volts and carry 1,875 amperes of current in their "on" state. Cost is high for these devices since the market does not yet demand them in sufficient quantities to make them off-the-shelf items. An SCR capable of handling 2,500 amperes and blocking 1,600 volts can be purchased for about $800 (Figure 1).

SCR's suffer from one basic shortcoming for power conditioning: a pulse at the gate will turn the device on at any point in the AC waveform, but it can be turned off only at a zero crossover unless elaborate commutating circuitry is utilized. A promising method of overcoming this shortcoming is development of a device called a gate-turn-off (GTO) SCR. This device is designed so that a reverse polarity pulse applied at the gate will turn the device off. However, at the present state-of-the-art, quite a large pulse is required to accomplish the turn-off, and many manufacturers feel that the device is not practical beyond its present capability of about 10 amperes. Further research is being conducted in industry to determine the future of this device.

A development with tremendous potential for Navy applications is the increasing power-handling capacity of transistors. Transistors are capable of more complete control of a waveform than SCR's because transistors are more easily turned off. Power transistors are now replacing

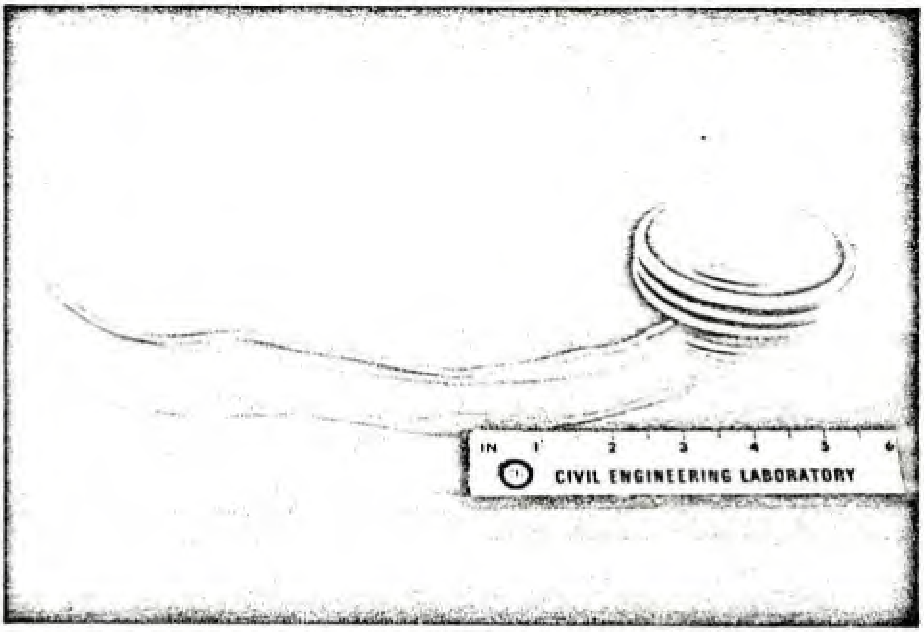


Figure 1. SCR With Blocking Voltage of 1600 Volts and ON State Current of 2500 Amps.

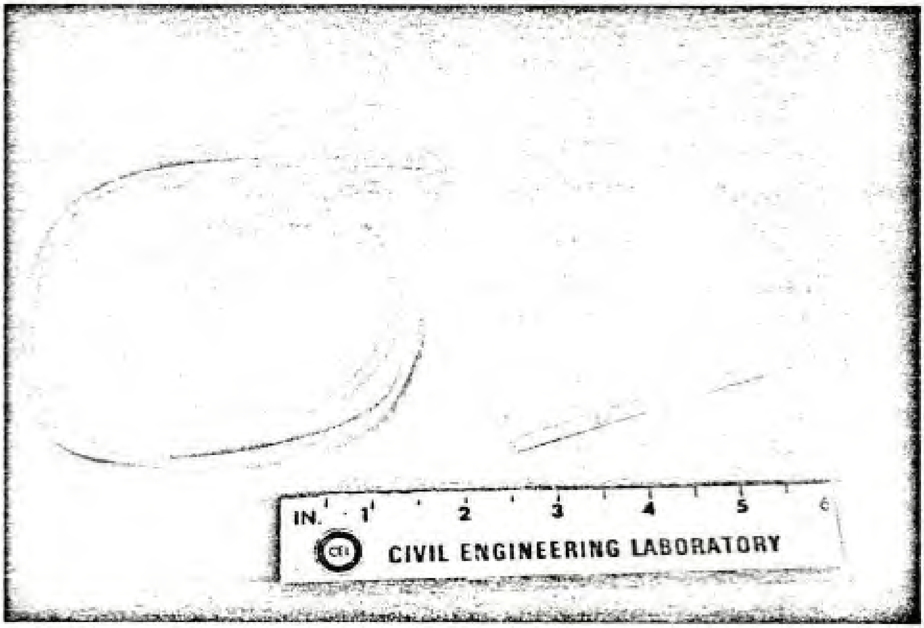


Figure 2. Transistor Pack Rated at 80 Volts and 1200 Amps.

SCR's in power conditioners in the five to fifteen kilowatt range (reference 2). This is due to a number of factors in addition to new power capabilities, including faster switching speeds and simpler drive circuitry. Predictions indicate that silicon power transistors will constitute one-fourth of a three-billion dollar market in discrete semiconductor devices by 1980 (reference 2). Power transistors rated at 80 volts and 1,200 amperes are commercially available for about $800 (Figure 2). The state of the art in power transistor technology is summarized in Figure 3.

An obvious shortcoming of the present power transistor technology is the lack of PNP devices with power capacities near those of silicon NPN devices. Complementary pairs of NPN and PNP transistors are desirable in many circuit designs including conditioning of AC power.

Solid State Component Design Techniques

Another important finding is that conventional circuit design techniques may have to be modified when incorporating high power devices into complex circuits. This is due to the importance of considering operating characteristics which not only are nonlinear, but also differ considerable from comparable characteristics in small signal devices. A good example is forward current gain (β) in a transistor. This parameter may show both increasing and decreasing trends with variations in operating current over the desired range.

There is general agreement in the industry that conventional methods for rating and characterizing the devices in terms of familiar small-signal parameters are not meaningful to the power circuit designer. Efforts are just getting under way in industry to establish new design techniques and new parameters for evaluating power device performance.

A contracted portion of this investigation, reported in enclosure (1) surveyed appropriate computer aided design and analysis (CADA) programs available for use in designing solid state devices/circuits for conditioning high levels of electrical power. Two selected programs (SPICE 2 and SUPER*SCEPTER) are presented and described in detail. This study also presents proven mathematical models of four typical solid state components: solid state diode, Zener diode, transistor, and silicon controlled rectifier. These models are broad enough in scope to accommodate both high-power and low-power devices.

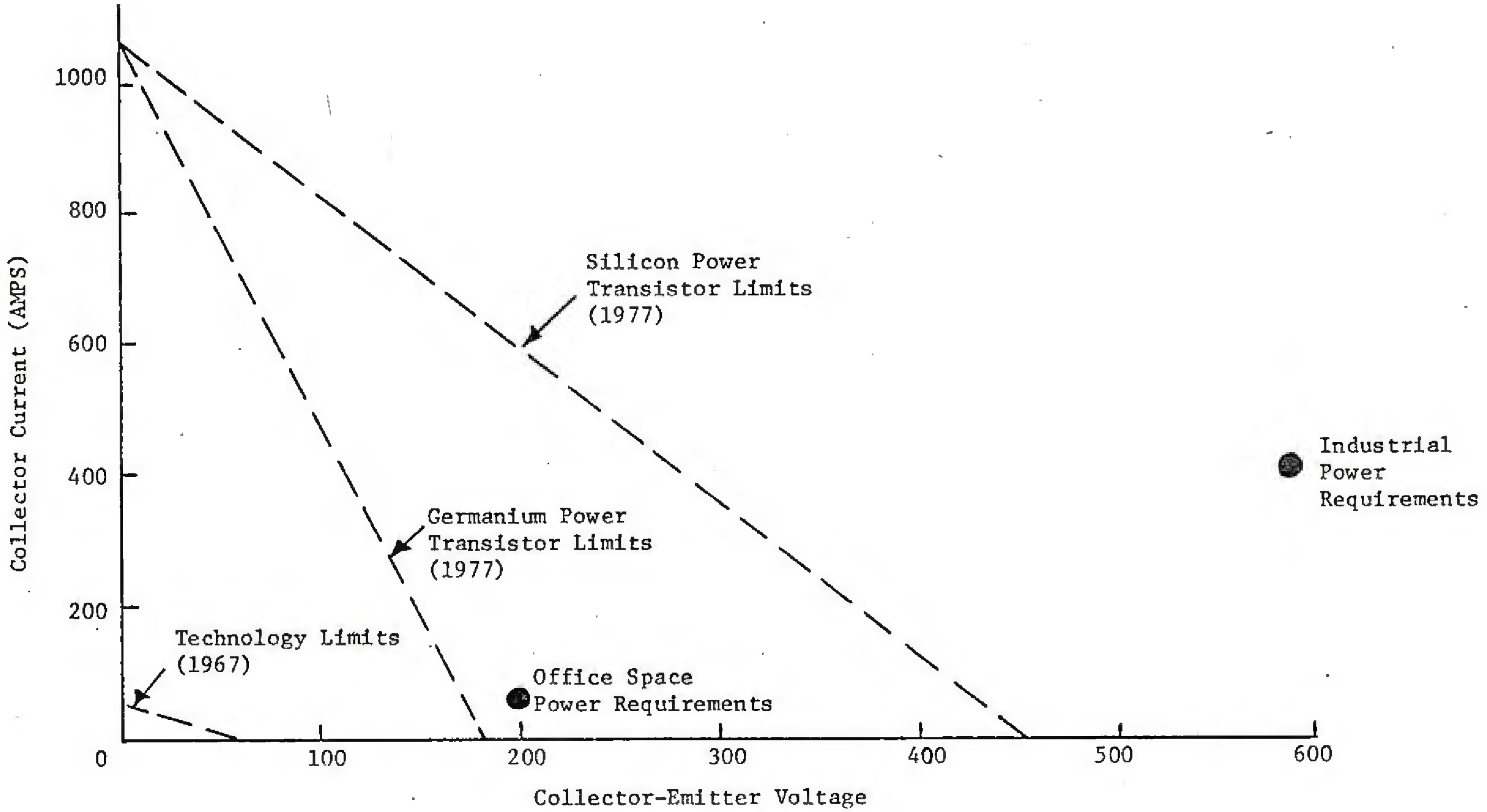


FIG. 3. TECHNOLOGY LIMITS FOR OFF THE SHELF POWER TRANSISTORS

A problem has been identified which involves the characteristic parameters of the devices to be used in the mathematical models. These parameters, which are required as input to the computer programs, are not generally available from the manufacturers of the devices, and must be measured by the user.

