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RUDIMENTS OF GOOD CIRCUIT DESIGN

Talk delivered by

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ABSTRACT

Circuits which depend on the absolute stability and reproducibility of components have proved to be unreliable and often impractical for field use. A study of the tolerances of a circuit to its component variations, when made a part of the design procedure, will lead to better equipment, producible and usable in the field. Such a study often leads to new circuits and new ways of obtaining results.

RUDIMENTS OF GOOD CIRCUIT DESIGN

I feel it is rather presumptive to attempt to present, in half an hour, a paper which will thoroughly cover the broad problem of good circuit design. I shall therefore confine my discussion to a philosophy of circuit evaluation which has been developed at the Digital Computer Laboratory (MIT) over a period of several years in connection with the somewhat large and complex system known as the WWI digital computer.

About four years ago I presented a paper at your symposium in Washington entitled "Marginal Checking as an Aid to Computer Reliability." Since that time, this concept of marginal checking has shown itself to be very useful, not only as a method of preventive maintenance which has the ability to predict incipient faults, but also as a design tool in measuring the margin of safety which has been designed into a circuit.

Concept of Tolerances

The concept of tolerances and safety margins which exist in circuits is one which most designers underestimate as a means of improving reliability in electronics. I am quite sure that the electronic designer is several decades behind the designers in other engineering activities in providing adequate safety margins to allow for the various disturbances to which a circuit may be exposed during its lifetime. The bridge designer and the power station designer habitually allow safety factors of 100% to 200%. They realize that the systems they are designing must withstand excessive strain and that failure may result in loss of human life or the expenditure of large

amounts of money. The circuit designer, until recently, has not been confronted with such catastrophic punishment should the results of his effort fail to perform under conditions of stress. It is very apparent, however, that electronics is becoming separated into two broad categories: one is associated with the amusement field; the other is associated with the communications and military fields. This latter area is now imposing the same sort of requirements on electronic circuit engineers which for many years have been imposed on engineers who design bridges, power stations, and the like.

Specifications Are Inadequate

When the average circuit designer is confronted with a problem, he usually is asked to make a circuit perform some specific function as a portion of a system. If I may use an example from the computer field, such a requirement may be for a high-speed switch. He may be given, as specifications, the limits on the speed of switching, the voltage swing which such a switch should deliver, the resolution time, and perhaps some power limitation. Occasionally some mention of high reliability or long life will be made as an adjunct to the functional specifications. The designer will complete a circuit within a few days or weeks and then, when asked if his circuit will be reliable, he will glibly say - "Certainly, it will be as reliable as the components." He will then turn to the component engineer and specify 1% resistors and tubes which must have closely held tolerances on plate current and transconductance; and he may go so far as to specify temperature and humidity stability. Seldom will he think of designing his circuit in such a manner that

its functions will not be dependent upon the complete stability of the components. More often than not, this lack of consideration for stability will result in poor reliability.

The question of stability is one of two problems in component manufacturing. The other is reproducibility. A word about each of these two factors may be enlightening:

Stability of any component is always in question. The 1% resistor does not always stay within 1% under various conditions of temperature and humidity, and very often, after several thousand hours, resistors change their values. The result can be catastrophic if one is dependent upon their being stable. The vacuum tube and crystal diode are also very vulnerable on this point of stability, and of course should never be used where tolerances of more than 10% or 20% are expected.

The reproducibility of a given component is another important consideration; 1% resistors, for instance, are now quite commonly available, but even a variation of plus or minus 1% in a resistor is enough to throw some circuits into the marginal category. No one has yet been able to make vacuum tubes or crystal diodes to such close tolerances, yet many circuit designers feel quite indignant that this is not possible.

Specification of Allowable Tolerances

The problem which the circuit designer really faces in view of the above comments on reproducibility and stability of components becomes one of designing highly stable and reliable circuitry made up of components which are never really reproducible nor stable. What I should like to stress today is

the importance of specifying to a designer the allowable component tolerances at the time a circuit is designed and putting this specification at the head of the list instead of at the bottom. I should also like to propose a method of evaluating a circuit while it is in the design stage to help the designer become keenly aware of the tolerance which the circuit has to component variations at the time he is designing it.

