Engineering Experience with the SEAC

RALPH J. SLUTZ

FROM the time of its early planning phases the SEAC program at the National Bureau of Standards has had a dual purpose. One objective has been, of course, the provision of a tool for use in the solution of problems in calculation, but a second and equally important aspect is the use of this equipment to provide experience with which better tools can be designed in the future. Thus about one-third of SEAC's time during the past year has been used for the testing out of new equipment in order to obtain design experience for further development.

First let me mention that the decision to use a full-fledged computer as a piece of test equipment has been amply justified. The two major such uses have been in conjunction with the design and evaluation of a full electrostatic-storage memory and also with the design of several varieties of magnetic tape devices for use as input-output devices and as auxiliary memory. When working with such devices, we test them first in the laboratory as carefully as is feasible without constructing overly complex laboratory equipment. Then they are tried with the SEAC, and invariably their use as part of a full computing system shows up weaknesses which have been overlooked in the laboratory. When these weaknesses have been corrected, the unit is then used in regular problem computation, and it has been our experience time and again that the variety of use such a unit gets in handling a large number of problems turns out to be a much more rigorous test than any acceptance test we have been able to devise. Thus the computing system has proved to be a most valuable piece of test equipment, especially so because of the great flexibility of test programs possible simply by putting different routines in the machine. It appears clear that in order to achieve as good results with specialized test equipment as we do with the computer, this specialized test equipment would have to be nearly as complex as a full computer; and to be as flexible as the computer is, it would have to have a great many of the characteristics of a computer—so it might as well be a computer.

On the other hand, in addition to using the SEAC to test out new and advanced equipment, the SEAC is itself continually testing the components which go to make it up, and these components have been selected to give information of interest to computer design. For instance, the decision was deliberately made to use as the major vacuum tube one on which relatively little experience was available, but which had been partly designed with computer use in mind. It is this sort of experience—experience in the operation of the computer itself—which I wish to describe here.

Over-all Performance

First I would like to mention the over-all performance that has been observed. This is not too easy a thing to express in quantitative form, since some numbers that might be assigned would give a very misleading impression of the usefulness of a computing installation. To show how this could be, imagine a computer which is working at a megacycle rate, but loses just one pulse every second. Then this computer would be making errors only 0.0001 per cent of the time but it would be almost completely useless for problem solution since there would never be more than a second's continuous good operating time. We have attempted to avoid this situation by using a definition of good operation which depends on the amount of useful work performed. Thus we call "bad" time for the computer the total time which it is estimated was lost as a result of computer malfunction. Thus it sometimes comes about that the computer will make an error at a time which invalidates previous good operation which may have extended for one or several hours, and in order to make further progress on the problem it is necessary to repeat this previous work in order to recover the lost information. With the definition we use, all of this time used in rerunning the problem is considered as "bad" time. It is obvious that the operating figure that results from this is a function not only of the computing equipment itself, but also of the type of problem which is being done, and of the skill of the problem preparer and machine operator in making provision for minimizing the effect of possible machine malfunctions. Also when errors occur during the checking of the coding of a problem, it is somewhat a matter of judgment as to just how much delay a given machine malfunction may have caused. We believe, however, that the definition which is used tends to err more on the conservative than on the optimistic side.

With these considerations in mind, then, we can turn to the experience for the past year—October 1950 through September 1951. On a weekly basis, the percentage of good time during that time of the machine which was assigned to problem solution varied from a low of 25 per cent to a high of 96 per cent, the over-all average for the year being 70 per cent. That is, if the machine had been working perfectly it would have turned out the same amount of results in 70 per cent of the time which actually was required.

