CONTROL AND MAINTENANCE PROBLEMS DURING OPERATION

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1. SCOPE OF STUDY

This study covers the problems associated with maintaining the analysed beam current of the two-mile accelerator within specified energy and intensity limits during the experimental time. The effects of various failures on machine operation are analysed in detail and procedures are proposed that may be used to restore service.

2. MAINTENANCE AND RELIABILITY

Maintenance efforts normally are directed toward a particular objective. The viewpoint taken here for this objective is the continuance of the analysed beam current within the desired specified limits during the experimental time. The maintenance policy adopted should be directed toward attaining this objective.

3. MAINTENANCE PROBLEM DURING OPERATION

The objective, as mentioned above, is the continuance of the analysed beam current. Partial or complete loss of this current is conditioned by two states the accelerator can assume in case of component failure, as follows.

a. In the first state the beam is shut off in the accelerator and there is no analysed current. This is caused by a failure in a subsystem which contributes a vital parameter, e.g., the failure of the electron gun, the frequency generator, etc. Such failures will be called <u>single-source failures</u>. Machine or personnel protective arrangements (the interlock systems) that turn off the beam are also classified as single-source failures.

b. In the second state the electron beam still exists in the accelerator but a change in the accelerator operating parameters has occurred, resulting in partial or complete loss of the analysed beam. A change in radiofrequency power or rf phase usually causes this effect. Many independent subsystems contribute to the rf output, hence loss of a single subsystem produces a change in the integrated rf power but does not produce a total loss of power. Such failures will be called <u>multiple-source failures</u>. The klystron power amplifiers and the associated supporting subsystems, such as water, vacuum, trigger, and drive power, contribute to multiple-source failures. Phase and energy variations also can be caused by variations of the operating parameters during operation.

All potential failures can be classified either as parameter changes, multiple-source failures, or single-source failures. The problem is to identify the underlying cause in case of analysed current failure and to find appropriate restoration procedures.

4. FAILURES AND THEIR EFFECT ON OPERATION

a. Parameter Changes

The parameters affecting the established beam and their relative influence are analysed in M Report No. 255.[1] The most significant of these parameters are klystron beam voltage, operating temperature of the accelerator, and phase shift in the rf system. The variations due to parameter changes are expected to be "slow," i.e., in the time range of several seconds to minutes or hours. The general effect will be an analysed current that continuously varies in intensity.

b. Multiple-Source Failures

Multiple-source failures have one common characteristic: They change the summation of the rf power in the accelerator, and hence the available beam energy, by an amount that depends on the number of sources disabled.

The source of rf power (the klystron power amplifier) depends on a number of subsystems for successful operation. The subsystems consist of a number of mutually independent units, each serving several klystrons. The smallest power loss is incurred when a single klystron or modulator fails. The increasing order of losses depends on the subsystems, as tabulated below (see Table I).

c. Single-Source Failures

The common characteristic of single-source failures is the complete loss of beam current in the accelerator. This can be caused either by the failure of a subsystem (e.g., the injector) which directly affects the transmitted beam, or by protective shutdown of an interlock circuit when a hazard is created.

The complete loss of rf power and/or electron beam pulses can occur. Either may be caused by a failure of the frequency or trigger generator.

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[1] K. E. Breymayer, "Problems in Beam Operation," M Report No. 255, Project M, Stanford University, Stanford, California, June 1961.

TABLE I

SUBSYSTEM UNITS AND ASSIGNED NUMBER OF KLYSTRONS

Subsystem Unit	Number of Units	Number of Sectors Per Subsystem Unit		Number of Klystrons Per Subsystem Unit	
		Stage I	Stage II	Stage I	Stage II
1. Main Booster*	5	6	6	48	192
2. Power Supply	8	4	1	32	32
3. Water	15	2	2	16	64
4. Vacuum	30	1	1	8	32
5. Sub-Booster	30	1	1	8	32
6. Trigger	30	1	1	8	32
7. Modulator	240 (1000)	-	-	1	(1)

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*The main boosters are series connected, and klystron losses depend on the position of the booster. Loss of the last booster is equivalent to the loss of 48 tubes.