To be concrete regarding the specifications, let us take as an example a flip-flop which should run at 2 megacycles with a rise time of 0.2 microsecond and a voltage swing of 20 volts across an impedance level of 1,000 ohms. One should also specify that all resistors in the circuit should be able to vary between limits no tighter than plus or minus 5%. Large signal transconductance should probably be specified as having limits of 50% around the nominal specifications for tubes, and crystal diode back resistance should be allowed to decrease an order of magnitude below nominal before circuit failure occurs. The last three items in this specification are much more stringent than the actual functional specifications first noted, and they are much more important in determining the usefulness of a given design. Most designers can reproduce a high-speed flip-flop from their notebooks, but one that will perform under such stringent conditions of component variations as specified would probably rule out the selection of many circuits and would make the designer think carefully about new ideas and new ways of doing the job.

A Method of Circuit Evaluation

I am sure that everyone here will agree that the above comments are very worthwhile, and some will say they are taken into account by most good circuit designers without such detailed specifications. Unfortunately,

the performance of electronics in military equipment has brought to light

the fact that we are not designing circuits which do have adequate tolerances,

and the resultant performance record of electronic circuitry in the field is

a sad commentary on our attention to such detail. I should like, therefore,

to propose a method of circuit evaluation which has evolved from a considera-

tion of margins and a study of why circuits failed in the Whirlwind I computer

system during the last two or three years.

I am going to show you a slide (Fig. 1) of a contour line which

represents the failure point of a circuit which is subject to variations.

The tolerance of one of the components in the circuit is plotted against the

variation in a marginal checking parameter in the same circuit. I shall first

discuss this chart in a general way as applied to any circuit and then apply

it to a specific portion of a flip-flop circuit which has been under develop-

ment at the Digital Computer Laboratory at MIT. The point in the center of

the parabola indicates the operating point of the circuit. This is the nor-

mal voltage on the circuit and the normal value of the components. If we

now consider the supply voltage as a marginal checking parameter and lower

it, we find a point on the contour line at which the circuit fails to per-

form. This failure can be defined as the point at which the function of the

circuit deviates from that prescribed in the specification. For instance, if

we are talking about an oscillator, we mean the point at which the frequency

shifts out of tolerance; if we are discussing a flip-flop, it becomes the

point at which some standard pulse fails to switch the position of the flip-

flop. If we now change the tolerance on the component by some factor such

as 10% in a negative direction and again cause the marginal checking voltage
to go through an excursion, a different failure point will result, such as
Point 2 on the curve. If we raise the tolerance of the component 10%, we will
plot another failure point, Point 3. If we continue this study, we can draw
a contour line which will represent the locus of the failure point of the cir-
cuit to tolerances in componentry as a function of some marginal checking
parameter. This sort of study often results in finding that the contour is
not symmetrical about the operating point and that wide safety margins often
occur on one side of the area but very narrow margins occur on the other. It
is interesting to note that such contours change radically depending on the
type of circuit. In most cases the contour would be a closed loop if the
marginal checking parameters could be varied far enough without damaging the
components.

Two points become clear to the designer:

1. The tolerance of the circuit to varying parameters is graphi-
cally clear -

2. The best method of marginal checking for a particular circuit
can be chosen. That is, the condition of a component in service can be
measured in terms of a marginal checking voltage.

It is probably evident to most of you that the plotting of the curve
and variation in each of the components in even a moderately complex circuit
represents a rather long and tedious study. I would submit, however, that
we are now talking about the design of circuits which are to be subject to
all sorts of variations, and whose failure will cause loss of life or loss

of large sums of money. When we take these factors into consideration, we

can hardly afford not to know how much margin a circuit has before it will

fail, and we can therefore not afford to be ignorant of this sort of data on

a circuit before placing it in a system.