Heat Removal from Solid State Components

A final technological area of interest is the need for heat sinking of high power devices. Presently, the design engineer must quite often deal with cooling "after the fact". However, design for cooling the device is a necessary part of the design of the end equipment and should be an integral part of the design process. Special designs are being developed for the components themselves to alleviate the heat removal problem, and many types of heat sinks, both air and water cooled, are available. Careful attention must be paid to the heat sinking since power handling capabilities of the devices are sensitive functions of the ability to remove heat. A whole new area of expertise is necessary to ensure adequate design of the heat sink system.

As a portion of this investigation, a contractor was engaged to survey and review the present status of heat removal from solid state electrical power components (enclosure 2). Based on this additional research,(enclosure 2)presents a general review and analysis of heat transfer and cooling methods as related to electronic and electrical equipment. These methods include various separate or combined applications of conduction, convection, evaporation, and radiation. This review examines currently available solid state devices, including the new transcalent devices, which are semiconductors with integrally incorporated heat pipes. It was found that water cooled hockey-puck shaped semiconductors with water passageways within the pole pieces will convey the highest current of any currently available devices, and that while the transcalent semiconductors do not perform better than water cooled devices, they represent the best available units from a weight standpoint when air cooled heat sinks will suffice. Enclosure 2 summarizes the present state of the art of heat removal from high-power solid state devices.

CONCLUSIONS

1. The present state of the art in SCR's is thousands of volts of blocking capability and thousands of amperes of on-state current in the same device.

2. State-of-the-art power transistors are replacing SCR's in switching applications up to 15KW. Power transistors provide more complete control of the power waveform with simpler drive circuitry.

3. Of all the computer aided design and analysis (CADA) programs evaluated, two are recommended for use in analyzing high power solid state devices. These are code-named SPICE 2 and SUPER*SCEPTER.

4. Mathematical models have been developed and proven for every solid state power device.

5. The characteristics of the solid state devices, which are the design parameters required as input to the computer programs using the mathematical models, must be measured, as they are not generally available from the manufacturers of the devices.

6. Water cooled hockey-puck type semiconductors with water passageways within the pole pieces carry the highest current of any currently commercially available devices.

7. Although transcalent semiconductors do not perform better than water cooled devices, they represent the best available units from a weight standpoint when air cooled heat sinks will suffice.

RECOMMENDATIONS

1. Periodic updating of the state-of-the-art search should be conducted to stay abreast of future developments.

2. Potential improvements in electrical power systems using solid state technology should be investigated.

PLANS FOR FUTURE WORK

1. Design parameters for typical solid state power components will be measured.

2. Feasibility studies will be made for the most promising concepts for improving electrical power systems.

REFERENCES

1. Civil Engineering Laboratory. Technical Memorandum No. M-62-77-03: Investigation of the state of the art in power handling capability of solid state devices, by Roger I. Staab, Ph.D., and James L. Brooks. Naval Construction Battalion Center, Port Hueneme, CA 93043. January 1977.

2. Walt Gorrell. Keynote address, Proceedings of POWER CON 3 (Third National Solid State Power Conversion Conference), Beverly Hills, CA. June 1976. pp. KN3-4.

BIBLIOGRAPHY

1. Allan, Roger (1975) "Power semiconductors", IEEE Spectrum, Vol 12, No. 11, November 1975, pp. 37-44.

2. Newell, William E. (1974) "Power electronics - emerging from limbo", IEEE Transactions on Industry Applications, Vol. IA-10, No. 1, January-February 1974, pp. 7-11.

3. Watson, William "The advantages of power transistors", Westcode World (Semiconductor Division, Westinghouse Brake and Signal Company, Ltd., Cowansville, Quebec), p. 2.

4. Solid State Power Conversion Magazine, all issues.

5. See extensive bibliographies in enclosures 1 and 2.

FINAL REPORT

for period August, September, October 1977

CADA PROGRAMS AND SOLID-STATE MODELS

Performed under NAVY P. O. NO. N62583/77 M R840

Naval Construction Battalion Center, CEL

Port Hueneme, Calif. 93043

James Brooks, Jr., Project Director

Work Director: Dr. James C. Bower
1348 Eckles Drive
Tampa, FL 33612
(813) 932-9853

FINAL REPORT

The purpose of this report is to summarize the available computer aided design and analysis (CADA) programs and to indicate the solid-state model configuration for power devices.

CADA Programs

Reference 1, enclosed, is a complete survey of all the appropriate CADA programs. Part I of this reference contains a mini-manual of every program. The mini-manuals contain detailed instructions for operating each of the programs. The Date of Release, Input Format, Output, Topological Limits, Language, Hardware and Availability are listed for each program. A complete practical example and detailed listing is also shown for each program.

In Part II of Reference 1, all of the CADA programs are evaluated by running eighteen widely varying circuits on each program. The results, advantages and disadvantages are summarized.

From the above Reference, from experience and from other sources, the two programs recommended to the Navy, as a result of this investigation, are SPICE 2 and SUPER*SCEPTRE.

Both programs can be made available to the NAVAL CONSTRUCTION BATTALION CENTER via the Control Data Corporation's Cybernetics Terminal. This terminal is already available at Port Hueneme and the CDC versions of the two programs are also available. To expedite matters, these two tapes will be forwarded directly to the CDC Los Angeles office, as a part of this study, at no additional cost to the government.

To properly use these two programs, user's manuals are necessary. The SPICE 2 program has a short manual which is enclosed as Reference 2. The SUPER*SCEPTRE program has two user's manuals. The enclosed textbook (Reference 3) describes how to use the program for all electrically oriented problems. Chapters 2 and 4 of the book outline the procedures and give many examples. Reference 4 is the SUPER*SCEPTRE user's manual and it indicates how to use all of the new, additional features which have been incorporated into the program, besides the pure electrical capability. The manual discusses and gives examples on how to use SUPER*SCEPTRE in the areas of mechanical, transfer functions, digital building blocks, non-linear blocks and any combinations of the above, including the original electrical components.

The two selected programs offer total coverage. Simply stated, if the problem to be analyzed contains only electrical components, with typical models, the SPICE 2 program is much faster and offers a wider range of analysis tools. If, however, the problem to be analyzed contains any non-electrical components, any non-linear equations or tabulated data, or if it requires any new or unusual model, the SUPER*SCEPTRE program is ideally suited to use. The CPU time will be longer, but no other program even approaches SUPER*SCEPTRE on versatility. In other words, any problems which can be run on SPICE 2 should be, all others should be run on SUPER*SCEPTRE with assurance that there is almost no problem of any type which it cannot handle effectively and accurately - and from a user's standpoint, in a very straight-forward and easy to code manner.

Simple examples* using each program will be given, followed by a summary of the program features.

The first several statements are used to define the transistor used for this circuit. In the SPICE 2 program the model equivalent circuits are all "built-in" for each solid-state device. Therefore, the user need only to state the values of the various parameters for the transistor being used. Section 2 of the Report discusses where these numbers come from for each different device. Unfortunately, they do not come from the data sheets.

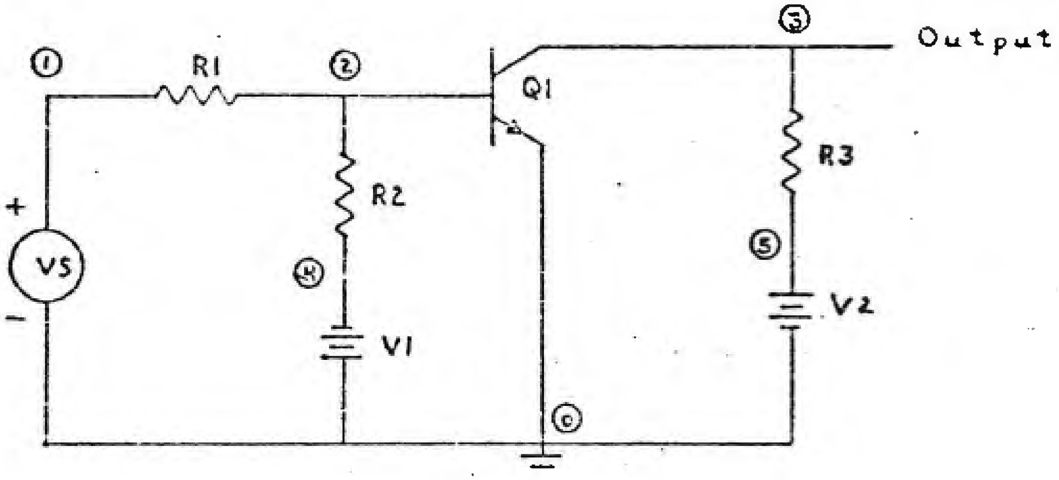
The other statements listed define the other circuit elements. Each statement is typed on a card, and the total is the complete deck necessary to run the problem. Certain control cards are needed on the top and bottom of the SPICE deck to call up the program, make the necessary charges to the user's job number, etc.

The details can be seen by studying the SPICE user's manual, but the procedures are seen to be simple. For example, to "enter-in" R2, all that is necessary is to state R2, the nodes connected and its value, 100KΩ. No

---

*Note to Reader: Solid-state models will be used in each of the following examples. If you are not already familiar with the CADA type solid-state models or equivalent circuits, simply overlook that portion of the examples until you have read the second section of this Report. In the second section models are explained and discussed in detail.

Figure 1. Single transistor inverter



```
CKT 1:  SINGLE TRANSISTOR INVERTER
.MODEL X2222A NPN (RB-1,RC=.27,RE=.20,
+                 BE=52,BR=6.76,
+                 CJE=21.7PF, CJC=10PF,
+                 TF=1E-21,TR=1.21E-21,
+                 IS=1E-14,C2=4.29,C4=5.78)
VS   1   0   PULSE (0   5   10US)
V1   0   4   10
V2   5   0   10
R1   1   2   10K
R2   2   4   100K
R3   3   5   970
Q1   3   2   0   X2222A
.PLOT TRAN V(1), V(3.0)
.TRAN .2US   20US
.END
```

Figure 2: SPICE 2 Coding for single transistor
Inverter of Figure 1

extraneous data is required and the user does not have to write any equations. The user only states the basic information in a very simple manner, and the program automatically both writes and solves all of the necessary electrical equations. It then prints out data and curves for all of the requested outputs.

The program features are as follows:

Network elements.

