THE EFFECT OF EXTENDED PULSE LENGTH ON THE MIRROR FUSION TEST FACILITY (MFTF)

G. D. Porter, R. H. Bulmer, F. H. Coensgen,
W. F. Cummins, R. S. Hornady, and R. R. Stone

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THE EFFECT OF EXTENDED PULSE LENGTH ON THE MIRROR FUSION TEST FACILITY (MFTF)

Abstract

The requirements and effects of operating Mirror Fusion Test Facility (MFTF) experiments with neutral-beam pulse durations in the range from 0.5 s to steady state are reexamined. We address two questions: 1) What is the maximum neutral-beam duration into the MFTF if the latter is built as described in the conceptual design document, and 2) What is required (and at what cost) to permit neutral-beam injection periods of 30 s in the MFTF? In both cases, we assume that the required neutral-beam modules are available. We find that the maximum practical pulse length consistent with the present conceptual design is 1.6 s. Increasing the pulse length to 30 s will require water-cooled beam dumps, protection against hot spots on the beam dumps, and modest expansion of the beam-control and data-acquisition systems. The estimated cost of the beam dumps and cooling system is \$10 million. We conclude that the present two-stage MFTF program plan is sound. This plan calls for establishing fundamental plasma scaling laws with 0.5-s operation and exploring nearly steady-state phenomena later with 30-s operation.

1. Introduction

This report is written as a supplement to the MX^{*} Major Project Proposal¹ in response to a concern expressed by the Open Systems Technical Review Panel² and others: the review panel felt that "the major technological goal [of the MFTF] is compromised by the ≤ 0.5 s duration beam time proposed for MX."

In this document, we reexamine in greater detail the requirements and effects of operating MFTF experiments for durations in the range from 0.5 s to steady state. Specifically, we address the following questions:

- Assuming the required neutral-beam modules are available, what is the maximum permissible duration of neutral-beam injection into MFTF if the latter is built as described in Ref. 1.
 - For an occasional maximum-duration run?
 - For routine maximum-duration operation?

^{*}The Mirror Experiment Facility (MX) has been renamed the Mirror Fusion Test Facility (MFTF) and will be referred to as MFTF in this report.

- Assuming that the required neutral-beam modules are available, what is required (and at what cost) to permit neutral-beam injection periods of 30 s in MFTF?
 - For an occasional single operation?
 - For routine operation?

To develop answers to these questions, we must consider how neutral-beam pulse lengths in the required range affect the entire system as well as recognize the obvious requirement for suitable neutral beam-systems that operate reliably. On the basis of considerations in this document, we have answered these questions as summarized below:

- Assuming that the neutral beams are not the limiting factor, the duration of the experiment probably can be extended to 1.6 s without modification of the present MFTF design being necessary. There is no difference between the requirements for occasional and routine maximum-duration operations.
- Extension of the confinement experiment to 30 s is compatible with the capabilities of the superconducting magnet, the steady-state cryopumping, and the 80-keV power supplies for the sustaining neutral beams. However, 30-s operation for even a single operation will require dynamically cooled beam dumps, protection against hot spots on the beam dumps, and modest expansion of the beam-control and data-acquisition systems. To avoid burning up the thin-walled, beam-dump structures, water cooling will be necessary for short-duration runs as well as for 30-s runs.

The estimated cost of the beam dumps and cooling system is \$10 million. Cost estimates for the other requirements are not available, but are expected to be small compared to \$10 million. If the decision were made now to add these items, and if the required funds were available, they probably could be constructed and installed without delaying the MFTF construction schedule. However, if projected FY 1978 funding is not increased, the addition of a 30-s capability for initial operation would probably delay MFTF.

Induced radioactivity levels increase with increased beam injection times, with increased repetition rates, with increased ion energy, with increased density, and with larger plasma volume. In the present MFTF program plan, induced radioactivity levels are kept to low levels by

limiting beam injection to 0.5 s during the physics investigations. However, routine 30-s operation would increase the level of induced radioactivity.

Debugging of the MFTF sustaining-beam systems is scheduled for mid FY 1981 (i.e., about April 1981). To enable procurement and installation of the modules by this date, the fabrication contract should be placed about 12 months earlier (April 1980). Assuming procurement placement requires only 90 days, module development must be complete by February 1980. However, because these modules are funded in the operating budget, fairly accurate cost estimates for the 30-s modules are needed by January 1978 for inclusion in the Form 189 planning document.