The latter also may be caused by a failure of either the injector or the beam steering system.

5. FAILURE RATES AND THEIR EFFECT ON BEAM-ON TIME

A table (Table II) has been prepared, which follows the above classifications, showing average failure rates and estimated repair rates. The rates given in this table should not be interpreted as predicted values. Rather, the data are meant to give a first order estimate of the relative influence of the various types of failures upon operation. Some of the basic assumptions used in the estimates are noted in the footnotes to Table II.

6. REPAIR OF SINGLE-SOURCE FAILURES

By definition, a single-source failure interrupts beam operation until service of the failed unit is restored. Repair can be achieved in a number of ways; e.g., the faulty component can be replaced, standby units can be used or efforts can be directed toward preventing the failure from occurring in the first place.

The following criteria can be used to classify the expected single-source failures with respect to the repair or maintenance approach. Any procedures selected can be called a policy. This policy should be optimum; i.e., it should minimize the outage time, given the cost of maintenance, or the minimum cost policy should be found, given the permissible outage time.

a. Access Time

When no radiation hazard exists, the equipment in question will be accessible immediately, allowing only time to get there. However, in case of radiation hazards, substantial delays may exist. All equipment outside the accelerator housing and switchyard normally will be immediately accessible. Inside the accelerator tunnel high radiation levels will exist, and long delays of the order of days to weeks may result.

b. Repair Time

This is the time from the beginning of the actual repair to the end. It includes determining the location of the exact trouble spot in the failed equipment and the replacement or adjustment of the faulty component.

c. Service Restoration Time

This is the time from the end of the repair, when the failed equipment is restored to operation, to the resumption of beam operation. For

TABLE II

ESTIMATED AVERAGE FAILURE RATES AND REPAIR RATES

RF LOSS EXPRESSED IN NUMBER OF KLYSTRONS	AVERAGE FAILURE RATE	AVERAGE REPAIR TIME HRS	SIX MONTHS OUTAGE DUE TO REPAIR		NUMBER OF FAILURES IN SIX MONTHS	
			HRS	%	NO.	%
1	1 per 4 hours[a,b]	1	1080	86.5	1080	95
2	1 per 2 weeks[c]	1	12	.96	12	1
8	1 per 6 days[d]	3	90	7.20	30	2.6
16	1 per 24 days[e]	3	22.5	1.80	7.5	0.7
32	1 per 6 months[f]	24	24	1.90	1	-
SINGLE-SOURCE FAILURES:						
12	1 per month[g]	3	18	1.4	6	0.5
			1246.5		1136.5	

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a. Tube failures account for 1 loss per 8 hours when 240 tubes are used.

b. Modulator failures account for 1 loss per 8 hours when 240 modulators are used. 1 modulator per 1775 hours is quoted by RCA in a memorandum of April 27, 1961. 2000 hours are assumed as an example.

c. One incident per 60 months is assumed. 120 transformers are used for modulator auxiliary power supply.

d. Due to failures in drive sub-boosters and trigger sub-boosters, 1 failure per year per subsystem unit is assumed. Drive and trigger systems have 30 units each.

e. Due to failure in water system, 1 failure per year per subsystem unit is assumed. There are 15 units.

f. Due to dc power supply system.

g. One failure per year per single-source system is assumed.

example, this time interval can be substantial in the case of vacuum failure.

With respect to access time and service restoration time, two possible basic policies are recognized for minimizing outages: (1) avoiding the placement of critical components in areas having a long access time, e.g., those in the accelerator housing or switchyard area; and (2) using preventive maintenance for equipment having a normal access time but an extended service restoration time. Some of the surface equipment located in the klystron gallery will be of the latter type.

The maintenance policy for the remaining surface equipment of the single-source type should be judged by its repair time requirements.