The circuit elements are specified by an element name of up to 8 characters, followed by the element node specifications and the element values. Element name prefixes are:

R	resistor
C	capacitor
L	inductor
K	mutual inductor
V	independent voltage source
G	nonlinear voltage-controlled current source
E	nonlinear voltage-controlled voltage source
F	nonlinear current-controlled current source
H	nonlinear current-controlled voltage source
I	independent current source
Q	Gummel-Poon transistor
D	Junction Diode
J	JFET
M	MOSFET
X	Subcircuit

The R and G elements must be constants, however, the C.L.G.E.F and H elements may be expressed in a nonlinear polynomial format. The independent sources may be constants or any of the functions. The models Q,D,J and M are designated as models. The subcircuit is a user-defined subcircuit.

Functions.

Any of the following functions may be used as values for independent sources:

Constants: AC or DC constant values. Constants may be suffixed with scaling factors as: $G = 10^9$, $MEG = 10^6$, $K = 10^3$, $M = 10^{-3}$, $U = 10^{-6}$, $N = 10^{-9}$, $P = 10^{-12}$.

Pulse: The pulse is defined with high and low values, rise and fall times, and pulse width and repetition rate.

Sinusoidal: exponentially decaying sinusoid.

Exp: sum of two exponential waveforms.

Piecewise linear: tabular function of time.

SFFM: single frequency, frequency modulated carrier waveform.

Models.

Built-in semiconductor Models

Gummel-Poon semiconductor models for bipolar transistors (NPN or PNP), junction diodes, junction field-effect transistors, and MOS field-effect transistors are described under the .MODEL control card. Each model is defined by over-riding default values of such parameters as saturation current, transient times, and semi-conductor junction resistances. Flicker noise response is included in these specifications. Semi-conductor models use standard terminology.

Subcircuits

Between the .SUBCKT and .ENDS controls, a list of circuit elements may be given to define an effective model. Subcircuits may be nested to any level and semiconductor models may be used within the subcircuit.

Outputs

Outputs are defined on the .PRINT and .PLOT control cards for tabular printing or line-printer plotting of outputs. These control cards define the output format of the DC, AC or transient response results. Only node voltages or voltage source currents may be requested. Noise and distortion outputs are also requested on these control cards.

Initial Conditions

Initial capacitor voltages and inductor currents are supplied following the value on the element specification card.

Run Controls

The .OPTIONS control card defines the run conditions. The options available include:

Tolerance adjustment: relative tolerance default .1%
absolute tolerance default 10^{-12} amps
transient tolerance default 10
charge tolerance default 10^{-14}

Iteration limits

Integration method: Gear of user-supplied maximum order 2 through 6 or trapezoidal.

Types of Analysis

.OP	Compute operating point
.DC	Compute DC transfer curves for given source variation within limits given.
.TF	Compute small signal DC gain from given source to given node voltage. Also compute input and output resistances at given points.
.SENS	Compute DC sensitivities of given node voltages with respect to all circuit parameters.
.AC	Compute small signal AC frequency response within given frequency limits.
.DISTO	Compute small signal distortion characteristics as part of the AC analysis at given load resistor.
.NOISE	Compute the noise voltage on a given node voltage due to a given noise input at various frequencies.
.TRAN	Compute the circuit transient response within a given time interval. This control also controls the specification of initial conditions prior to the transient.
.FOUR	Compute a Fourier analysis of the last output cycle in a transient run for the given output variable about a given fundamental frequency.
.TEMP	Specify temperatures at which the circuit is to be simulated. .MODEL's and resistors have temperature variations and temperature defaults to 27°C.

SUPER*SCEPTRE Examples

The same circuit used for the SPICE example is shown here coded in the SUPER*SCEPTRE format. The transistor model is stored on the SUPER*SCEPTRE model library tape, therefore it only "shows-up" as a call-out item under CIRCUIT DESCRIPTION, by T1, 3-1-6 = MODEL 2N2222A.

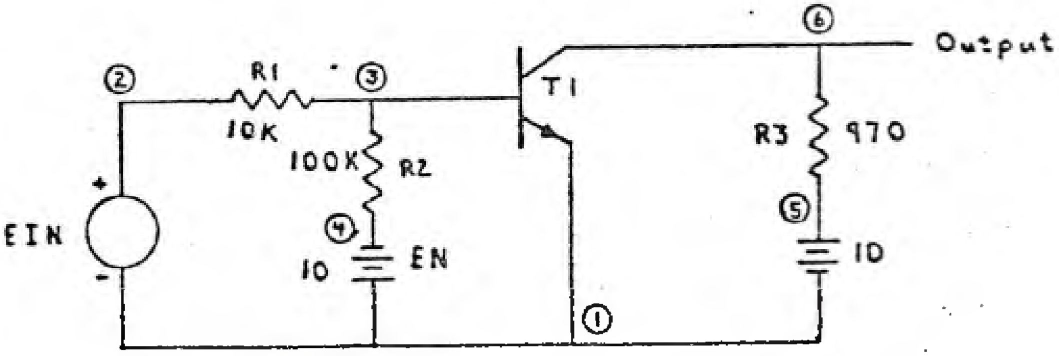


Figure 3. Single transistor inverter

The listing is as follows:

```
CIRCUIT DESCRIPTION
ELEMENTS
EIN, 1-2 = TABLE 1
R1, 2-3 = 10E3
R2, 3-4 = 100E3
R3, 5-6 = 970
E1, 1-5 = 10
EN, 1-4 = -10
T1, 3-1-6 = MODEL 2N2222A
FUNCTIONS
TABLE 1
0, 0, .1E-4, 0, .1E-4, 5, .2E - 4, 5
OUTPUTS
PVCET1(OUTPUT), PLOT
RUN CONTROLS
STOP TIME = .2E-4
INTEGRATION ROUTINE = IMPLICIT
RUN INITIAL CONDITIONS
END
```

From the preceding listing, it is seen that the SPICE and SUPER*SCEPTRE coding formats are similar. The explanation of the details of the listing can be understood readily by reading chapters 2 and 4 of Reference 3.

As mentioned earlier, the SUPER*SCEPTRE program also handles many other disciplines, closely related to "pure" electronic analysis. The following examples illustrates the concept.

Figure 4 is the block diagram of a seismometer. The electromechanical transducer produces an output voltage which is a function of the velocity of vibration of its base. The output voltage of the transducer is amplified and integrated to obtain displacement. The output of the integrator is applied to the input of a strip-chart recorder. A threshold detector monitors the output of the amplifier and switches the recorder on only when a disturbance of significant magnitude occurs.

The diagram of this system is redrawn in Figure 5 in the SUPER*SCEPTRE format. The transfer functions are represented by four-terminal black-box models, and the details of the transducer and threshold detector are shown. Resistors RI and RX are the inputs to the recorder.

The complete SUPER*SCEPTRE listing follows Figs. 4 & 5. The terminal models for the amplifier and integrator are generated automatically by the entries under the TRANSFER FUNCTION DESCRIPTION heading. The LOGIC DESCRIPTION heading is employed to generate models for the inverter, or gate, and monostable.

The transfer functions and logic models are connected to other elements in the system under the CIRCUIT DESCRIPTION heading. The winding inductance (LS) and series resistance (RS) of the transducer are specified and the input resistance of the amplifier is approximated by RIN. EMF is the voltage generated by the transducer and is specified using the expression format. Its value is equal to 20 times the relative velocity of the transducer mass (PVM). Other electrical elements are constants or are models which are previously defined. The mechanical elements in the system are connected under the MECHANICAL DESCRIPTION heading. RF is the force generated by the "back EMF" of voltage source EMF. This value is entered at the expression X2 and is equal to 20 times the back EMF current, IEMF. The applied velocity UA is a damped sinusoid and is also entered in expression form. Other elements are constants. The OUTPUT section calls for printing these mechanical system outputs; the mass acceleration (AMI), mass velocity (VMI), mass displacement (SMI), the spring force (FK1), transducer force (RF), applied velocity (UA), and relative displacement (PVM). In addition these electrical outputs are printed: transducer voltage (EMF), source resistance and inductance voltage (VRS, VLS), and other resistor voltage (VR1, VR2, VRI, VRX). All variables are plotted versus time with the PLOT request.

Figure 4 – Block diagram of the seismometer

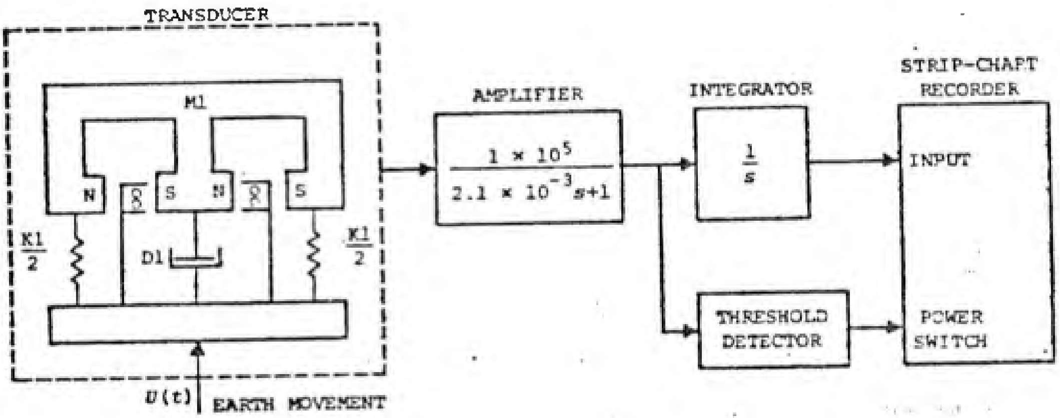
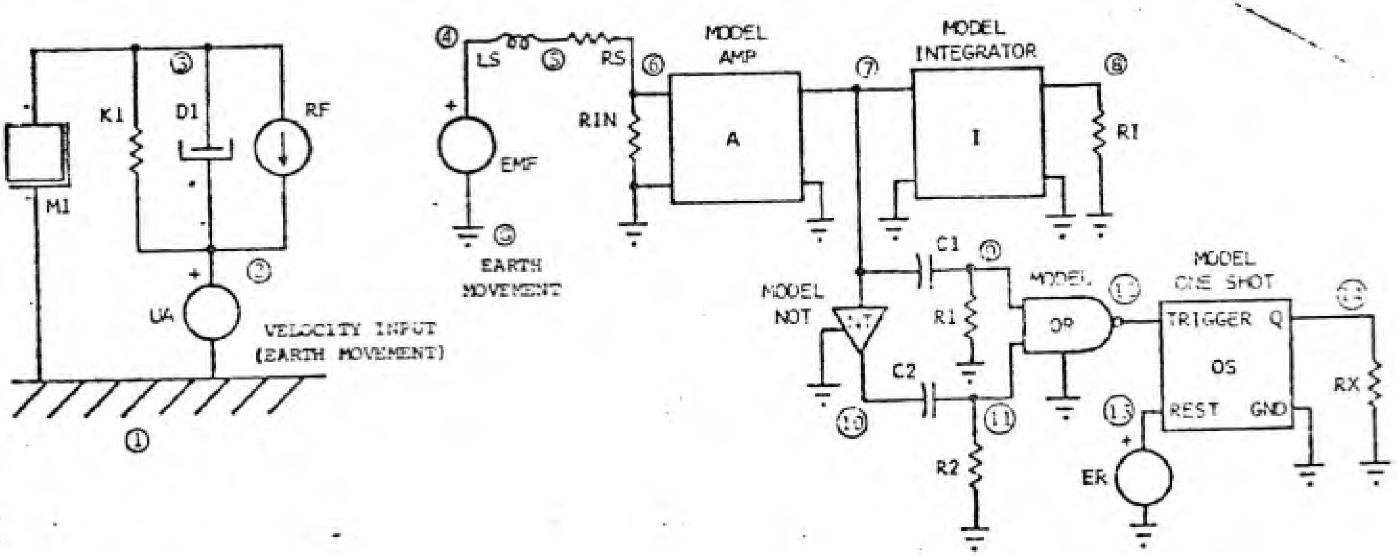