To evaluate the advantages of initial operation with 30-s beam duration, we review the MFTF program plan upon which the MFTF proposal is based. This program is a two-stage plan in which the fundamental plasma scaling laws are established with 0.5-s operation and a nearly steady-state condition is explored later with 30-s operation.

The relevant scaling laws are the dependencies of $n\tau$ upon mean ion energy (E_i), electron temperature (T_e), and plasma radius and length (R_p/ρ_i and L/ρ_i). For the MFTF design goal of $n\tau = 10^{12} \text{ cm}^{-3} \cdot \text{s}$ and $\beta = 0.5$, 0.5-s operation is 50 times the mean energy containment time ($50 \tau_E = 0.5 \text{ s}$), and thus it allows the plasma to reach plasma steady-state equilibrium.

The first-stage, 0.5-s-operation experiments constitute a significant step in addressing the technological goals because the following developments are required:

- High-speed, high-volume vacuum pumps operating in the pressure range 10^{-9} to 10^{-5} Torr.
- 80-keV, 30-A neutral-beam modules.
- 80-keV, 30-A power supplies.
- Neutral-beam system control and operation.
- Superconducting magnets.
- Operation of plasma diagnostics in a cryogenic environment.
- Development of near steady-state plasma diagnostics.

In the second-stage MFTF experiments, after the beam injection requirements have been determined and steady-state neutral beams have been developed, beam injection times would be extended to 30-s. Thirty-second operation adds the capability to study plasma sustenance with neutral-beam injection under steady-state vacuum conditions, that is, when the gettered walls (which are necessary

for startup) have become saturated with gas and one atom is returned to the volume for each atom that strikes the wall. Thirty-second operation is also compatible with the investigation of equilibrium physics for $n\tau > 10^{13} \text{ cm}^{-3}\cdot\text{s}$. This latter consideration could be important if field reversal is achieved in MFTF.

In planning the MFTF program, it was considered important to minimize the risks of schedule and cost over-runs while maintaining the capability for conversion to longer-duration experiments mainly by adding to the initial installation rather than by extensive rebuilding and replacement of original subsystems. In summary, 0.5-s operation was chosen for the initial experiments on the basis of the following considerations:

- Progress in the development of neutral beams for the Tokamak Fusion Test Reactor (TFTR) assured the availability of 0.5-s-duration neutral-beam technology.
- Steady-state neutral beams may require water cooling in the grid wires; this presents a high risk of "up-to-water"* accidents that would seriously delay the important physics scaling experiments.
- The required water-cooled beam dumps would also present a high risk of an up-to-water accident.
- Half-second operation permits the earliest acquisition of the physics data base for design of future experiments and reactors.
- Half-second operation permits the development of steady-state neutral beams and beam dumps to proceed independently of MFTF operation and allows these steady-state systems to be added as a second stage; this sequence minimizes schedule, costs, and operation risks for the initial MFTF experiments.

Because of the need for early confirmation of the physics scaling laws, and because the considerations listed above are still valid, it appears prudent to bring MFTF on in two stages: first for 0.5-s operation as planned and second for 30-s operation to make the transition to steady state.

*"Up-to-water" accidents occur when water-carrying vessels within a vacuum rupture and release significant amounts of water in the vacuum chamber.

2. Effect on Beam Dump Design

If neutral-beam modules with long pulse lengths were available, the sub-system limiting the experimental time in the present conceptual design would be the energetic beam dumps. In the conceptual design of MFTF, the duration of the injected neutral beam is 0.5 s and all beam dumps are inertially cooled; i.e., the energy is absorbed in the dump itself which is, in turn, cooled between shots with a modest amount of circulating water system. (Note that the water cooling on inertial dumps is located on the back of a thick plate and hence does not pose the threat of an up-to-water accident.) The maximum duration consistent with such dumps is determined by the time required to melt the surface of the dump. This time, in turn, depends upon the power flux incident on each beam dump.