However, while this sort of figure on over-all operation is of interest in connection with the efficiency of a given computing installation, it does not tell us much about the performance of the individual parts which go to make up the computer. A breakdown of the relative number of hours lost for various reasons will give something more along this line, although it is necessarily somewhat rough because many intermittent troubles have unknown causes. Of the total trouble time some 34 per cent was produced by such undetermined causes or by a variety of different reasons, each a small percentage in itself. Thirty-six per cent of the trouble time was attributed to errors in the input-output equipment, the majority of these being caused by malfunctioning of the mechanical parts of the electric typewriter used, or its associated relay and electronic circuitry. Seventeen per cent of the bad time was attributed to errors in the delay line memory—either the loss or pick-up of pulses such as might be caused by improper gain of the recirculation amplifier, but which were not attributable to any particular tube or diode circuit in the system. Only a small proportion of the errors was directly attributable to the tubes and diodes, 8 per cent for diodes, 5 per cent for tubes, and 0.5 per cent for electrical delay lines.

Tube Life

Let us look at the data that have been accumulated on tube life. The SEAC uses mainly one kind of tube, the *6AN5*; nearly 75 per cent of all the tubes in the machine are of this one kind. Half of the remaining tubes are *6AK5*, the remainder being made up of a large variety. A bit of an engineering gamble, call it calculated risk if you will, was undertaken in

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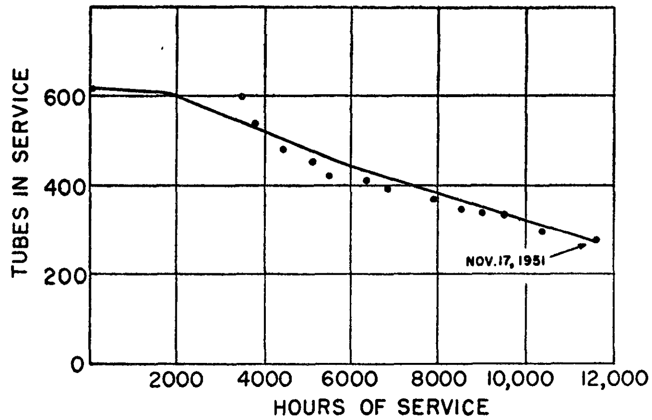

Figure 1. 6AN5 tube life inSEAC

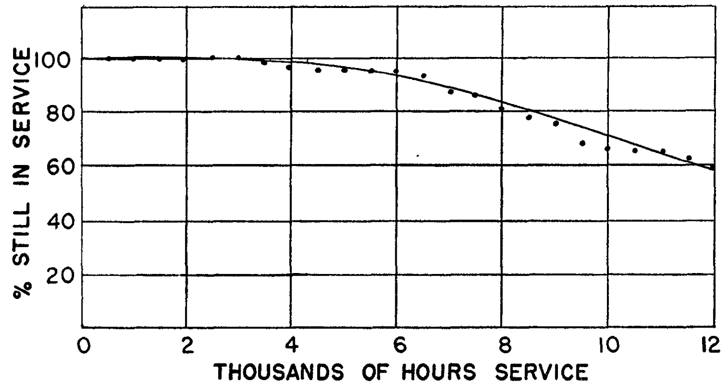

Figure 2. A history of 350 tubes in SEAC

using this *6AN5* so extensively. At the time the SEAC program was initiated, very little life experience was available on this tube, but it was selected because its characteristics had been developed partly to meet computer requirements, and in its design a great deal of attention had been put toward doing as much as was known to make a reliable tube. The tube was initially developed during the war as a high-gain broad-band intermediate frequency or video amplifier. Its characteristics looked sufficiently promising so that as part of a program of component development for the Army Ordnance Department the National Bureau of Standards sponsored further design work aimed at unusually high reliability. Care is taken in the filament construction to prevent weak spots which would be likely to open up. Passive nickel is used for the cathode to avoid interface troubles; and particular attention is paid to keeping the grids cool and preventing emission from them. The tube goes through a careful inspection procedure, and costs accordingly. These points in the design seem to have produced good results. In the SEAC operation, no attention is paid to any particular cycle for turning the filaments on or off. They are simply snapped on or off whenever desired, and yet filament failures in over 1,000 tubes are almost completely unknown. In the last year not more than two or three have been observed. Similarly there has been no evidence of cathode interface formation or trouble from grid emission.