Figure 5 – System prepared for SUPER*SCEPTRE input



```
TRANSFER FUNCTION DESCRIPTION
MODEL AMP
K = 1E5
D = (2.1E-3, 1)
MODEL INTEGRATOR
D = 0
LOGIC DESCRIPTION
MODEL NOT (INVERTER)
IN = (.8)
OUT = (.2, 3.4)
MODEL OR (OR)
IN = (.8)
OUT = (.2, 3.4)
MODEL ONE SHOT (MONOSTABLE)
IN = (.8)
OUT = (.2, 3.4)
PW = .8
CIRCUIT DESCRIPTION
ELEMENTS
EMF, G-4 = X4(20*PVM)
LS, 4-5 = .35
RS, 5-6 = 370
A, 6-G-7-G = MODEL AMP
RIN, 6-G = 2E5
I, 7-G-8-G = MODEL INTEGRATOR
C1, 7-9 = 2E-6
R1, 9-6 = 1E4
C2, 10-11 = 2E-6
R2, 11-G = 1E4
OR, 9-11-12-G = MODEL OR
NT, 7-10-G = MODEL NOT
OS, 12-13-14-G = MODEL ONE SHOT
ER,G-13 = 1
RI, 8-G = 1E3
RX, 14-G = 200
```

```
OUTPUTS
EMF, VRS, VLS, VR1, VR2, VRI, VRX, PLOT
MECHANICAL DESCRIPTION
ELEMENTS
RF, 3-2 = X2(20*IEMF)
UA, 1-2 = X1(1E-4*DEXP(-2.5*TIME)*DSIN(60*TIME))
M1, 3-1 = .5
K1, 3-2 = 4E4
D1, 3-2 = 2.9E2
DEFINED PARAMETERS
PVM = X3(UA - VM1)
OUTPUTS
AM1, VM1, SM1, FK1, RF, UA, PVM

RUN CONTROLS
INTEGRATION ROUTINE = IMPLICIT
STOP TIME = 1

END
```

The coding details for the preceding example are given in Reference 4. The additional program features are as follows:

Network Elements.

The ELEMENTS subheading card begins the element definitions. Elements are made up of from one to six character names, a comma, the node connections separated by dashes, an equals sign and the element value. Legal element prefixes are:

R	resistor
C	capacitor
L	inductor
M	mutual inductance
E	voltage source
J	current source
(any other)	model designator

The DEFINED PARAMETERS subheading card defines any user specified parameter or parameter derivative. Parameter derivatives are automatically integrated in a transient solution.

Elements and defined parameters may be constants or may take on the value of any function.

Functions

Expressions and equations

Any FORTRAN one-line expression may be generated and must be named. Expression arguments may be any element name, any element voltage or current or any defined parameter.

Tables

Piecewise linear tabular functions are detailed under the FUNCTIONS subheader and are named. Tables may be a function of any circuit parameter.

FORTRAN Function Subroutines

Any multiple line FORTRAN Function may be written by the user and utilized as element or defined parameter values.

Models

Circuit models made up of any elements and defined parameters may be generated and named. The models are entered in the circuit using the model designator element. Internal model parameters are referenced in the circuit by suffixing the model designator to the required parameter.

SUPER*SCEPTRE also has built-in models for the following:

Transfer functions for transient analysis only.

Logic models

Mechanical functions

Outputs

Any element, element voltage or current, defined parameter, and various system parameters (TIME, FREQ, Step sizes, error criterion, etc) may be requested in either or both of tabular listings or printer plots.

Initial Conditions

The INITIAL CONDITIONS subheading card begins the definition of initial capacitor voltages or inductor currents.

Also, initial values of defined parameter derivatives may be specified.

All initial conditions assume a vlue of zero.

Run Controls

An extensive list of RUN CONTROLS is available to control the simulation. The most commonly used are:

Transient and DC error adjustment (relative and absolute)

Step size control (minimum and maximum)

Choice of four integration methods

System information printout

Information and [illegible] from Control

Types of Analysis

The RUN CONTROLS subheading card also begins the description of analysis mode and control:

Transient analysis mode is assumed and start and stop times control the transient run. Also a logical termination condition can be supplied.

DC analysis may be requested and the form of analysis (Newton-Raphson or steady-state transient) is specified.

NOTE: the following subsections are applicable to IBM version only.

AC analysis may be requested (but not with a transient run) and the frequency range, frequency step and linear or logarithmic step choices are specified.

Sensitivity analysis is performed on a prohibitive set of dependent parameters versus a set of independent parameters.

Monte Carlo analysis may be performed using a randomly varying (Gaussian or Normal distribution) set of parameters on a DC solution.

Worst case analysis performs a variation on a set of independent parameters to force an objective parameter to a local maximum.

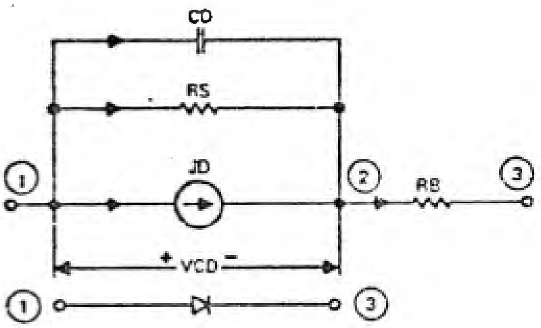
Optimization studies are performed on varying independent parameters to force an objective parameter to a local minimum.

CADA Summary

In summary, the two suggested programs provide the power electronics designer, total flexability to design and analyze a very wide spectrum of circuits and systems. The programs are fast and accurate and easy to learn. No previous knowledge of computers or programming is required. The enclosed User's Manuals [References 2, 3, 4] are all self contained and self explanatory.

CADA MODELS FOR POWER ELECTRONICS

The area of modeling is divided into two technologies. The first involving the creation of an equivalent circuit and the corresponding equations. The second technology involves the determination of the parameter data for each particular device. For example, Figure 6 illustrates the generally accepted large-signal, equivalent circuit (model) for the solid-state diode. This general model is applicable to low and high power devices.



$$JD = IS(e^{\Theta \cdot VCD} - 1)$$

$$CD = \frac{CO}{(\phi - VCD)^n} + KD(JD+IS)$$

Figure 6 Sceptre diode model and defining equations

The two equations shown in the Figure are derived from the Physics of the device.

All of the terms necessary for the diode derivation are defined as follows:

CD = The sum of the diode transition and diffusion capacitances. Where,

$\frac{CO}{(\phi-VCD)}$ = Transition Capacitance = CJ, and KD(JD+IS)=Diffusion Capacitance

JD = Current generator representing the diode junction current. The generator is a function of the voltage VCD.

IS = Diode Saturation Current

RB = Diode Bulk Resistance

Θ = Constant of the diode equation

CO = Constant of the transition capacitance equation

ϕ = Junction Contact Potential

n = Junction Grading Constant

KD = Diffusion Capacitance Constant = $\frac{\Theta}{2\pi F}$

F = Frequency Parameter

VCD = Voltage across capacitor CD, which is equal to the diode junction voltage

It can be shown mathematically and in the lab that the Diode model does in fact duplicate quite accurately the physical diode, and hence is an accurate model or equivalent circuit.

The second technology involves the fact that all of the constants shown in Figure 6 will have different values, depending upon what actual diode is being modeled. Chapter 3 of Reference 3 contains complete information about how this is actually done in practice. The Chapter not only explains the process but shows the equipment used for the various measurements.

The procedures shown in Chapter 3 of Reference 3 have been improved and automated by the Department of Electrical Engineering at the University of South Florida in Tampa. Companies and agencies desiring parameter data for any given solid-state devices may call the writer for time and cost details [(813)974-2581]. To give an idea of how the data appears in SCEPTRE format, two diodes are chosen - one a low power and one a high power. The listings appear as follows: (The units are volts, ohms, farads, heneries, amps)

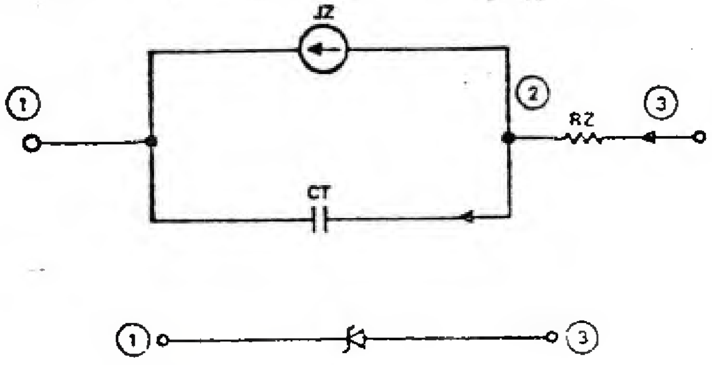
```
MODEL 1N4532 (PERM) (A-K)
SILICON HIGH SPEED SWITCH
TEMPERATURE= +25 DEGREES CENTIGRADE
SUPPLIED BY UNIVERSITY OF SOUTH FLORIDA,TAMPA,FLORIDA,1974
EBERS MOLL DIODE EQUIVALENT CIRCUIT
UNITS:   VOLTS   OHMS   AMPS   FARADS   HENRIES   SECONDS
ELEMENTS
JD,A-1=DIODE Q(4.8E-9,19.5)
RE,1-K=1.27
RS,A-1=1E9
CD,A-1=Q1(1E-12,7.8E-8,JD,4.8E-9)
FUNCTIONS
Q1(A,B,C,D)=(A+B*(C+D))
```

```
MODEL 1N4050 (PERM) (A-K)
HIGH CURRENT DIODE
SUPPLIED BY THE UNIVERSITY OF SOUTH FLORIDA
UNITS: OHMS VOLTS AMPS HENRIES FARADS SECONDS
ELEMENTS
RB,A-1=6E-4
RS,1-K=T1(VCD)
JD,1-K=DIODE Q(5E-11,35.0)
CD,1-K=Q1(3E-9,1,VCD,.5,3E-4,JD,5E-11)
FUNCTIONS
Q1(A,B,C,D,E,F,G)=((A/DABS(B-C)**D)+E*(F+G))
T1=-800,100, -700,100, -600,6E3, -500,2.5E5, -200,2E6, 0,2E6
```

The other solid-state models of interest to a power electronics designer include the zener diode, transistor and the silicon controlled rectifier.