To estimate the power fluxes, we have assumed a neutral current of 750 A incident on the plasma. The best estimate for the average energy of this beam is 60 keV; therefore, the power incident on the plasma is 45 MW. Since the profile of the beam is Gaussian, about 25% of the incident beam will miss the plasma. Hence, approximately $45 \times 1.25 = 56.2$ MW must be injected into the plasma chamber to achieve a power of 45 MW into the plasma. The remainder of the power, 11.6 MW, will be absorbed in the untrapped neutral-beam dump. The power efficiency of 77% that is assumed for the beam line includes an estimate of power absorbed by apertures and an estimate of the performance level of the MFTF neutral-beam system. Thus, the power emerging from the neutralizers is $56.2 \times 1/0.77 = 73$ MW. Note that only a relatively small fraction of the 16.8 MW lost because of transport efficiency appears on the apertures. The overall neutralizer power efficiency is estimated to be 65%. Hence, the ion power incident on the neutralizer must be $73 \times 1/0.65 = 112$ MW. Thus, a total of 39 MW appears in the unneutralized ion beam and must be absorbed by the ion beam dump. The power flux on the ion beam dump is estimated to be 2 kW/cm^2 .¹

We used the plasma profile calculated by the radially dependent buildup code³ to calculate the power flux on the other beam dumps. Beam injection parameters were adjusted to produce a flat profile with a radius of 30 cm. The plasma density was $8.5 \times 10^{13} \text{ cm}^{-3}$. The resulting power fluxes incident on the beam dumps are shown in Table 1. The largest power flux appears on the ion beam dump; therefore, the maximum pulse length is determined by the melting of this surface.

Table 1. Beam dump power flux, assuming a 60-keV, 750-A neutral current incident on the plasma.

Beam dump	Total power incident (MW)	Power flux (kW/cm ²)
Ion dump	39	2
Untrapped neutral-beam dump (includes charge-exchange losses on the neutral beam and 25% losses due to the Gaussian shape of the beam)	23.4	<0.5
End-loss beam dump	28	0.50 ^a
Charge-exchange losses on gas	4.8	<0.10

^aTo calculate this number, we assumed that the energy would be dumped near the chamber wall. Any object that must be inserted closer than this will receive a significantly higher power flux.

To calculate the surface temperature of the ion beam dump, we assumed a semi-infinite slab heated on one face:

$$\Delta T(\tau) = 2P'' \left(\frac{\tau}{\pi k \rho c_p} \right)^{1/2},$$

where ΔT = the temperature increase,

τ = the elapsed time,

P'' = the power flux,

k = thermal conductivity,

ρ = mass density, and

c_p = specific heat.

The time for the surface temperature of the ion beam dump to go from 300 K to 80% of its melting point (T_{mp}) is plotted in Fig. 1 as a function of power flux. Three materials are considered: copper, molybdenum, and tungsten. The Princeton Plasma Physics group has done some experimental work on inertial dumps made from these materials.⁴ In successfully operating a copper dump to 80% of its melting point for 1000 shots, they observed little evidence of excessive thermal stresses.

If, instead, the thickness of the ion beam dump is less than that necessary to be considered infinite, the surface temperature rises faster. The modest cooling envisioned for these dumps is insufficient to alter the surface temperature during the shot with a power loading of 2 kW/cm². Hence, the required dump

Fig. 1. Time required for the surface temperature to go from 300 K to 80% of the melting temperature, for three possible materials for inertially cooled dumps.

thickness can be calculated as that necessary to be considered infinite. If this thickness (x_{∞}) is defined such that the temperature at a distance x_{∞} from the surface of a semi-infinite slab is 0.2% of the surface temperature,

$$x_{\infty} = \frac{2[\pi k \Delta T(\tau)]^{1/2}}{p''}.$$

This thickness, together with the mass of each dump (assuming a surface area of 1 m^2) is tabulated in Table 2 for a power loading of 2 kW/cm^2 .

For estimating costs of the ion beam dumps in the MFTF, we assume that each dump is made of 3.5-cm-thick copper. This thickness can be considered infinite for a surface temperature rise of approximately 500°C . The maximum pulse length compatible with this design is 0.6 s; however, if the thickness is increased to 5.6 cm, the pulse length can be extended to about 1.6 s. This would increase

Table 2. Thermal properties of possible beam-dump materials.