Another design decision was that the tube would not be derated but used in the computer in such fashion that under certain combinations of circumstances the element dissipations or currents might reach those specified by the manufacturer. Actually, the circuit in which it is used is limited not by plate but by screen grid dissipation. Plate saturation takes place and the plate dissipation can only reach one-third to one-half the manufacturer's rating while the screen grid reaches the full rating. On the other hand, under certain circumstances peak currents of as much as 100 milliamperes at 50 per cent duty factor are drawn from the cathode.

Up to the present the SEAC has been in operation for somewhat over 12,000 hours, and Figure 1 shows the experience with the 600 tubes which made up the first installation. You will note that 50 per cent of them were in service slightly more than 10,000 hours. The rejections on which this curve is based are not in general for failure in service, but rather for passing our lower specification limit in routine maintenance tests. These specifications are shown in Appendix I, and are based mostly on arbitrary judgment. How this curve would be affected under changes in the specifications is not known.

Looking at the curve, you will note that there were very few failures for the first 3,500 hours, followed by a rather rapid drop-off. When we noticed this sudden drop-off, we found that due to an error some 250 of the tubes were installed such that their filament voltage was from 5 to 10 per cent higher than 6.3 volts. These tubes were failing to pass specifications rapidly at about 3,500 hours, which shows as anyone would guess that at least in this instance abnormally high filament voltage is not conducive to long life. When these abnormally run tubes are removed from the sample, the curve shown in Figure 2 is obtained. This you will see is quite a bit smoother and indicates that nearly 60 per cent of the tubes are still in operation after 12,000 hours of service. An interesting feature of this curve is that it leaves the 100 per cent line gradually and at least for the life observed here is concave downward rather than being concave upward as would be the case if the failures were purely a random phenomenon. The situation shown in the curve is very desirable for computer operation since it means that early failures are almost negligible and even without testing them this particular group of tubes could be depended on for the first 3,000 or 4,000 hours. If the failure of the tube were a purely random function of time, the curve would be an exponential one dropping away very quickly from the 100 per cent point, and it would require very long average life indeed to provide similar reliability during the first few thousand hours of life.

Since the tube has a passive nickel cathode sleeve, it of course is relatively hard to activate stably. We find that an initial aging period of the order of 100 hours is essential for new tubes, since in at least some cases we have observed during aging a drop in plate current of 50 per cent during the first 10 or 20 hours, with complete recovery at the end of 100 hours.

The general conclusion is that the *6AN5* is a very satisfactory tube for computer use. Whether derating the tube would make its life any better than what is shown from these figures I cannot say. As it stands its life is only a very minor source of trouble in the computer.

Germanium Diode Life

When we turn to look at data on germanium diode life we find that it is a little bit obscured by procurement difficulties in the initial installation of the SEAC. At the time of the initial construction of the SEAC our diode specifications were less stringent than at present, particularly with regard to diodes whose back characteristic "creeps" or "wiggles"; that is, changes either slowly or rapidly during test. However, at that time we had considerable difficulty in obtaining enough diodes even of the weaker specifications to fill the machine, so we installed quite a large number of diodes which were somewhat below the installation specifications we were shooting for even at that time. It took nearly 8,000 hours of machine operation before the job was completed of insuring that all of the diodes in the machine met our present specification on installation. This specification is shown in Appendix II.

During the last 4,600 hours, while the specifications were being tightened on the diodes, some 11.5 per cent were replaced. This of course is not a very fair figure because of the change in specifications but is at least an upper bound, even if probably a very lax one, on what the true failure rate would be during this time. A much better figure comes from the experience subsequent to the uniform installation of the diodes. Here we have some 7,700 tests on individual diodes, and because of the sequential nature of the routine maintenance testing we can infer that each of these diodes passed specifications at a time which averages about 5,000 hours before the current series of tests. This series of tests rejected 2.2 per cent of the diodes, so we can say that of 7,700 diodes that were acceptable at a given time, 5,000 hours later 2.2 per cent of them had been rejected for failing to pass specifications. I want to emphasize that again, as in case of the tube failures, these rejections of the diodes were based on failure to meet a quite arbitrary specification and not on complete short or open circuit of the diodes. These diodes were removed during routine maintenance periods. Actually, out of approximately 15,000 diodes in the machine and over a period of a full year, only 20 diodes were removed for having been found to be the direct cause of failures in attempts at solving problems. All the rest were rejected as a part of the preventive maintenance procedure.