Application to a Flip-flop Circuit

I should like now to present the data on two of the component

tolerance studies which have been made on a new high-speed flip-flop which

has been under design at MIT and compare it with the same study made on a

circuit designed four years ago when such a tolerance study was made on a

rather hit-or-miss basis without the concept of marginal checking as a de-

sign tool. Fig. 2 shows a study of the tolerance of a flip-flop circuit to

variations in the cross-over arms in the resistive network which is effective

in holding one tube in the "off" condition while the other tube is in the "on"

condition. On the chart, the inside diamond-shaped contour represents the

failure locus of a flip-flop circuit designed to a specification where com-

ponent tolerances were not given as being of prime importance. The outside

contour is one resulting from a circuit design where the specification was

given that the tolerances on the parts should be very wide and that no re-

sistance which demanded a 1% tolerance should be used. The two circuits

have a similar frequency response and resolution time and perform inter-

changeably in the system. It is obvious from the curve that the area of

performance is about 8 times greater in the latter design and the tolerance

on any one component about double.

The straight lines represent measured failure contours and are

not just calculations plotted for the end points. The extensions of the

lines beyond to the axes represent negative tolerances on the particular measurement being made. The two sides of the diamond with a negative slope represent tolerance contours of the lower resistance in the voltage divider to positive or negative excursions of the **marginal voltage**. **The sides with** positive slopes are for **the upper sections of the divider.**

In order to make this point a little more interesting, and also to show that the specification of tolerances is a way of stimulating ideas which lead toward better circuitry, I should like to show you the two circuits and discuss briefly the merits of the latter.

The first circuit, with the lower margins of performance, is a dual-pentode flip-flop shown in Fig. 3. It uses high-performance pentode tubes and high-precision cross-resistance in the network which determines one tube to be on and the other off. It is a typical Eccles-Jordan type circuit which is quite familiar to most computer engineers and is becoming widely used in many fields. The marginal checking voltage chosen to make the tolerance study is indicated as a voltage inserted at the base of the voltage dividing network.

Fig. 4 shows an improved version of the first circuit; it performs this same function but uses low-performance triodes to accomplish the result. The diagram shows that cathode-follower tubes were used to link the two halves of the flip-flop together. This provides a decoupling medium between the grid of one triode and the plate of the opposite triode and allows wide-band video circuitry, using low-performance tube types. The grid of a cathode follower has two diode circuits which limit the swing of

the signal passed to the opposite tube and make the level of this signal insensitive to variation in the plate current of the driving tube. I realize that this is not a startling new development nor a completely new idea, but it is a wise choice of components to do a job which has resulted in a much wider tolerance and much wider margins of performance than were previously believed possible. Furthermore, this improvement was achieved without the use of high-performance tube types or high-precision components in the circuit.

A second component study on these same two circuits may be seen in Fig. 5. This study shows allowable plate current variations in the tubes as a function of the marginal checking voltage inserted in the grid circuit. With no voltage inserted, the older circuit can tolerate a tube imbalance of only 30%, but with balanced tubes, the older circuit can tolerate only 1/3 the voltage imbalance available to the improved design. The outer curves do not close in this diagram because of the unavailability of tubes unbalanced enough to cause failure with no marginal voltage inserted, but about a 70% imbalance in plate current is estimated as the tolerance on this circuit.

I feel quite sure that this circuit would not have been expolited unless the original specification to the designer had indicated that he must not use high-precision resistors in order to achieve his result, nor must he use tubes of a very high-performance type. The medium-mu triodes used can be made with small production variations, and grid spacing is such that a minimum of intermittent shorts are present. It is apparent from this example that the designer used more components than in the first case. Four triodes were used, as opposed to two pentodes. In addition, several diodes were added.

The important point is that the tolerances of the components in the latter circuit may be allowed to vary over much wider limits than those of the fewer components in the first circuit, and the overall circuit performance has been improved considerably. This example is one of many circuits used in a computer. I hope it has served to demonstrate a principle applicable to almost all circuits beyond those used in the computing field.