7. REPAIR OF MULTIPLE-SOURCE FAILURES

By definition, multiple-source failures lead to a change in rf power, but not necessarily to an integrated beam loss. The beam continues to exist in the accelerator but fails to reach the target because its energy has changed. It is discharged entirely on the slit plates and may thus cause a radiation and heat problem. This situation determines the viewpoint to be taken for restoration of operation. The overriding consideration is the need for quick elimination of the radiation and heat transfer hazard created, while maintaining a favorable beam-on time ratio. The allowable time for action with respect to eliminating the hazards is on the order of much less than one second.

There are two basic solutions available to meet these requirements. Either the beam can be turned off or the loss in rf power can be recovered quickly by suitable means without turning off the accelerator.

The two most promising schemes for restoration of beam operation have the following characteristics.

a. Both eliminate the radiation hazard immediately but with respect to beam-on time some differences exist.

b. Turning off the beam will have an unfavorable effect on beam-on time when the failure rate is high due to the time involved in getting back to operation.

c. The energy restoration scheme is basically optimum, both to radiation elimination and beam-on time, when designed for an appropriate automatic procedure.

As shown in Table II, frequent events are associated with small rf losses, mainly of the one-klystron type. The opposite holds where the frequency of the event decreases.

It appears that energy restoration should be attempted where rf power losses are frequent and small. The beam turn-off procedure should be used where the power losses are high and less frequent. In terms of the failure classifications, the beam turn-off procedure is equivalent to a single-source failure in its effect. As such, it can be judged from the discussion in Section 6.

8. BEAM CONTROL REQUIREMENTS

The principal operating parameters contributing to energy and phase variations are the klystron beam voltage, the accelerator temperature, and the phase shift in the drive system. These changes can produce substantial variations in the magnitude of the analysed current, as has been shown in M Report No. 255.[2] Based on the relations described in that report, the following data are derived.

a. Klystron Beam Voltage

Two effects result: the rf power output is changed, and a phase shift is produced.

1. Energy change due to rf power change

$$dV/V = 1.25 \times 0.25 \times 10^{-2} = 0.31\%$$

where 0.25×10^{-2} is the assumed tolerance on beam voltage.

2. Phase change due to beam voltage change

$$d\varphi = -10.2 \times 0.25 \times 10^{-2} = -2.5 \times 10^{-2} \text{ rad or } 1.43^{\circ}$$

3. Energy change due to the phase variation

$$\left.\frac{dV}{V}\right|_{\varphi} = \frac{d\varphi^2}{2} = \frac{2.5^2 \times 10^{-4}}{2} = 3.2 \times 10^{-4} \text{ or } 0.032\%$$

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[2] M Report No. 255, *op.cit.*

b. Accelerator Temperature

The energy change associated with a change in temperature can be estimated from the expression derived by Neal[3]

$$dV/V = 8.1 \times 10^{-3}\ (dT)^2$$

For 0.37°C,

$$dV/V = 8.1 \times 10^{-3} \times 0.37^2 = 1.11 \times 10^{-3} \text{ or } 0.11\%$$

For 0.70°C,

$$dV/V = 8.1 \times 10^{-3} \times 0.70^2 = 4 \times 10^{-3} \text{ or } 0.4\%$$

c. Phase Shift in the Drive System

A phase shift of 5° is assumed. This value may be reached when all shifts in the drive system move in the same direction. The maximum energy change associated with this shift can be assessed from

$$\frac{dV}{V} = \frac{d\varphi^2}{2} = \frac{0.09^2}{2} = 0.4\%$$

d. Summary of Energy and Phase Variations Due to Parameter Changes

Parameter	Assumed Tolerance	Energy Change	Phase Change
Klystron beam voltage	± 0.25%	$\left.\frac{dV}{V}\right\rvert_p = .31\%$	0.025 rad or 1.4°
Accelerator temperature	± 0.37°C	0.11%	.04 rad or 2.5°
	± 0.70°C	0.40%	.080 rad or 5°
Drive system phase	± 5°	0.4%	

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[3] "Project M Source Book," Project M, Stanford University, Stanford, California, Section II.B.3 (p. 22), July 1960.