The appropriate models for these will now be shown.

Zener Diode



JZ = ZENER CURRENT GENERATOR IN TABULAR FORM

$$CT = \frac{CO}{(\Phi - VCT)^n}$$

Figure 7 SCEPTRE Zener diode model

where,

JZ = Current generator representing the forward and reverse characteristics of the Zener excluding bulk resistance. This generator is a function of the voltage across capacitor CT.

CT = Diode Transition Capacitance.

CO = Constant of the transition capacitance equation.

ϕ = Junction Contact Potential.

n = Exponent of transition capacitance equation.

RZ = Bulk resistance of the Zener in the breakdown region.

Transistor

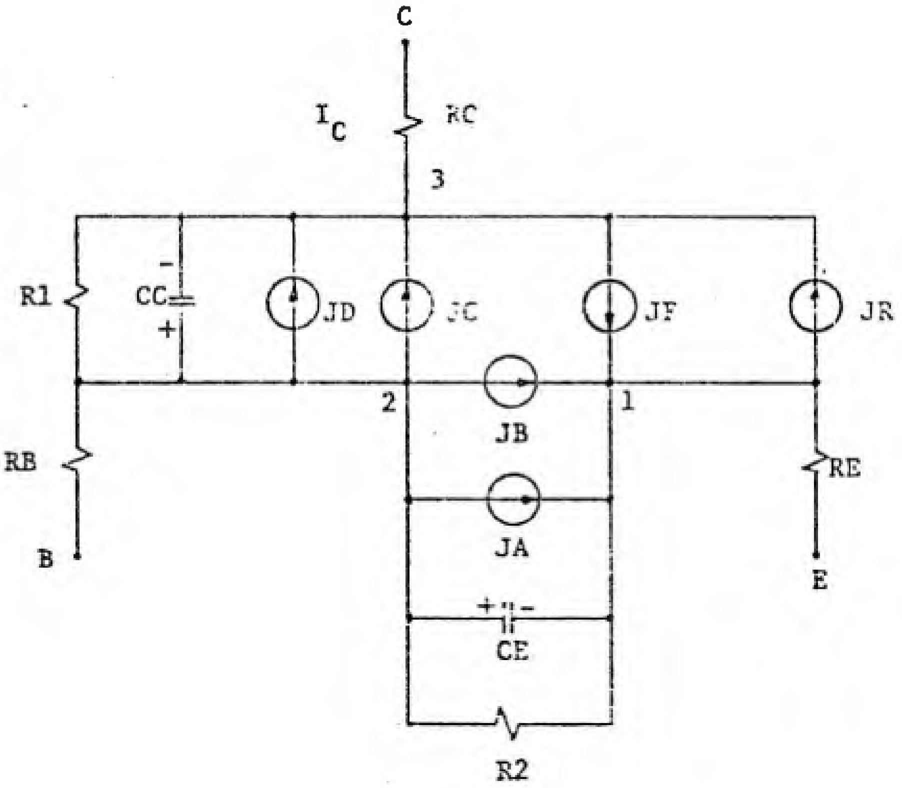
The popular Ebers-Moll[5] model used frequently in the past by many CADA designers is not accurate enough for most power electronics applications. The model now on the scene which does handle high power transistors is the so-called Gummel-Poon[6,7] model. Fortunately, it is also equally accurate for low power applications. Therefore, the general model recommended for use in all areas is as shown in Figure 8.

SCR Model

The previous models shown are equally applicable to the SPICE 2 and the SUPER*SCEPTRE program. In the SUPER*SCEPTRE program they are usually available on a stored model library tape that has been created (and continually added to) by the users. In the SPICE 2 program, all of the solid-state equivalent circuits are permanently stored in the program. The users must supply the parameter data as a part of each individual run. Both approaches have advantages and disadvantages. One of the disadvantages of the built-in model approach used by SPICE is that when new or improved models are generated, it is not easy to incorporate these new,unique equivalent circuits into SPICE.

The SCR is a case in point. When the SPICE 2 program was completed, there was no SCR equivalent circuit available. Therefore no built-in SCR model was included in the SPICE program. Since then, a general purpose SCR model[8] has been developed, but is difficult to incorporate into SPICE*. The model is easily included into SUPER*SCEPTRE, since any user created model can be added. Therefore, the SCR model shown in Figure 9 is, at present, only available for operation on the SUPER*SCEPTRE program, but accurately accommodates low and high power devices[9].

*Work is proceeding at U.S.F. to convert the SUPER*SCEPTRE, SCR model, to an acceptable SPICE 2 format. Contact the writer for further information.



$$JA = C_2 I_s (e^{V_{BE}/n_e V_T} - 1) \qquad JB = \frac{I_s}{\beta_F} (e^{V_{BE}/V_T} - 1)$$

$$JC = C_4 I_s (e^{V_{BC}/n_c V_T} - 1) \qquad JD = I_s/\beta_R (e^{V_{BC}/V_T} - 1)$$

$$JF = \frac{\beta_F J_B}{Q_B} \qquad JR = \frac{\beta_R J_D}{Q_B}$$

$$Q_1 = \frac{1}{1 - (V_{BC}/V_A) - (V_{BE}/V_B)}$$

$$Q_2 = \frac{I_s}{I_{KF}} (e^{V_{BE}/V_T} - 1) + \frac{I_s}{I_{KR}} (e^{V_{BE}/V_T} - 1) + \frac{I_s}{I_{KR}} (e^{V_{BC}/V_T} - 1)$$

$$Q_B = \frac{Q_1}{2}(1 + \sqrt{1 + 4Q_2})$$

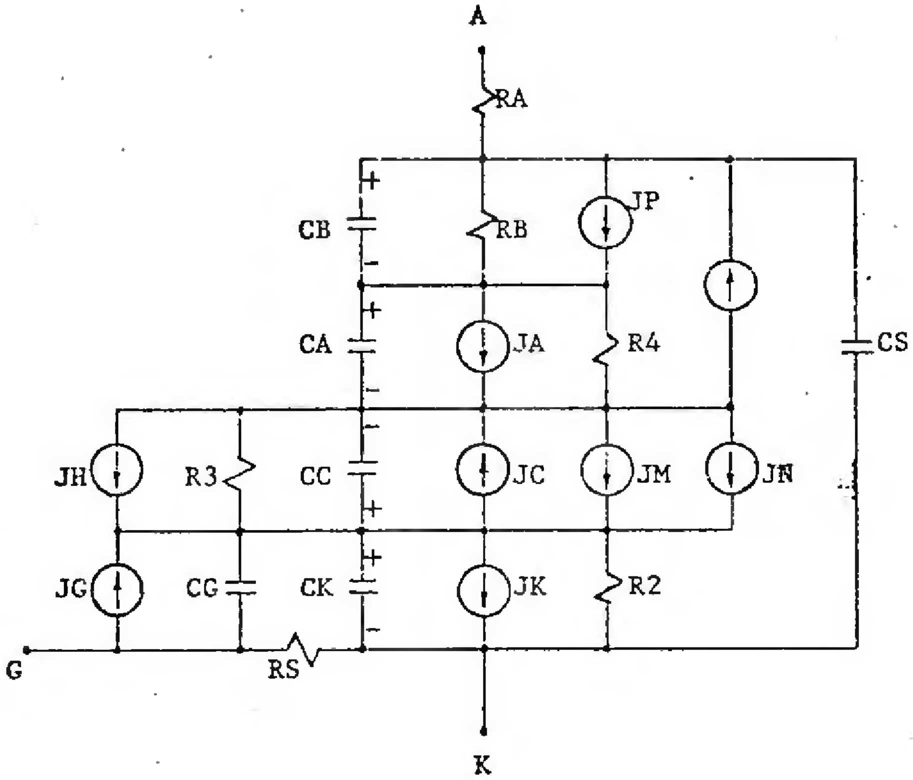
$$CC = \frac{C_{OC}}{[\phi_C - V_{CC}]^{n_c}} + \frac{T_c}{V_T} [JC + I_s] \qquad CE = \frac{C_{OE}}{[\phi_E - V_{CE}]^{n_e}} + \frac{T_E}{V_T} [JA + I_s]$$

Figure 8 SCEPTRE Gummel Poon Model (NPN) and Defining Equations

where,

JA, JB = current generators representing emitter-base junction
JC, JD = current generators representing collector-base junction
JF = source dependent on base-emitter junction current JB
JR = source dependent on collector-base junction current JD
I_s = saturation current measured in the active region
n_c = collector junction grading constant
n_e = emitter junction grading constant
V_T = $\frac{q}{kT}$
C_2, C_4 = slope modifiers to the beta curve
β_f = midrange common emitter forward current gain
β_r = midrange common emitter inverse current gain
T_E = Time constant of the emitter diffusion capacitance equation
T_c = Time constant of the collector diffusion capacitance equation
V_A, V_B = constants used in simulating early effect

I_{KF} = Forward knee current
I_{KR} = Reverse knee current
R_B = Base bulk resistance
R_E = Emitter bulk resistance
R_C = Collector bulk resistance
R_1 = Collector-base junction leakage resistance
R_2 = Emitter-base junction leakage resistance
C_{OC} = constant of the collector transition capacitance equation
C_{OE} = constant of the emitter transition capacitance equation
ϕ_E = Emitter base junction contact potential (volts)
ϕ_C = collector base junction contact potential (volts)



$JM = \alpha_1(JK)*JK$

$JN = \alpha_2(JA)*JA$

$JH = \alpha_3(JG)*JK$

$JP = \alpha_a*JA$

$JI = \alpha_i(JC)*JC$

$RB = f_1(VCA)$

$CB = f_2(VCA)$

$CA = C_{ta} + K_{da}*JA$

$CC = C_{tc} + K_{dc}*JC$

$CK = C_{tk} + K_{dk}*JK$

Figure 9 SCEPTRE SCR Model and Defining Equations

Where,

JK = Current source representing the Cathode Junction

JC = Current source representing the Collector Junction

JA = Current source representing the Anode Junction

JH = Dependent current source simulating Latch In

JI = Dependent current source simulating Inverse Current Gain

JM,JN = Dependent current sources simulating Forward Current Gain

JG = Non-Linear resistance between the gate and active portions of the Outer Cathode Junction.