Conclusion

In summary, may I repeat that it is important for the circuit designer to value a philosophy of design which places the tolerance of components at the head of his list of specifications instead of at the bottom. I should like, also, to suggest that, in the evaluation of a circuit, its appraisal be based on its ability to perform with exceptionally wide tolerances to component values instead of on how well it does the specific, particular, functional job.

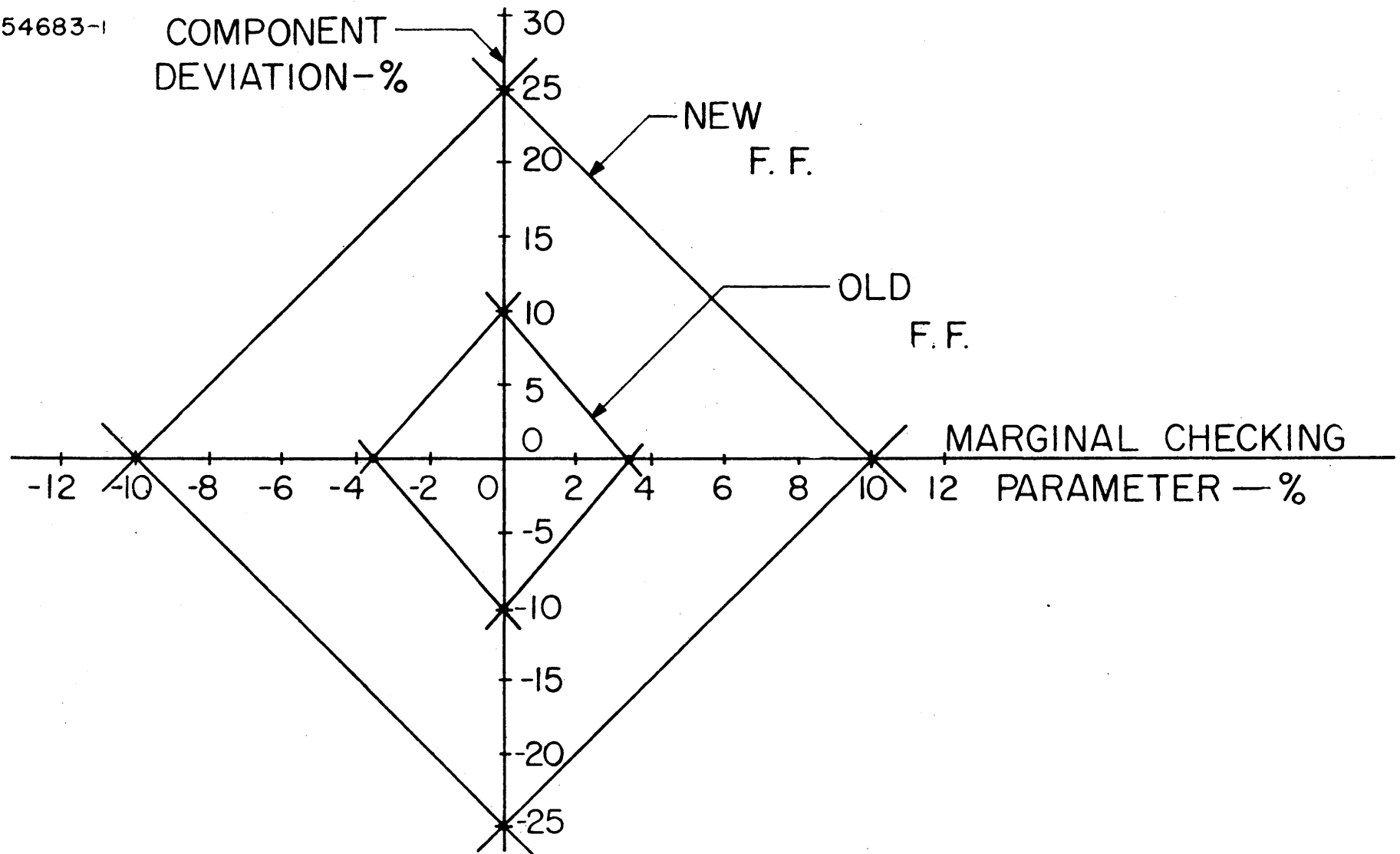Signed...................
N. H. Taylor

Approved...................
J. W. Forrester

NHT:jrt
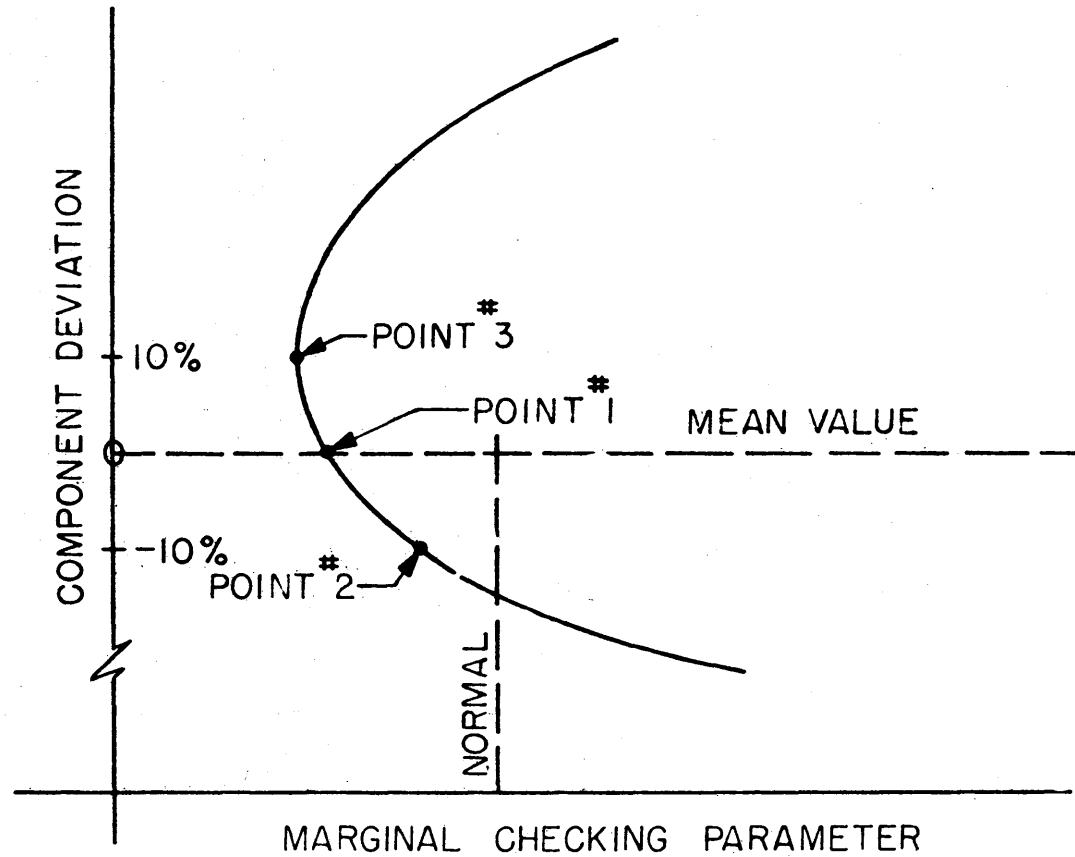
LOCUS OF FAILURE POINTS IN A TYPICAL CIRCUIT