9. ENERGY RECOVERY SCHEMES

Multiple-source failures and parameter changes produce energy and phase variations that must be offset in order to maintain the intensity of the analysed current within specified limits. The potential variations produced by parameter changes are analysed above in Section 8. Each of the three parameters considered can produce a maximum energy change of about 0.4%. The limit of the total change to be expected is the linear sum of the individual changes. This will also be the limit of the control range for a scheme used to offset these changes. A value of 1.0% is assumed. The time domain of these changes, i.e., their rate of change, will be on the order of seconds to minutes.

Multiple-source failures produce discrete changes in energy. The changes can take place in units of 1 klystron, 8 klystrons, etc., as shown above in Table I.

In Stage I a loss of one klystron represents a 0.4% loss of energy, and a loss of 8 klystrons represents a 3.2% loss of energy. Measures taken to recover such losses should be performed in a short enough time to minimize the heat and radiation problems they create.

There is a need for the continuous adjustment of energy during beam operation through a potential range of about 1.0%. There is also a need to recover energy lost, due to losses in klystron power, on the order of 0.4% and up. The latter requires fast action. The investigation of suitable energy recovery schemes will be directed toward arrangements with an adjustment range capable of recovering energy lost, as specified above. Examples of the suitable means available are listed and discussed below.

a. Klystron beam-voltage adjustment
b. Klystron drive-level adjustment
c. Standby klystrons
d. Beam-loading effect
e. Pair-wise dephasing

a. Klystron Beam-Voltage Adjustment

This scheme permits all klystrons to operate at their normal level. In case of a loss, the applied voltage on all or some of the operating tubes can be adjusted so that the rf power loss is recovered and a constant beam energy is maintained.

The adjustment of the beam voltage can be made via the power supplies. A suitable control point is the so-called "de-q'ing" circuit of the modulator. A fast-acting control to maintain pulse-to-pulse voltage stability is provided there. Small variations in the dc charging level can be obtained via the de-q'ing reference voltage. There is one such control voltage for each 32 tubes of a common power supply.

The side effects involved are twofold. A dc voltage control of the klystron produces a phase shift through the tube, and some increase in power loss is incurred in the de-q'ing circuit when the dc charging level is reduced to obtain a suitable control margin. The phase shift generated can be offset in principle by the phase-compensating control. A detailed analysis of this problem will have to be made to establish that the energy and phase control can work independently of each other.

The following example will illustrate the necessary beam-voltage adjustment, power increase, and energy control range. A general range of about 1%, a minimum energy adjustment of 0.1%, and, in addition, the problem of extending the range to about 3% will be considered. The example demonstrates the use of one controlled power supply and failures within or without this unit.

1. Adjustment for a 1% and a 0.1% beam-energy control

When N is the total number of klystrons and N_1 the number to be adjusted, then the necessary increase of rf power in N_1 for an increase in total energy V is given by

$$P_1 = P_0 \left[\left(\frac{V - V_0}{V_0}\right)\left(\frac{N}{N_1}\right) + 1\right]^{2\,*}$$

For the above case

$$P_1 = P_0\,(0.01 \times 240/32 + 1)^2 = 1.16\%$$

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[*] Derived by K. Mallory.

For a minimum energy adjustment of 0.1% the necessary power increase is 0.015 or 1.5%.

The necessary increase in beam voltage is derived from the relation $P \sim V_K^{5/2}$, which holds when the klystron is operated under optimum conditions. For small changes in P_1 the approximation $dV/V \sim 2/5\ dP/P$ is used.

Thus, a 1% adjustment in total energy requires a power increase of 16%, or a beam voltage increase of 6% in 32 klystrons. For a 0.1% energy adjustment the power and voltage corrections are 1.5% and 0.6% respectively.