CA = Anode Junction Capacitance

CB = Spreading Effect Capacitance

CC = Collector Junction Capacitance

CK = Cathode Junction Capacitance

CG, R_2, R_3, R_4, RA are components added because of SEPTRE program requirements

RS = Shorted Emitter Resistance between gate and cathode

CS = Lumped Stray Capacitances

C_{ta}, C_{tc}, C_{tk} = Depletion Layer Capacitances

K_{da}, K_{dc}, K_{dk} = Diffusion Capacitance proportionality constants

RB = Non-Linear Dynamic on resistance

JP = Bypass Current Source to obtain lower static on resistance

Conclusions

This investigation had three goals:

1) Determine CADA programs applicable to power electronics design and analysis.
2) Determine solid-state models applicable for the required CADA programs.
3) Make an extensive literature search of topics (1) and (2).

The first section of this Final Report concludes that of the many CADA programs available, the SPICE 2 and SUPER*SCEPTRE programs are the two recommended for the task. Both are to be made available on the Port Hueneme terminal.

The second goal was also met. The second section of this Report presents a proven Solid-State model for every commonly used device.

The Appendices have two parts. Appendix I contains a list of numerous solid-state devices, with all of the parameter data given in SUPER*SCEPTRE format. Appendix II shows three circuits. Each one has been coded for SUPER*SCEPTRE and SPICE 2. The results of several output plots are included.

Finally, the Reference section of this Report contains numerous articles and texts pertaining to the general field of CADA and Modeling.

The most important References have been included with this Report as supplements, as a convenience for the reader [Ref. 1, 2, 3, 4, and 8 enclosed].

REVIEW OF THE STATE OF THE ART IN HEAT REMOVAL FROM SOLID STATE ELECTRICAL POWER COMPONENTS

by

Roy Scott Hickman

for

Naval Construction Battalion Center
Port Hueneme, California 93403

Contract No. N62583/77MR753

REVIEW OF THE STATE OF THE ART IN HEAT REMOVAL FROM SOLID STATE ELECTRICAL POWER COMPONENTS

by

Roy Scott Hickman

I. INTRODUCTION

The development of electronic circuits is of critical importance to any modern technical system. In the early development of electronics, vacuum tubes were used. These tubes always had heated filaments, which dissipated considerable waste heat and had to be cooled to maintain a reasonable operating temperature. As solid state devices became available in the late 1950's, the problem of the cooling electronic packages became easier simply because less waste heat was generated in the circuit elements. The cooling problem gave the impression of disappearing altogether as integrated circuitry became common in the 1970's. Unfortunately, even though individual components generated less and less waste heat, the increased number of components required large power supplies which dissipate considerable power. Also, in some applications, large amounts of power are required for certain individual circuit elements.

Solid state devices depend upon trace impurities in a very pure base semiconductor. The way that the impurity regions are manufactured is usually by exposing the base semiconductor to the impurity and allowing diffusion of the impurity into the material. This process is controlled as accurately as possible, and diffusion in layers of a few microns are commonly reported. If the semiconductor device is allowed to reach a temperature at which significant additional diffusion of the impurity occurs, its electrical properties can change and the devices' normal rating may not be achieved. To maintain the desirable electrical properties of the chip, it is necessary to operate the semiconductor at or below 150°C. Several types of failure can occur if the mean chip temperature exceeds this value. Hot "filaments" can occur in the chip which can approach 1100°C. As these filaments are generated, catastrophic melting is common. Thus, the ultimate power densities in semiconductor devices appear to be temperature limited. All modes of heat transfer (conduction, convection, boiling, and radiation) depend upon the geometry of the semiconductor, some thermal properties of the materials, and finally the maximum and minimum temperatures. Thus, for very simple geometries of a given semiconductor material, the maximum heat flux will be a definite value, and will place an upper limit on the power that can be dissipated in a particular device.

This report describes the heat transfer mechanisms, the cooling techniques commonly used, and what appears to be the current state of the art. The various manufacturers concerned with high power semiconductor devices are briefly discussed, and finally a section is presented in which the limit of power densities is defined.

II. LITERATURE REVIEW

In order to determine the state of the art of high power semiconductor devices, a literature search was conducted. Three computer data banks were searched. The Lockheed "Dialog" computer program was used to search the Compendix file containing the engineering index and major abstracting services. In addition, the NTIAS file was searched. These computer searches yielded 53 references to "semiconductor" and "heat transfer or cooling" key words. In addition, the computer link between CEL and the Defense Documentation Center was searched using the key words "thermal conductivity and semiconductors." 223 accessions were recorded with 59 within the last ten years.

In addition the Engineering Index Annual (72 to Feb. 77) and the Electrical and Electronic Abstracts (Jan 75 - July 76) were manually searched. To complete the search, the Science Citation index was examined for current references to papers referenced in the RCA publications dealing with the new integral heat pipe devices (Transcalent). Finally, the Powercon Conference series and the International Semiconductor Power Converter Conference proceedings were investigated. In all, 65 publications were identified as being actually or potentially useful. Approximately one half of these have been obtained.

III. REVIEW OF HEAT TRANSFER AND COOLING METHODS

All electronic equipment needs cooling, whether it uses only a few low power transistors or many high power tubes. In most equipment, the cooling design is as important as the electronic design itself. The cooling design and modes used can present special difficulties because the design engineer must quite often deal with cooling "after the fact." To minimize costs, manufacturers must build standard semiconductor packages and this affects the ability of a particular design to dissipate power. If cost is not a key factor for a particular design, it is possible to increase the power capability by special design of the semiconductor.

As a review, the modes of heat transfer will be briefly discussed and especially the effect of cooling methods upon operation of semiconductor devices. All of the waste heat generated in an electrical device must ultimately be removed by conduction, convection, evaporation or radiation, or by a combination of several of these modes.[1-13] For instance, a highly effective means of thermal transport is via conduction. The Fourier law of conduction may be written (for a uniform area rod)

$$q = kA\Delta T/L \qquad (1)$$

where

q = waste heat watts

k = thermal conductivity

L = length of rod

ΔT = temperature difference

Equation (1) is usually rewritten by electrical engineers into the form

$$q = \Delta T/R \qquad (2)$$

where R = L/kA. R is called the thermal resistance and plays the same role in heat transfer that electrical resistance plays in a circuit. In fact, if the analogy of thermal resistance is extended it can be applied to non-uniform conduction geometry, convection, heat transfer, evaporation heat transfer and, for small temperature differences, to radiation heat transfer. Conduction is present in all electrical power dissipation problems. For a bare chip exposed to an evaporating liquid, the waste heat must be conducted from the region in the chip where the dissipation occurs to the surface of the chip. The other modes of heat transfer may or may not be present. The relative ability to transfer energy by different modes is given in Fig. 1.

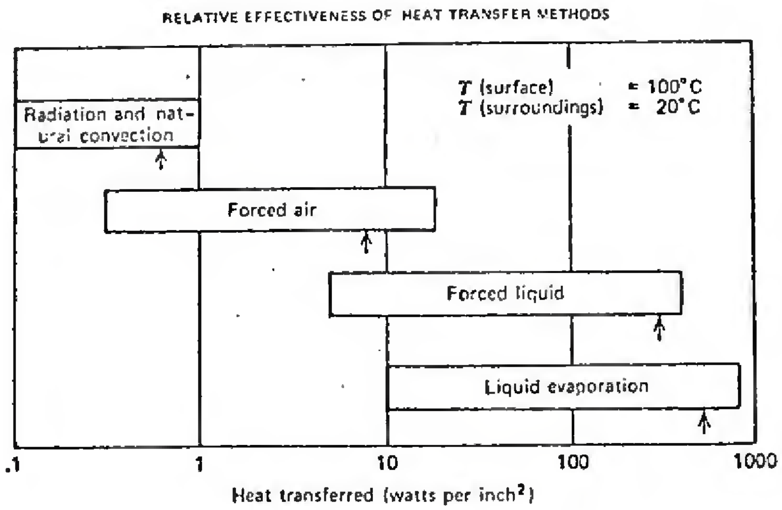


Fig. 1

Radiation and natural convection are the simplest to use of all the heat transfer methods. No auxiliary equipment is required; just the cooling fins themselves. The hot fins radiate heat directly to the cooler surroundings. At the same time, the air near the hot fins is heated and rises, and is replaced by cooler air. This convective air current provides additional heat transfer. In most electronic equipment, heat transfer occurs by radiation and natural convection simultaneously. However, the amount of heat transferred by each method depends on heat sink temperature, geometry, and orientation in different ways.

The amount of heat that can be transferred by radiation depends on:

1. The temperature of the radiating surface.
2. The temperature of the surroundings.
3. Surface conditions of the fins.
4. Shielding effects of adjacent fins.

The amount of heat that can be transferred by natural convection depends on:

1. Temperature difference between the surface and the surrounding air.
2. Dimensions of the surface.
3. Orientation of the surface.
4. Spacing between adjacent surfaces.
5. Altitude (which determines air density).

As Figure 1 shows, the amount of heat that can be transferred from a given cooling fin area is increased by more than an order of magnitude by blowing air over the cooling fins, rather than relying on radiation and nautral convection. Forced air cooling is more complicated to implement than cooling by radiation and natural convection, because a fan and the associated fan components are required. Forced air cooling is however, much simpler than forced liquid cooling, because a supply of cooling air is readily available and air does not have the freezing, boiling, or dripping problems of cooling liquids.

The design of air cooling poses two problems:

1. Choice of the fan or blower.

2. Design of the cooling fin geometry.

These two problems must be solved jointly. The amount of air flow that a particular fan can provide is determined by the pressure into which the fan must work. Both the amount of heat transfer that can be obtained from forced air cooling, and the pressure required to force air through the cooling fins depends on air flow and fin geometry. Consequently, the choice of fan must be made in conjunction with the fin design.

Forced air cooling, although simpler to implement than forced liquid cooling, does have several disadvantages. Forced air cooling may not be suitable for electronic equipment which must be operated at high altitudes where air density is low. The acoustic noise of the fan may be objectionable and the vibration of the fan may adversely affect the performance of the electronic equipment. The hot air ejected from the electronic package may also be objectionable.