Preventive Maintenance

In order to clarify these figures let me describe the system of maintenance used on the SEAC. The machine is scheduled on the basis of 24 hours a day, seven days a week, which is a total of 168 hours per week Out of this time something like 10 or 20 hours are scheduled each week for preventive maintenance. During this time the tubes and diodes in two or three chassis are removed and tested individually, adjustments are made to the mechanical devices, the central clock phasing is tested, test routines are run, and marginal testing is used. This marginal testing procedure is particularly simple with the circuitry that is used. The positive pulse output of every stage in the computer appears on one winding of a pulse transformer, one side of which is returned to a bus at -10 volts. Thereafter, d-c coupling is used to the grid of any tubes which are to be activated by this pulse. Thus if this -10 volt bus is made more negative, every pulse in the computer is weakened in its action on the succeeding stage, and any which are marginally low in amplitude will produce failures. Similarly the negative outputs used to inhibit the action of gates are returned from a transformer winding to a bus at $+4$ volts, so raising the voltage of this bus is sufficient to induce errors in any stage which has a marginal amplitude. Thus the maintenance procedure is a combination of direct testing of components and marginal checking. We believe that in the case of the circuits that we use, both are desirable. The typical stage in the computer is operated with the vacuum tubes output limited by plate saturation. Thus as the emission of the tube deteriorates, there is for a long time almost no effect on the output pulse characteristics, and then quite suddenly the output pulse becomes unacceptable. This maintenance procedure has been quite effective in catching the components which are becoming weak and removing them during the routine maintenance period and before they have a chance to cause difficulties in the problem computations. For example, during the past year among the *6AN5* vacuum tubes, 410 have been rejected as a part of preventive maintenance, but only seven have been removed for causing trouble during scheduled problem time. This is an average of only one tube in nearly two months that definitely failed during scheduled problem times. Similarly, out of all the thousands of germanium diodes that are in the SEAC, only 20 have been removed in the last year for causing trouble during problem solutions. The great preponderance of those which have been replaced have been as a result of preventive maintenance operations.

I might discuss this question of component reliability a bit at this point. One naturally tends to assume that in order to insure reliable operation of large aggregations of tubes and germanium diodes it is necessary that each component be able to be depended on for reliable operation for a large number of thousands of hours. This, it is true, is desirable but is by no means necessary. If it is present it can result in long periods of good operation between maintenance repair activities and is the dream of every computer engineer. On the other hand, though, on the large installations where only a small fraction of the cost of operation is necessary to have maintenance personnel on hand reasonably frequently, it is only necessary that there be some reasonably simple test which will permit the removal of those elements which are likely to fail before the next maintenance period. For example, if one could predict the future operation of a computer component for no more than half a day but it only took a few minutes of diagnostic test to locate those components prone to failure in the next half day, it would be entirely reasonable to do this diagnostic test procedure a couple of times a day, and the over-all problem-solving performance of the computer would be entirely satisfactory.

This is another way of saying that what we need for reliable computer performance is primarily predictably low failure rates for a given period of time. If the failure is unpredictable, it is necessary that the failure rate be very low to permit reliable operation. For instance, it would make only a very modest difference to the operating cost of a large computer if every tube in it had to be changed after 1,000 hours, provided good operation is guaranteed for this time. As another example, a vacuum tube which fails due to gradually decreasing emission can easily be detected by preventive maintenance and removed before it causes any unreliability. On the other hand, a vacuum tube which fails by a sudden short circuit or by a suddenly open-circuited filament is difficult to live with.