2. Adjustment when one klystron fails

Two cases are considered: the loss occurs either inside or outside the controlled unit. When N_1 denotes the number of controlled klystrons and N_0 the loss, then the increase in power in N_1 is given by

$$P_1 = P_0 \left[\frac{(N_0 + N_1)}{N_1} \right]^{2\,*}$$

For $N_1 = 32$ and $N_0 = 1$ and a loss outside the controlling unit, the power increase in N_1 is 6% and the beam-voltage increase is 2%.

When the loss occurs within the controlling unit $N_1 = 31$ and the power and voltage adjustments are 7% and 3% respectively.

3. Adjustment when 8 klystrons are lost

The two situations under the previous example are considered. When the loss is outside the controlling unit $N_0 = 8$ and $N_1 = 32$. The power and voltage increase in N_1 is 57% and 20% respectively. When the loss occurs within the controlled units $N_1 = 24$ and $N_0 = 8$. Power and voltage adjustment then become 78% and 23% respectively.

If the beam voltage adjustment per klystron is limited to 10%, the number of controlled units must be increased. For $N_1 = 96$, i.e., three controlled power supplies, the simultaneous loss of 8 tubes can be compensated by the voltage adjustments of 7.2% and 7.6% respectively for inside or outside losses.

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*Derived by K. Mallory.

b. Klystron Drive-Level Adjustment

Output variations can be obtained by control of the drive level. However, klystrons are normally operated under "optimum" drive conditions. In such a case, the output power is rather insensitive to drive-level variations.

In order to obtain a suitable control margin, the input drive level has to be reduced below the optimum level. The drawback of this adjustment is a reduction in operating efficiency of the klystron.

There are also technical problems in drive-level control. Existing means of control produce substantial phase shifts. Fast controls are available at low power levels; however, for levels on the order of kilowatts or higher, a mechanical regulator is presently necessary. This would lead to either great numbers of low-level controls for the fast adjustments or one or two high-level controls with slow reaction time. This scheme can be both continuous and fast in principle. However, it does not appear very attractive because of the regulation problems and the side effects mentioned above.

c. Klystron Standby

In this system a preassigned number of standby units is set aside and the desired energy is established with the operating units. Whenever a loss occurs, a standby klystron is switched into operation immediately as a replacement for the disabled unit.

Standby, permitting quick operation, can be provided by removing the drive, or by trigger blocking with the tube otherwise ready for operation, or by outphasing, i.e., triggering between the main pulses so that the rf generated has no influence on the electron beam.

Trigger blocking removes the dc load from the klystron collector and reduces stress on the windows. The associated accelerator section will go through a temperature transient period, when the tube is activated and rf is fed to the accelerator. The tube may be operated up to 20 or 30 hours without side effects on the cathode when the beam voltage is removed.

Outphasing, or time-displacing of the trigger, puts continuous stress on tube and windows but will minimize the heat change problems in the associated accelerator section.

Removing the drive operates the tube in diode fashion and puts the tube, with respect to stress, between the trigger blocking and outphasing schemes.

Klystron standby offers a quick and discrete form of energy adjustment. However, it is not suitable for correction of energy changes due to continuous parameter variations.

d. Beam-Loading Effect

The relations existing between beam current, energy, and analysed current are given in M Report No. 255.[4] By the definition of beam loading used by Project M, a change in beam current of 1% produces a change of 0.1% energy. With the model used in the M-255 analysis, this corresponds to a 10% variation of the analysed current.

Hence, for heavy beam loading, substantial control over the analysed current can be obtained with small changes in beam current. For light beam loading this form of control is less attractive.

The scheme outlined above has the advantage of being simple, continuous and fast.

e. Pair-Wise Dephasing

When the energy vector in a section is shifted in phase with respect to the beam reference vector, the energy contribution of the accelerator length involved is reduced by an amount corresponding to the cosine of the angle. If another vector of the same length is shifted in the opposite direction by the same amount, the sum vector will be in phase with the reference. This pair-wise dephasing does not change the spectrum width. If an energy loss occurs, the energy "stored away" by this technique can be used to recover the operating energy by suitably reducing the phase angle. The amount of initial dephasing required obviously depends on the amount of energy to be recovered and the number of sections involved.