All of these disadvantages of forced air cooling are eliminated by the use of forced liquid cooling. The cooling pumps and coolant reservoir can be removed from the electronic package, so that quiet, vibration-free operation can be maintained. As shown in Figure 1, the use of forced liquid cooling provides an order of magnitude greater heat transfer per unit area than forced air cooling. For very high power electronic equipment, this greater heat transfer capability is a necessity, where the cooling fin area cannot be made great enough to transfer the heat by forced air cooling. The use of liquid cooling also permits high density mounting of lower power electronic components. This high density mounting may not only be desirable from a packaging standpoint; it may be a necessity to achieve required electronic performance.

Evaporation cooling can be used in the following different ways in electronic equipment:

1. Cooling of high power components at high power densities.
2. Cooling of all components in the electronic equipment by immersing the entire assembly in a package filled with dielectric oil.
3. Maintaining a constant temperature bath for electronic components.
4. Simple expendable cooling systems.

Some tubes or devices are specifically designed for liquid cooling by evaporation. In a typical arrangement, the anode of a tube, where heat is generated, is immersed in liquid. Heat is transferred from the tube by boiling the liquid. The vapor from the boiling process rises from the liquid bath, is condensed in a condenser, and is then returned to the cooling bath. The condenser heat transfer area can be made large enough, because it is separated from the electronic equipment, so that heat can be transferred from it to the surroundings by radiation and convection or by forced air cooling.

No coolant pumps are needed for evaporation cooling. Consequently, it is an extremely simple cooling method. As shown in Figure 1, evaporation cooling provides greater heat transfer per unit surface area than any of the other methods.

The disadvantages of cooling by evaporation are:

1. The system can operate in one orientation only, with the liquid bath at the lowest point in the system.
2. Immediate destruction of the electronic component occurs if the maximum heat transfer rate is exceeded, because the temperature of the component increases very rapidly above the critical heat transfer rate.

The effective cooling design of electronic equipment requires minimizing both the temperature rise required for conducting heat from the electronic component to the cooling fins, and the temperature rise required for transferring heat from the cooling fins to the surroundings. Both factors contribute to the operating temperature of the electronic component.

In many designs, sufficient space may be available for a large number of cooling fins, but the major problem is conducting the heat from the electronic component to the cooling fins. Even if the heat sink is made of copper, the temperature rise due to conduction may be excessive.

Heat pipes offer a solution to this problem. A schematic drawing of a heat pipe is shown in Figure 2. The heat pipe consists of a hollow tube which

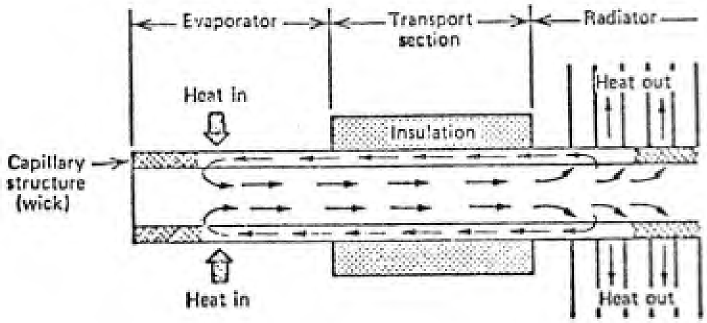
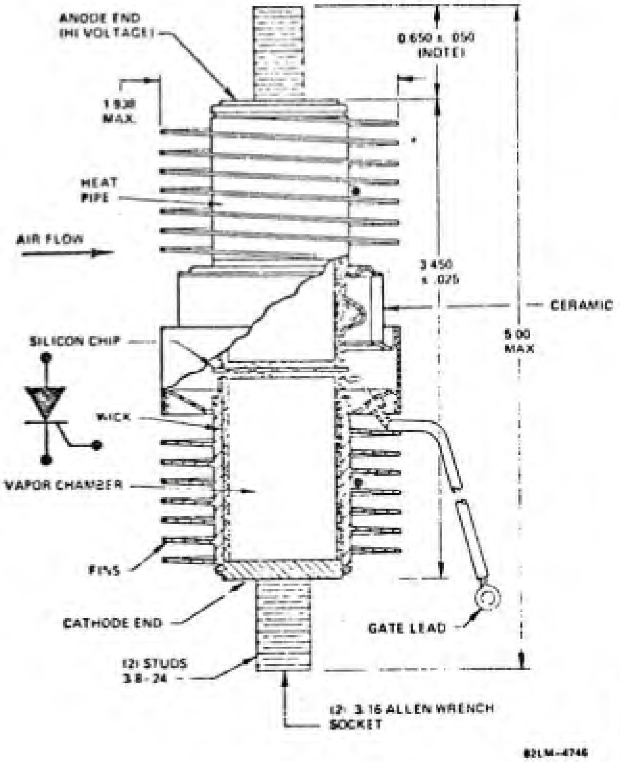


Fig. 2

has been evacuated and then filled with a coolant liquid. The incident heat evaporates the liquid at one end of the pipe and the vapor transports the heat to the other cooler end of the pipe. At the cool end of the pipe the liquid condenses and transfers the heat. So far, this means of heat transfer is the same as evaporation cooling. However, the heat pipe has an additional feature that permits it to be operated in any orientation. The inner surface of the heat pipe contains a capillary structure or "wick" which returns the condensed liquid to the hot evaporator end of the pipe by capillary action. The heat pipe can therefore even operate against gravity, that is, with its evaporator end upward.

For a given temperature rise, a heat pipe can conduct several orders of magnitude more heat than a solid copper rod of the same diameter. Consequently, heat pipes are finding increased use for the conduction of heat in electronic equipment.

A research and development group at RCA has built semiconductors with heat pipes built into the electrical device. These are called Transcalent devices and represent a major change in attitude in semiconductor design because the heat transfer problem is approached directly as an integral part of the overall design. Figure 3 is a cross-sectional view of a Transcalent Thyristor capable of 400 amps RMS forward current.



Dimensions are in Inches

● Temperature Measurement Point

Note – Threads – 0.550" min.

Fig. 3

Heat pipes, especially the Transcalent devices, depend upon film evaporation at a surface for thermal transport. The power flux for this evaporation is in the range of 50 to 150 watts/in^2. Furthermore, a heat pipe system may not be able to handle power surges (because the wick return of liquid may not be sufficiently responsive). A solution to this would be to build a Transcalent type device in which a spray of coolant is directed onto the chip surface. With proper design using water as the coolant, a heat transfer rate of 900 watts/in^2 can be achieved if the semiconductor surface temperature is maintained at 125°C. In a literature search no mention of an actively pumped evaporation cooling device based upon this principle was found.

IV. SEMICONDUCTOR STATE OF ART

Large semiconductor thyristors which are capable of carrying as much as 3000 A have been reported in the literature. These high current devices depend upon silicon chips as large as 102 mm in diameter.[23] Using the data available in the literature, it appears that semiconductor chips in the 25 mm to 100 mm range can carry 40 to 50 amperes/cm^2 assuming the chip to be at 125°C and sufficient coolant is available.[24-26]

The current density of 50A/cm^2 appears to be reasonable for hockey puc type devices and for the new transcalent semiconductors. Water cooled Hockey Puc type semiconductors with water passageways within the pole pieces appear to carry the highest current of any currently commercially available devices. With water cooling there is no reason to believe that larger diameter hockey puc semiconductor devices will not be as good as any other devices available. The new transcalent semiconductors being produced by RCA are inherently easier to use in a power supply because they can be used with forced or free air convection. They do not appear to be able to perform better than water cooled devices; however they represent the best available units when air cooled heat sinks are required. Furthermore, there does not appear to be any limitation on the diameter of the transcalent devices providing careful attention is paid to the design of the return wicks in the heat pipes so that the present current of 250 A to 400 A may be increased in the future.

Some of the largest chips are being manufactured in the U.S. and in Japan. For instance, a 1500 A, 4000 V SCR has recently been reported in Japan.[65] Appendices I and II list manufacturers of large semiconductor devices and cooling equipment.

BIBLIOGRAPHY

1. "Cooling of Electronic Equipment," Scott, Wiley and Sons, 1974.

2. "Cooling Electronics 1", M. J. Dalley, Engineering Materials and Design, Oct. 1974.

3. "Cooling Electronics 2", Graham Tuck,,Engineering Materials and Design, Oct. 1974.

4. "Cool Through Turbulence," John Chisholm, Electronic Design 9, April 1975.

5. "Power Semiconductor Equipment Cooling Methods," M. H. McLqughlin and E. E. Vanzastrono, IEEE Transactions, Vol. lA - 11, No. 5, Sept. Oct. 1975.

6. "Miniature Refrigerators for Electronic Devices," A. Daniels and F. K. duPre, Phillips Tech Rev. 32, No. 2, pp. 49-56, 1971.

7. "The Thermal Demands of Electronic Design," S. E. Grossman, Electronics, Nov. 1973, pp. 98-101.

8. "Plastic Power ICS Need Skillful Thermal Design," S. B. Marshall and R. F. Dewey, Electronics, No. 1973.

9. "Analysis Can Take the Heat Off Power Semiconductors," F. B. Golden, Electronics, Dec. 1973, pp. 103-109.

10. "Forced Air Cooling in High Density Systems," G. M. Taylor, Electronics, Jan. 1974, pp. 87-89.

11. "Liquid Cooling Safeguards High Power Semiconductors," J. A. Gardner, Electronics, Feb. 1974, pp. 103-108.

12. "Network Analog Maps Heat Flow," L. J. Feldmanis, Electronics, May 1974, pp. 116-121.

13. "Air Through Hollow Cards Cools High Power LSI," L. Laumer, Electronics, June 1974, pp. 113-118.

14. "Fluid Cooling of High Power Density Semiconductor Devices," B. K. Ericksen, General Electric Report No. R76EMH5, Jan. 1976.

15. "A Novel Method of Cooling Semiconductor Devices for Power Electronics," H. Birnbriur, et al., Brown, Beneri and Ci Zentrales Forschungslab (West Germany), Report No. BMFT-FB-T-73-02.

16. "Final Technical Report," R. G. Erdman, RCA Communications Systems Div. Camden, N. J., Report #AF-9-12951-AVW, Nov. 1972.

17. "Final Report," J. V. Stover, et al., Report No. AF-30(602)-3654, Aug. 1966.

18. "Thermal Performance Evaluation of the 10 kw Direct Current Turbo-Rectifier Set," J. S. Todd, Solar Report No. ER-2422-F, Nov. 1972.

19. "Module Combining Techniques," Alfred Morse, Westinghouse Defense and Electronic Systems Final Report on contract #F30602-74-C-0166.