This desirable predictability of performance has definitely been shown by the diodes used and by the *6AN5* tubes. It is a very startling fact that so few tubes and diodes have visibly failed during scheduled computations—only seven tubes and 20 diodes in a year's operation. This leads a computer designer to look forward to the time, maybe not this year or next, but eventually, when equipment of this degree of complexity can be so designed that an over-all operating rate of 70 per cent would be considered to be grossly inefficient.

Appendix I. 6AN5 Test Specifications in SEAC

The *6AN5*'s used in SEAC are tested as follows, with 60 volts on plate and screen:

1. I_p is read with 6.3 volts on the filament with
   (A) Grid grounded
   (B) Grid at -5.7 volts

2. I_p is read with 5.7 volts on the filament with

(A) Grid grounded

(B) Grid at -5.7 volts

The tube is rejected if any one of the following conditions apply:

Reading 1(A) is under 25 milliamperes or over 55 millampered.

Reading 1(B) is greater than 8 milliamperes.

Reading 2(A) is less than 75 per cent of 1(A).

Reading 2(A) is less than 25 milliamperes and also is less than 85 per cent of 1(A).

Appendix II. Diode Test Specifications in SEAC

All diodes are tested before clustering and again before installation in the machine.

All diodes are kept under test for at least 0.5 minute on both the forward- and back-current test, and the readings are taken at the end of that period.

A "creeper" is a diode whose back current is not steady, but tends to drift in either direction. Such a diode is acceptable only if its back current drifts less than 50 microamperes in 0.5 minute and is stable at the end of that period within the below specifications.

A "wiggler" is a diode whose back current is not steady, but tends to vary suddenly about some particular point. A "wiggler" is acceptable only if the total back current variation is less than 10 microamperes and is within the below specifications for a normal diode.

Acceptance specifications are given in the following table:

At least 100 diodes of each shipment received are tested at both room temperature and 50 degrees centigrade, and the data recorded for each individual diode. The remainder of the diodes are tested first at room temperature and to the room temperature specifications. The ones which pass this test are accepted without further testing, but the diodes which fail the room temperature test are tested again at 50 degrees centigrade for possible acceptance. These diodes are left in the oven for at least two hours at 50 degrees centigrade before readings are taken. Any diodes which fail both the room temperature and the 50-degree centigrade test are absolute rejects.

	Maximum I_b at 40 Volts: Normal	Maximum I_b at 40 Volts: Creeper	Maximum E_f at 20 Ma
Before Clustering	150 μa at room temp. / 250 μa at 50°C	100 μa at room temp. / 150 μa at 50°C	2.0 volts
Before Installation	200 μa at room temp. / 300 μa at 50°C	150 μa at room temp. / 200 μa at 50°C	2.0 volts
In Service	400 μa at room temp. / 750 μa at 50°C	250 μa at room temp. / 500 μa at 50°C	2.3 volts

Joint Discussion*

J. Naines (Northwestern University): Mr. Slutz, would you please explain what you mean by creeper failure with diodes?

R. J. Slutz: When you put a diode on a test to watch its specifications, you observe that a sizable percentage of the diodes do not have a steady back current. For instance, our particular test is made at 40 volts back voltage on a diode of essentially the *1N34* characteristic (a little bit tighter here and there). You observe when you have tested a large number of diodes that quite a few of them do not come to a fixed back current when you first turn the voltage on but gradually change over a period of time. This may be for 10 seconds, it may be for a minute or, in the case of some of them we have observed, may carry on for several hours, with the back current sometimes gradually decreasing, sometimes gradually increasing, and sometimes doing both, going up for half a minute and then back down.

This kind of diode we define as a creeper, the back current showing a gradual change. We have found that there are enough of them so that to keep our machines supplied with diodes we cannot throw all of them out. Consequently, we have specifications which allow for this phenomenon, and we consider a diode acceptable for the machine if (a) the total amount of creep over the period of a minute is less than 50 microamperes and if (b) under these circumstances it passes a somewhat tighter specification than in the case of diodes which do not creep.