Materials	k (W/cm $\cdot$ K)	ρ (g/cm 3)	c_p (J/gm $\cdot$ K)	T_{mp} (K)	τ_{max} (s)	x_{∞} (cm)	Mass (kg/m 2)
Cu	4.01	8.6	0.385	1356	1.6	5.6	483
Mo	1.35	10.1	0.250	2890	2.7	1.3	487
W	1.70	18.8	0.132	3643	5.7	7.9	1487

the cost of these dumps by approximately \$130 thousand. The pulse length could be extended even further by making the dumps of either molybdenum or tungsten. However, the cost of such a system is higher. A preliminary estimate indicates that molybdenum dumps would cost \$500 thousand more than copper and that tungsten dumps would cost \$3 million more than copper. Improved cost estimates are being prepared. At this time, the increased cost of molybdenum or tungsten over that of copper dumps does not appear to be justified on the basis of physics goals and cannot be justified as a developmental step toward steady-state operation.

Extending the pulse length beyond the limit imposed by inertial dumps requires extensive design changes in these beam dumps so that they can operate steady state. There are at least two ways to achieve this. The first is a "brute-force" approach of having high-pressure, high-velocity water flow past a thin plate; the second is to remove a significant portion of the beam energy electrically i.e., to use beam direct converters. Direct energy recovery is preferable in terms of bridging the gap between present experiment and large steady-state devices, but it is not necessary for multisecond operation of MFTF. We have used the Lawrence Livermore Laboratory (LLL) MATS-III source for beam direct conversion experiments.⁵ The power flux into the direct conversion experiments from this 15-keV source, which operates at steady state, was about 4.8 kW/cm^2 . Approximately 70% of the beam energy was removed electrically. The rest of the energy was spread over a sufficient area that it was possible to operate the molybdenum collector electrode with only radiation cooling. A similar direct conversion experiment is scheduled for the 120-keV TFTR/4 source at Lawrence Berkeley Laboratory (LBL). However, both the MATS-III and the TFTR/4 experiments separate the electrons from the ions electrostatically, a technique that puts rather restrictive limits on both the beam shape and the vacuum requirements. The MAT-III experiment is being modified to study magnetic separation, and we have initiated a study of the feasibility of using beam direct converters on the MFTF. If such converters are developed, the maximum power flux in the MFTF to be removed thermally would be $\leq 0.6 \text{ kW/cm}^2$.

We have estimated the cost of one brute-force approach to steady-state operation of the ion beam dumps in the MFTF. If we assume a power flux of 2 kW/cm^2 , this approach requires a flow of 45,000 gal/min of water past a thin copper plate. Figure 2 shows a rough sketch of a dump contained in an RCA proposal for TFTR.⁶ The high-volume flow is achieved by moving the water from high-pressure (~500-psi) supply tanks through the dumps and into a return tank

Fig. 2. Conceptual design of a dynamically cooled beam dump. (Illustration used with permission of RCA Corp.)

maintained at 100 psi to avoid boiling. The water is then pumped through a heat exchanger and back to the supply tanks in preparation for the next shot. Such a system is not a true steady-state device because only the water stored in the supply tanks can be pushed through the dumps by the pressure difference. However, a system can be designed for sufficient water storage to permit 30-s operation.

Cooling water for beam dumps handling a power flux in excess of 0.5 kW/cm^2 must be high-purity. For example, cooling-water specifications for an RCA high-power-density tube⁷ are:

$$\begin{aligned} \text{Resistivity} &\geq 10^6 \Omega \cdot \text{cm} \\ \text{CO} &\leq 0.05 \text{ ppm} \\ \text{O}_2 &\leq 0.5 \text{ ppm} \\ \text{CO}_2 &\leq 0.5 \text{ ppm} \\ \text{Total solids} &\leq 3.0 \text{ ppm} \end{aligned}$$

For 30-s beam injection into the MFTF, the total cooling system for the ion dumps would consist of two 30,000-gal tanks (one supply and one return), a low-volume pump to continuously circulate water through the dump, a continuous water-purification loop, a high-capacity pump to move the water from the return tank to the supply tank, and heat exchangers to remove the heat from the high-purity water after each shot. Table 3 lists cost estimates for each of these components for the ion beam dumps.

The ion dumps remove 41% of the total energy (see Table 1). A rough estimate for the total cost of beam dumps to remove all injected power for 30-s

Table 3. Cost estimate for dynamically cooled ion beam dumps.

Item	Cost (in \$1000's)
Ion dumps (24)	\$ 500
Water purification systems	120
Pumps	55
Tanks	650
Pipes (large)	105
Heat exchangers	410
Diagnostics ^a	150
Assembly costs	500
	<hr/> \$2490
Miscellaneous (pipes, gages, valves, etc)	310
Total:	<hr/> \$2800

^aSee Section 4.

operation would therefore be $2.8 \times 1/0.41 = \$6.8$ million. Using a contingency and escalation factor of 50% raises the estimate to \$10 million.