FIG. 1

A-54683-1

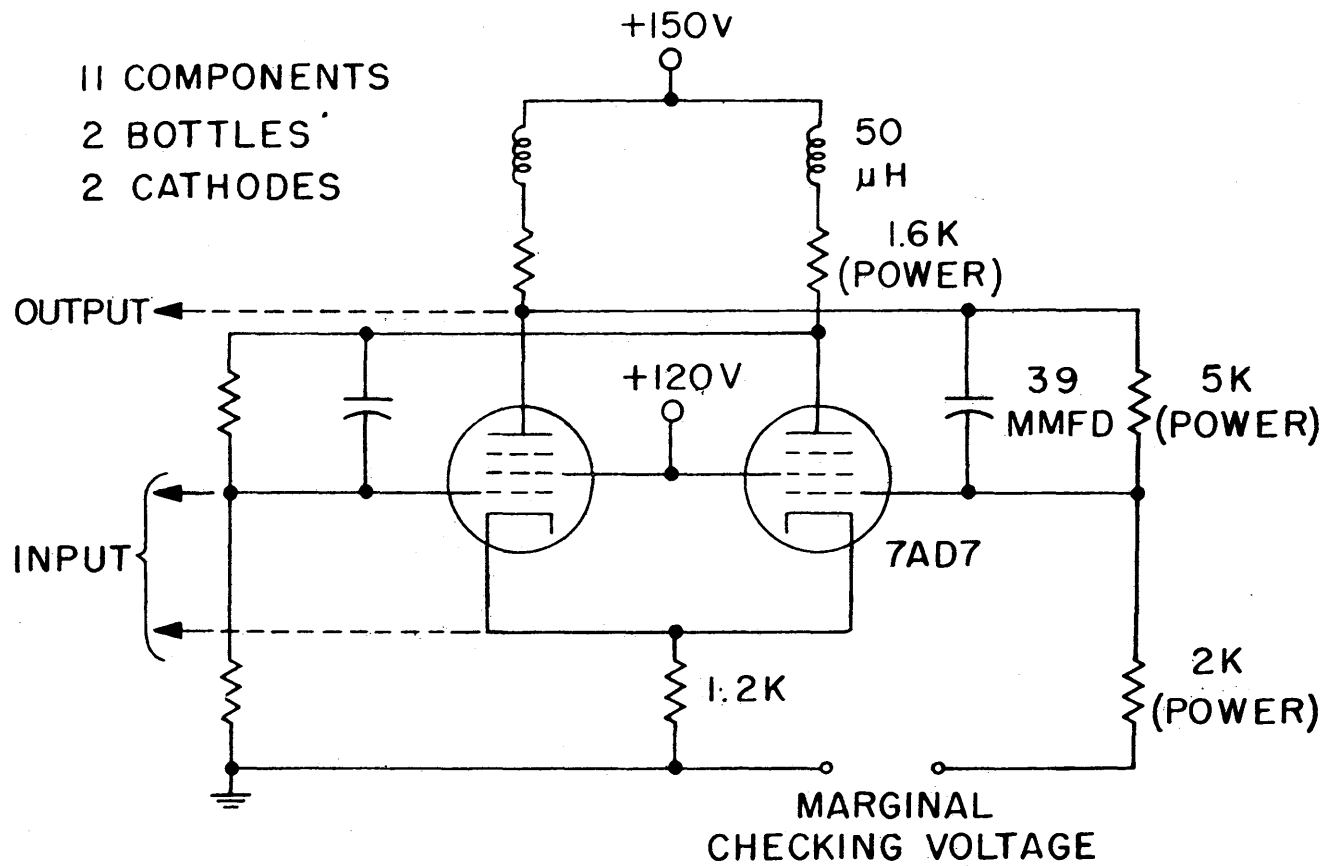A TOLERANCE STUDY