Similarly, you also find diodes which are what we call wigglers, in which this characteristic changes, not gradually, but very abruptly. It may just jump from one current value to another. Again we have not felt it necessary to throw all these out of our initial specification, but we do throw them out if this jumping, (not a single jump, but jump up, jump down, jump up, jump down), is more than 10 microamperes. If it is less, we are willing to accept it at the present time.

I may complete that by saying we have not thrown them out because we do not know whether they are particularly poorer in life than the others. Our system now is set up so that we can keep complete track of every one of the 15,000 diodes in the machine, each of which has a number, and every time it is tested its test is recorded against that particular diode. We hope as time goes on to get more information which will show us whether or not we really should throw out all these wigglers and creepers.

G. Hand (Technitrol Engineering Company): The question I have concerns the wide use of plug-in techniques. I would like to know if you have experienced any large failure of plugs and sockets.

R. J. Slutz: We have had a phenomenally low failure rate in plugs and sockets. The commonest plug-in arrangement actually used in the machine at the present time is the standard octal tube base and tube socket, which was chosen for availability and cost. It is an inexpensive combination to use as the standard plug-in unit for assemblies of diodes and for pulse transformers and delay lines. The failure rate of these plugs and sockets is not significant. I think since the project has started we have replaced, perhaps, three of these octal tube sockets in the entire machine.

L. F. G. Jones (Eckert-Mauchly Computer Corporation): On your *6AN5's* do you operate the heaters at reduced voltage or are they operated at exactly 6.3 volts?

R. J. Slutz: We try to operate them fairly near to 6.3 volts, although again in view of the experimental nature of the SEAC, we do not attempt to hold it too closely, as a matter of fact. The filament transformer is on the bottom of the rack and usually adjusted so that the tubes in the bottom rows are held pretty nearly at 6.3 volts. As you go up the rack, they drop down to about 6 volts, or even 5.9 at the very top. We know this and we have left it in the machine. We are keeping records on the filament voltages of the individual tubes. When a tube fails, the filament voltage at that particular socket is measured and recorded, and eventually, as data goes on, we hope to be able to break it down in accordance with filament voltage to see if we get significantly different records for tubes run at 6.3, at 6.15, and 6.0.

L. F. G. Jones: How many channels do you have on your magnetic tape?

R. J. Slutz: We have one channel on the currently used magnetic tapes, on the 0.25 inch tape, using a standard audio recording and reading head, which I believe leaves an eighth of an inch wide channel. Experience indicates that this tends to reduce the number of errors produced by dust particles getting onto the tape and from the number of flaws as compared to what you would get in very narrow channels.

A. S. Roberts (Rector, Pa.): On your plug-in components, do you replace them in the same location after testing? In other words, do they go back in the identical spot in the circuit?

R. J. Slutz: Yes.

A. S. Roberts: Does that include tubes, too?

R. J. Slutz: Yes; each tube is numbered and it goes in the same socket after testing.

J. Levy (Arlington, Va): There is an apparent plateau in the curves of tube life in the failures, which seems to be cyclic. Has there been any attempt to correlate this data? Do you correlate manufacturer's tube lots with your overhaul and inspection reports?

R. J. Slutz: You say the plateau seems to be cyclic?

J. Levy: About every three points there was a flattening and then drop, and three

* This joint discussion covers both this and the preceding paper by S. N. Alexander on The National Bureau of Standards Eastern Automatic Computer.

points later a flattening and drop–this may only be apparent–it may not be really a plateau.

R. J. Slutz: I have not felt that the details within three or four points were really reliable.

J. Levy: This may need some action by the tube manufacturer in his test program if it can be correlated with particular lots.

R. E. Wilson (Radio Corporation of America): Dr. Alexander, you explained that your pulses are distributed at low impedance. I would be interested in knowing what the pulse level is and what the maximum cross-talk level measures?