In summary, the cost estimate for the beam dump design described in the MFTF proposal was for 0.5-s operation. These inertially cooled dumps can be upgraded for use with 1.6-s pulse lengths with approximately a \$130 thousand increase in cost. The pulse length can be extended even further by using either molybdenum or tungsten instead of copper. However, the additional cost is then significantly higher, at least \$0.5 million more for molybdenum or \$3 million more for tungsten (without contingency, escalation or added administrative costs). Steady-state operation of beam dumps requires high-velocity, high-pressure water flow past a thin plate. Such a cooling system will add approximately \$10 million to the cost of the MFTF. The power flux to the ion beam dumps could be reduced from 2 kW/cm^2 to $\leq 0.6 \text{ kW/cm}^2$ by direct energy conversion techniques. However, this would not significantly reduce the cost of beam dumps for multisecond operation. Alternate techniques such as heat pipes must be evaluated before final steady-state beam dumps are designed.

Our estimates of the additional beam dump costs accrued by extending the beam pulse length on the MFTF use only a conceptual design for these dumps. The additional problems that must be addressed during the final design of these dumps include an accurate determination of the anticipated power loadings, temperature distributions, thermal stresses, and surface microdamage that may restrict the lifetime of the dump. Furthermore, the operation of high-temperature beam dumps could have adverse effects on the cryogenic and vacuum systems of the MFTF. We consider these latter problems and control methods in the next section.

3. Effects of Thermal Radiation on Cryopumping

Operation of MFTF with extended pulse lengths could produce a temperature rise in the cryogenic surfaces caused by radiant heat transfer from the beam dump. A temperature rise in surfaces cooled by liquid nitrogen (LN) would desorb gases such as argon and methane that freeze out at 77 K. A temperature rise in the surfaces cooled by liquid helium (LHe) would first decrease the pumping speed of the cryopanel; then, as the temperature rose even further, the gas frozen on these surfaces would boil off. This rise in the neutral gas pressure would lead to loss of neutral beam (the Culham effect) and increased charge-exchange losses of the trapped plasma. We have used a simplified

numerical model in cylindrical geometry to make a first estimate of the magnitude of this problem. The elements used in the model are listed in Table 4.

For the inertially cooled dumps, the estimated rise in the temperature of the dump surface is calculated using the semi-infinite slab relation (as described above). After beam turn-off, the surface is cooled, first by thermal diffusion through the dump, then by a modest flow of water past the back surface. The cooling-water flow is assumed to be about 10 gal/min for each ion dump.

For multisecond operation, we assume that the cooling-water flow is adequate to hold the surface temperature at 700 K. After 30-s operation, the surface is cooled by this flow. With both inertially and dynamically cooled dumps, the temperature response of the cryogenic surfaces is tracked as a function of time, with energy being removed by vaporization of the cryogenic fluids.

For 0.5-s operation, the rise in the temperature of all cryogenic surfaces is well below that required to produce any adverse effects. Extending the pulse length to 1.6 s produces a boil off of 48 litres of liquid nitrogen per shot. With an average of 1 shot/5 min, this would represent about a 10% increase in the total LN boil off. Although this boil off will require careful design of the LN system to prevent overpressure, it is not considered a major problem. A more significant problem appears to be the increase in the temperature of the LN-cooled chevron. We expect the cooling channel in these chevrons to be at the apex (see Fig. 3). Hence, there can be a significant thermal gradient across the face of the chevron facing the beam dump. Our calculations indicate that the temperature rise could be as much as 6 K, a difference that would lead to boil off of the gases frozen on the LN-cooled chevron. For

Table 4. Geometry assumed for radiant heat transfer calculations.

Surface	Material	Radius (m)	Thickness (mm)	Initial temperature (K)
Dump surface	Copper	1.0	—	300
LN-cooled chevrons	Copper	2.0	6.0	77
LHe-cooled cryopanel	Stainless steel	2.2	4.0	4
LN-cooled cryopanel	Stainless steel	2.3	4.0	77
Vessel wall	Stainless steel	2.4	25.0	300

Fig. 3. Typical cryopanel arrangement.