OF FLIP-FLOP
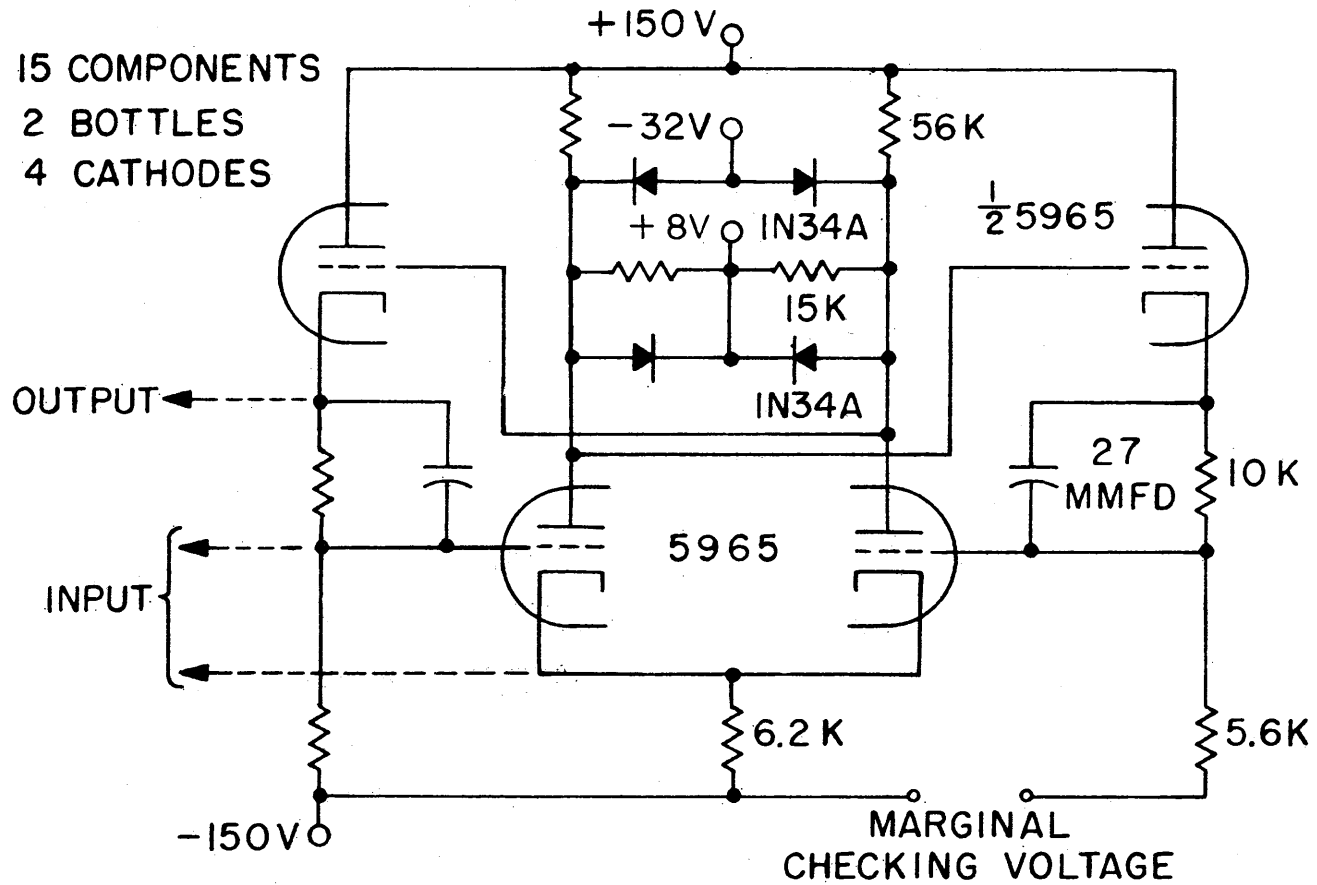CROSS-OVER RESISTORS