Phase control can be achieved by ferrite-type phase shifters with dc excitation. This scheme would be continuous and fast enough to meet the objective. A maximum phase shift of up to 60° appears to be feasible with ferrite-type phase shifters. When a loss of energy occurs in the

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[4] M Report No. 255, op.cit.

controlled vectors, one vector is shortened and a phase in the sum vector is introduced. In this case, the phased vectors assume different angles with the reference and the control problem is complicated. A similar situation is created when parameter changes lead to phase changes or to energy changes of the individual vector in the controlled units.

The following illustration assumes the changes to happen outside the phased vectors and necessary dephasing for an energy range of 1% of the total energy or a loss of one klystron is worked out. A total of 240 tubes are assumed for the accelerator with 8 klystrons in each phased vector. A 1% change in total energy is a 15% share of the contribution of 16 tubes. In order to "store away" that much energy, each vector should be dephased by ~ 30°. The stored-away energy has to be recovered by suitably adjusting all or part of the accelerator. This reserve is then available during operation. Similarly, provisions for the loss of one klystron can be made by a 20° dephasing.

10. BRIEF COMPARISON AND RATING OF THE SCHEMES

Obviously, any amount of energy to be used for control or reserve purposes must come from the total energy available. Hence, if control means are to be provided, there must be a reserve.

With respect to the viewpoint taken in selecting a suitable energy recovery scheme, the drive-level control and standby schemes are ruled out. The former has undesirable side effects and the latter does not meet the requirements of being continuous. The remaining schemes have merit in various ways and are compared as follows.

a. Klystron Beam-Voltage Control

This requires one control point where basic control is already provided in the form of a de-q'ing circuit control. It is continuous and fast and covers the energy range of 1% and the loss of one tube. It is probable that tube losses up to eight can be recovered if three control points are provided when each control point regulates 32 tubes.

b. Pair-Wise Dephasing

In this scheme a larger number of control points is necessary. Continuous and fast control over a range of 1% of energy covers energy losses up to one tube. Control becomes more complex when range is extended or losses occur in controlled units.

c. Beam-Loading Effects

While basically simple, the range is limited and this method functions well only at high beam current.

11. SUMMARY

Analysis of the problems during operation indicates that the analysed beam current is expected to change continuously due to parameter variations such as accelerator temperature, and that the most frequent source of failure will be the loss of rf power from one klystron. The latter is due to failures in klystron and modulator operation. Based on information presently available, this is expected to happen every four hours on the average.

Klystron beam-voltage adjustment at a selected number of tubes, e.g., 32, can be used to control the energy variation caused by the failures mentioned above. Phase variation can be offset by a phase control system acting on the buncher. The required control information is, in principle, available from a change in beam energy and beam spectrum width. This information can be made available from secondary electron monitors suitably placed across the energy-defining slits. These corrections can be made automatically and, when an energy reserve of 1% is provided, klystron losses of up to two can be controlled. This implies that such losses be rectified immediately when they occur so that, on the average, no more than 2 klystrons will be out of service at one time.

If such a policy is not feasible, a klystron standby system also will have to be provided to allow for greater numbers of klystrons or modulators in need of repair.

Simultaneous losses of larger numbers of klystrons will be rated as single-source failures and will shut down operation while service at the failed unit is restored. The maintenance policy to be used in this case will be a mixture of repair when failures occur and of preventive maintenance. The selection of a proper policy can be based on criteria such as developed above in Section 6, which describes repair of a single-source failure.

The repair effort should be laid out so that the outage caused is an acceptable fraction of the experimental time. It is evident that control and maintenance have to be combined in a suitable way to achieve optimum operating efficiency, i.e., the maximum use of the accelerator for experimental purposes at minimum cost.