20. "Heat Pipe Cooling of Airborne Phased Array Radar," Patent Application by J. L. Haros, Dept. of the Air Force, Washington, D. C., Patent Appl.- 604530.

21. "Reliability/Design Handbook. Thermal Applications Vol. III," Thermal Technology Lab., July 1973, AD-A009016.

22. "Cooling Compression Type Semiconductor Devices," B. West and R. Lavochkin (Wakefield Engineering).

23. "State of the Art in Power Semiconductor Devices," H. Herlet and P. Voss, Proceedings of 1977 IEEE/IAS International Semiconductor Power Converter Conference.

24. "First Quarterly Progress Report MM and T Measure for Fabrication of Silicon Transcalent Thyristor," RCA Report for Contract DAAB07-76-C-8120, Dec. 31, 1976, ADA038429.

25. "Second Quarterly Progress Report MM and T Measure for Fabrication of Silicon Transcalent Thyristor," RCA Report for Contract DAAB07-76-C-8120, March 31, 1977.

26. "Third Quarterly Progress Report MM and T Measure for Fabrication of Silicon Transcalent Thyristor," RCA Report for Contract DAAB07-76-C-8120, June 30, 1977.

27. "Semiconductor Power Devices," Chandi, Wiley Interscience, 1977.

28. "Development of Transcalent Semiconductors," S. W. Kessler, AD DN481013.

29. "Type J-15401 Developmental Transcalent Rectifier," G. Y. Eastman, AD DAOK3718.

30. "250 Ampere Transcalent Rectifier," G. Y. Eastman, AD DAOH3614.

31. "Electronic Equipment Cold Plates," C. J. Feldmanis, 1976, NITIAS No. BO13904L.

32. "Thermal Control of Airborne Electronic Equipment, Vol. II," R. J. Gianetti, M. A. Merrigan, L. A. Nelson, 1973, AD AO39185.

33. "Application of Cold Plates to Electronic Equipment Cooling," C. J. Feldmanis, 1972, AD 906907L.

34. "Effects of Gravity on Gas Loaded Variable Conductance Heat Pipes," M. D. Kelleher, AD A039185, 1977. Also see previous reports AD 914495L, and AD 914496L.

35. "Development of a 250 Ampere Transcalent Rectifier," S. W. Kessler, June 1970, AD 875548. See reports AD 865664L, AD 722813.

36. "High Power Semiconductor Rectifier Equipment Using Boiling and Condensing Heat Transfer," S. Otani, O. Tanaka, T. Suzuki, Y. Shikano, and G. Kabayashi, IAS (IEEE Ind Appl Sci) Record of 10th Annual Meeting, 1975.

37. "Radiatory S Igol Chatym Orebreniem Deya Silovkh Poluprovodnikovh Priborov," E. M. Novokhatskii, Y. V. Osipov, Izv Vyssh Vehebn Zaned Energ., No. 6, 1976 (In Russian) "Needle finning of thermos radiators for cooling semiconductors).

38. "Integrated Power Switch," P. P. Balthasar, E. Reimers, IEEE Trans. Ind. Appl., Vol. LA-12, No. 2, 1976.

39. "Method for Calculating the Design Data of Air Cooled Heat Sinks for High-Power Thyristors," T. Salanki, Siemens, Z., Vol. 50, No. 3, March 1976.

40. "Method of Thermal Calculation of Finned Coolers of Semiconductor Power Devices with Forced Air Cooling," A. A. Rabinerson, I. P. Osipova Elecktrotechnika, No. 7, July 1975 (in Russian).

41. "Sitor Thyristor Sets of Compact Design for Static Converters," P. Bachmann, H. Kelkel, Z. Siemens, Vol. 50, No. 1, Janl 1976.

42. "Heat Pipe Cooling of Semiconductor Power Devices," H. Birnbreier, F. Gross, U. Heidtmann, Proceedings of 10th Inter. Society Energy Conversion Engineering Conference, Aug. 1975.

43. "Fabrication and Application of 76 mm and 102 mm Power Semiconductors, J. DeWarga, J. E. Mungensot, IEEE Ind Appl Soc Annual Meeting 9th Conference Record., 1974.

44. "Transient Thermal Response Measurements of Power Transistors," D. L. Blackburn, F. F. Oettinger, IEEE Power Electron Specialist Conference Proceedings, 1974.

45. "Disk-Type Power Semiconductor Devices and Their Possible Applications," E. Lehmann, H. Martin, Siemans Rev., Vol. 42, No. 4, Apr. 1975.

46. "Evaluation of Current Capacity of Power Semiconductor Devices," E. Lehmann, Elektrotech Z Ausg B., Vol. 26, No. 17, 1974.

47. "Dynamic Thermal Resistance of Diodes and Transistors," C. Plata, Elektronika, Vol. 14, No. 11, 1973 (in Polish).

48. "Has Electronic Miniaturization Overlooked Power Supplies?", B. Bixby, L. Carver, Machine Design, Vol. 46, No. 7, 1974.

49. "Thermal Design - 5. Liquid Cooling Safeguards High Power Semidonductors, J. A. Gardner, Electronics, Vol. 47, No. 4, 1974.

50. "Novel Method of Cooling Semiconducting Power Devices," H. Birnbreier, G. Gammel, U. Heidtmann, M. Joens, P. Pawloski, Bundesminist Forschung Technology Forschungaber. Technol Forsch Entusckl, No. 73-02, 1973; also NASA N74-11739/available from NTIAS.

51. "Cooling Off Power Semiconductors," R. S. Horm, Design Engineering, Aug. 1973.

52. "Steady-State Junction Temperatures of Semiconductor Chips," R. Lindsted, R. Surty, IEEE Trans Electron Devices, Vol. ED-19, No. 1, Jan. 1972.

53. "Taking the Guesswork Out of Semicondcutor Heatsink Selection," J. J. Robinson, Electron Eng., Vol. 43, No. 517, 1971.

54. "Fans and Heat Sinks for Cooling Semiconductors," B. West, Electron Prod., Vol. 13, No. 12, 1971.

55. "New Heavy-Current Rectibloc Rectifiers Using 400 A Silicon Diodes," W. Brandenberger, E. Keller, Brown Baneri Rev., Vol. 57, No. 11, 1970.

56. "Design and Selection of Heat Sinks for Semiconductor Diodes," J. Wieland, W. Wolczynski and E. Bartosinki, Przegl. Elektrotech., Vol. 46, No. 2, 1970.

57. "H.V.D.C. Thyristor Converter Development in Japan," N. Yamada, K, Hidaka, T. Horigome, K. Kishi, H. Takabayashi, I. Mikami, Direct Current, Vol. 1, No. 4, 1970.

58. "Chemical Liquid Cooling and Construction for Power Thyristors," T. Matsumoto, Sakiyama, A. Ishikawa, and M. Nishio, Conf. on Power Thyristors and Their Applications, IEEE Conf. Proceedings Inst of Elec Eng, London, England, 1969.

59. "Optimal Design of Radiators for Air-Cooled Semiconductor Power Diodes," Przeglad Elektronski, Vol. 10, No. 6, 1969.

60. "Fluid Cooling of High Power Density Semiconductor Devices," B. K. Erikson, AD-A025 815/2ST, Jan 1976.

61. "Japanese Laboratory is Growing Silicon Ingots 5 Inches in Diameter," Electronics International 11/10/77.

62. "Thermal/Performance Evaluation of the 10 KW Direct Current Turbo-Rectifier Set," J. S. Todd, AD-765505/3.

63. "Module Combining Techniques," A. W. Morse, AD-A019384/7ST, May 1975.

64. "Heat Pipe Cooling of Airborne Phased Array Radar," J. L. Haros, AD-D001451/4ST, Aug. 1975.

65. "Reliability/Design Handbook Thermal Applications, Vol. III," Thermal Tech. Lab. AD-A009015/9ST, July 1973.

66. "Application of Cold Plates to Electronic Equipment Cooling," Air Force Flight Dynamics Lab, AD-906907L.

67. "Effect of Collector Design on Hot Spot Formation and Second Breakdown in Transistors," B. Reich and E. Hakim, Feb. 1968, AD-668-903.

68. "IEDM Heralds Breakthroughs in LSI Fabrication Power Discretes," L. Altman and L. Mattera, Electronics, Dec. 8, 1977, pp. 109-112.

APPENDIX 1

Semiconductor Manufacturers	Products
Motorola Box 20912 Phoenix, AZ	
Semicoa 333 Melormick Ave. Costa Mesa, CA	
International Rectifier Semiconductor Division 233 Kansas St. El Segundo, CA 90245	Hockey pucs, Stud mounted heat exchangers and hardware
Power Tech, Inc. 9 Baker Court Clifton, NJ 07011	Ultra high power transistors
Westinghouse Electric Corporation Semiconductor Division Youngwood, PA 15697	Disc, stud SCR's
General Electric Semiconductor Products Dept. Syracuse, NY	Press pak Stud mounted packages
Toshiba Electronics Solid State Inc. 46 Farrand St. Bloomfield, NJ 07003 1-800-631-2075	Giant transistors SCR's
RCA Electronic Components Lancaster, PA 17604	

APPENDIX 2

Cooling Device Manufacturers	Products
Aham 968 W. Foothill Blvd. Azusa, CA	Heat sinks
Astrodyne Inc. 353 Middlesex Ave. Wilmington, MA	Liquid cooling system Heat pipes
International Electronics Research Corp. (IERC) 135 W. Magnolia Blvd. Burbank, CA 91502	Fins, air cooled heat sinks, water cooled heat sinks
Dean Products, Inc. 985 G Dean St. Brooklyn, NY 11238	Heat pipes
Dynatherm Corp. Marble Center Indst Lane Cockeysville, MD 21030	Heat pipes
Hughes Aircraft Electron Dynamics Div. Dept. G 3100 W. Comita Blvd. Torrance, CA 90509	Heat pipes
McLean Eng. Labs, Inc. 70G Washington Rd. Princeton Junction, NJ	Heat pipes
Nobel Electronics ELECS Inc. 265 G Little Tar Road S. New City, NY	Heat pipes
Noren Products Inc. Dept. G 846 Blandeford Blvd. Redwood City, CA 94062	Heat pipes
Kooltranic Inc. 1700 Morse Ave. Ventura, CA 93003	Heat exchangers Blowers
Thermalloy, Inc. 2021 West Valley Viero Lane Dallas, TX 75234	Fins Heat sinks

APPENDIX 2 (Continued)

TOR Corp. 14715 Armiento St. Van Nuys, CA 91402	Heat sinks
Wakefield Engineering Inc. Wakefield, MA 01882	Heat sinks Heat exchangers Liquid coolers
WEI Corporation 1405 So. Village Way Santa Ana, CA 92711	Heat sinks