FIG. 2

II COMPONENTS
2 BOTTLES
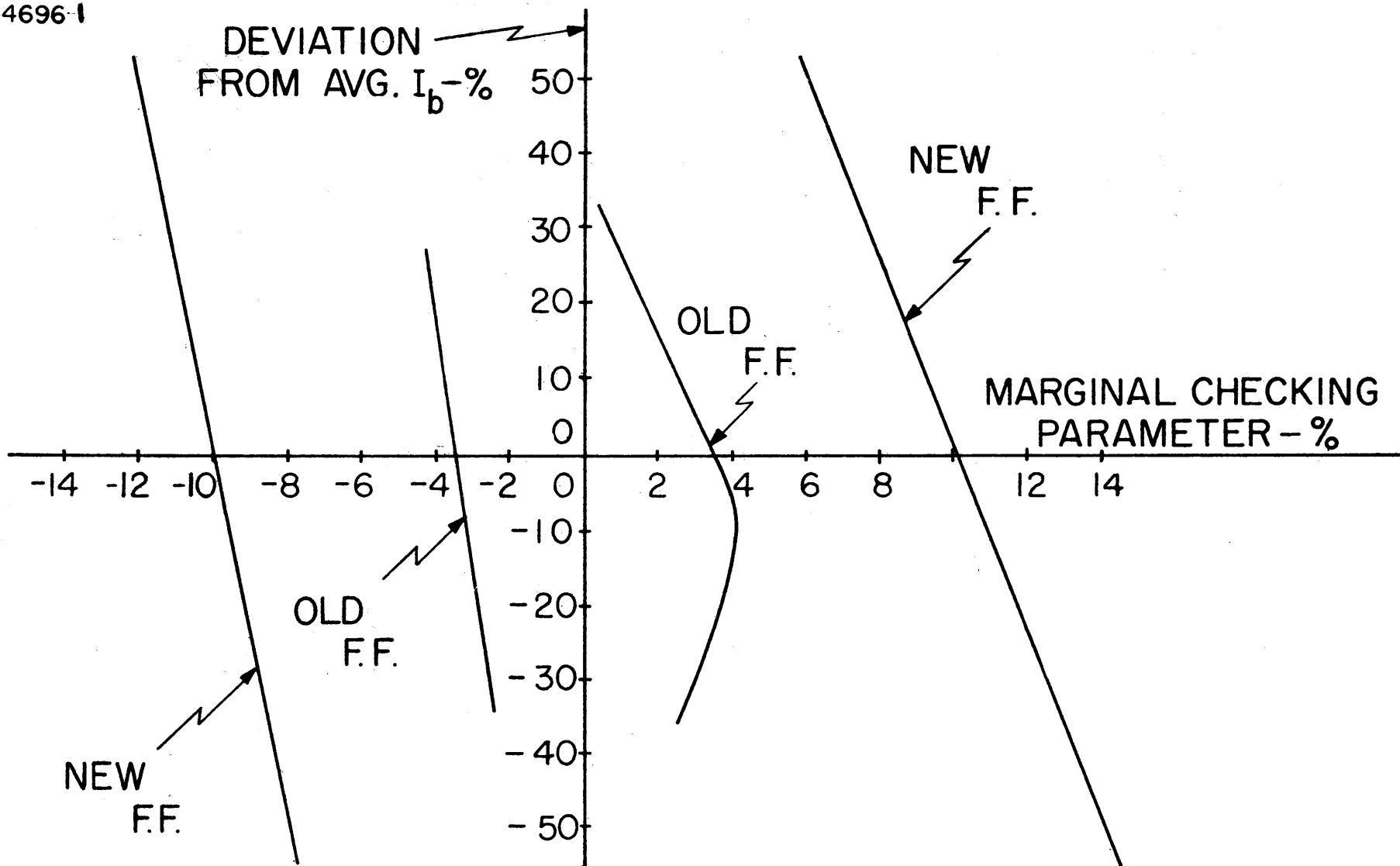2 CATHODES

+150V

50 μH

1.6 K
(POWER)

OUTPUT

+120V

39 MMFD

5K
(POWER)

INPUT

7AD7

1.2K

2K
(POWER)

MARGINAL
CHECKING VOLTAGE

4MC FLIP-FLOP

FIG. 3

15 COMPONENTS
2 BOTTLES
4 CATHODES

+150 V

−32V

56K

+8V   1N34A

½ 5965

15K

1N34A

OUTPUT

27
MMFD

10 K

INPUT

5965

−150 V

6.2 K

5.6K

MARGINAL
CHECKING VOLTAGE

2MC FLIP−FLOP

FIG. 4

A-54696-1

DEVIATION FROM AVG. I_b – %

MARGINAL CHECKING PARAMETER – %

NEW F.F.

OLD F.F.

OLD F.F.

NEW F.F.

A TOLERANCE STUDY OF FLIP-FLOP TUBE PLATE CURRENT

FIG. 5