S. N. Alexander: By our definition the cross-talk level is zero, simply because it is below the clipping level. This clipping level was set by the inherent disturbance signals that occur in the germanium diode gating circuits. We found that when we had completed the design of these circuits so that they would discriminate against the inherent disturbance signals, the cross-talk from other circuits was less than these disturbance signals. It is very hard to define an impedance level in nonlinear circuits, but the average volt-ampere impedance level in SEAC is of the order of 300 ohms and the signal level of the order of 17 volts. With clamping and disconnecting circuits used throughout, the grids of the tubes simply see no signals unless the driving source can override the clamping and disconnect diodes and get above the clipping level.

I might say this is an example of the virtue of operating with telegraphy—all the old troubles of telephony technique go out the window. You have new kinds of troubles—different kinds of troubles—but you do get the advantage of zero disturbance up to a certain threshold.

J. Paivinen (Burroughs Adding Machine Company): Would you care to indicate something of the minimum performance characteristics assumed in your pulse circuit design and the possible effects on any bottomed operation that might be useable in the design of the machine with the *6AN5*.

R. J. Slutz: The *6AN5* we test for a minimum, at 60 volts on the plate and the screen, of 25 milliamperes plate current. In addition, we reject if there is a change in plate current of 25 per cent for a drop in filament voltage of 10 per cent. We also reject it if the change in plate current is 15 per cent for a drop of filament voltage of 10 per cent, and the lower of these two values of plate current is less than 25 milliamperes. The complete specifications are given in the paper.

The bottomed operation gives a uniformity of pulse output regardless of the strength of the tube. The plate current on test at 60 volts on the plate and screen may vary from 25 to 50 milliamperes, but the pulse out of that typical stage will vary at most by no more than about 5 to 10 per cent between these two tubes.

Because the tube is operating bottomed we do not attain standard plate dissipation. The limitation in dissipation is for the screen grid; the plate therefore is running cooler than the allowed manufacturer's rating. We believe that this probably gives us a trifle better life than would be the case if both the plate and screen were run at full plate dissipation.

J. F. Lash (General Motors Research Laboratory): I wonder if you could tell me approximately what is the maximum footage of magnetic tape that you run into the cells of the tape handling mechanism.

R. J. Slutz: A regular reel of tape, about 1,200 feet, is used in each bin.

Computing Machines in Aircraft Engineering

CHARLES R. STRANG

I HAVE been specifically asked to present a user's critical view of computing machinery with emphasis on its limitations.

This is an inversion of the situation in which aircraft manufacturers usually find themselves. We are normally the supplier rather than the user, and the users of our products rarely need this much encouragement to present their views of us very critically indeed.

Aircraft, like computing machines, are complicated to design and difficult to build. You will find those who struggle with aircraft design problems understanding and sympathetic with the difficulties involved in computing machine design.

We have gone far enough to see that there are special problems in making really full scale use of machine computing in our engineering work. There are marked differences between our work and the more academic or scientific applications for which many of the present machines were developed. I will try to convey an understanding of what our work is like.

Before I do make such comments as I have in mind, I should perhaps give some idea of how much of a user of computing equipment the Douglas Company has actually been, so that you may judge how to evaluate my remarks. In considering these data it should be kept in mind that we take a rather hard-boiled engineering view of our own work. We do not fancy ourselves as scientists and we do not undertake mathematical investigations for the sheer intellectual joy of doing so. Furthermore I do not wish to leave the impression that everything we do is dependent on large scale calculation. I suppose about 15 to 20 per cent our total work is mathematical in nature. Much of that work is a miscellany of casual calculations too small to benefit from high speed computing machinery. On the other hand, a great deal of our mathematical work tends to be concerned with operations that occur early in the formative stages of the design when much of what follows can only be tentative until the calculations are well advanced. Most of the remainder is concerned with formal demonstration that the design complies with all its requirements.

A few miscellaneous numbers may serve to give some idea of the scale of present-day aircraft engineering and manufacturing operations. For example, if we were to commit ourselves today to a 4-engine jet transport development program (which, incidentally, the newspapers say we should do) the cost up to first flight would not be less than $25,000,000, and probably more. The business risk involved is very much greater than that figure because competitive sales prices have to be set at a level such that a considerable number of airplanes must be sold before the break-even point is reached. As an example of engineering

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