0.5-s-operation, this will not be a serious problem for two reasons. First, because of thermal inertia, this temperature rise occurs after the termination of the shot; the boil off of gas therefore will not affect the plasma. The gas will migrate to the surface of the LHe-cooled cryopanel, which is not affected because the chevron surface nearest to the LHe is held at the LN temperature. Second, our calculations are overly pessimistic because of the assumption that the surface of the dump radiates directly to the LN-cooled chevron. In fact, much of the dump surface will be shielded so that the heat load on the chevron will be somewhat lower.

The use of inertially cooled molybdenum or tungsten beam dumps to extend the MFiF operation beyond 1.6 s means that the surface of the dump will reach higher temperatures than are possible using copper dumps. Hence, the radiant heat load on the LN-cooled chevron will be significantly higher, and the problems accompanying temperature increases in these surfaces will be more severe. The magnitudes of these effects have not been evaluated for molybdenum or tungsten dumps. However, additional radiation shields probably would be required.

For multisecond operation, the LN boil-off rate and the increase in chevron temperature are even smaller than for 1.6-s operation because the surface of the dump never rises above 700 K. The LN boil-off rate is limited to approximately 10 litres/shot. The increase in the chevron temperature could be as high as 4 K; this is sufficient to boil off the argon and methane that are frozen on the chevron. The resulting pressure increase has not been calculated.

However, because the surface of the LHe-cooled cryopanel is not affected, its pumping speed is high and the pressure increase is expected to be small. As before, the estimated increase in the temperature of the LN-cooled chevron is probably an overestimate, and further study is needed to determine the effect of multisecond beam injection.

In summary, radiant heat loads on cryogenic surfaces resulting from high-temperature ion dumps do not appear to be a major difficulty. The heat can be absorbed in boil off of liquid nitrogen. The pumping speed of the LHe-cooled surfaces is not affected. Thermal gradients across the LN-cooled chevrons may be large enough that gas will be released: this will require more detailed analysis. It seems probable that such an analysis will show that the temperature increase in the chevron will be less than the 4 K indicated here. If not, additional radiation shields will be required for multisecond operation. However, for beam injection times of 1 to 2 s, the gas is released after the shot because of thermal inertia and therefore does not affect the plasma.

4. Effect on Beam-Dump Instrumentation

INERTIALLY COOLED DUMPS

Extended-pulse operation of the MFTF with inertially cooled dumps does not appear to pose any instrumentation problems. In principle, either optical pyrometric or optical radiometric techniques can be used to monitor surface temperatures. However, determination of the surface temperature with either of these techniques requires careful analysis of data taken during the beam-on time. Because surface imperfections and dust (which have poor thermal contact with the bulk of the dump material) will be heated to incandescence, optical pyrometric techniques that rely on the detection of radiation at a particular wavelength to determine the temperature will in fact determine the temperature of these very localized hot spots. Using optical radiometric techniques, one can minimize this problem by measuring the radiation emitted over a reasonable surface area (10 to 100 cm²). However, radiometric techniques require frequent calibration to account for variation in the condition of the surface of the dump (oxides, roughness, etc.). Furthermore, because of the localized incandescence, the calibration may be different with the beam on.

However, both of these techniques can be used after the beam is turned off and the local hot spots have cooled by radiation. Thus, the pulse length could

be gradually increased until the surface temperature reaches the maximum considered safe. If this temperature is exceeded on one dump, only that dump surface is damaged.

DYNAMICALLY COOLED DUMPS

Operation of the MFTF with pulse lengths that require dynamic cooling, i.e., multisecond operation with the steady-state beam dumps, will require very careful instrumentation for protection of the facility. When steady-state beam dumps are used, exceeding the maximum safe temperature can result in an up-to-water accident. If the thin wall of the beam dump is ruptured, the cooling water will be released to the vacuum. Freezing this water places a very large heat load on the cryogenic system. If not properly designed, the resulting boil off could lead to an overpressure and to rupture of the cryogenic lines. Because the boil off of LHe could cause the magnet to warm and go normal, the magnet current must be quenched immediately. Since the potential for damage is great, the facility must be instrumented so that the probability of such an accident is extremely small.

Standard methods for sensing water temperature would be inadequate; because the outlet water will be 5% steam/boiling water, the temperature is controlled by the water pressure. Water-pressure sensors can be used to shut down the experiment when the pressure falls, indicating a rupture of a water line, and to prevent personnel from starting the experiment if there is no inlet water flow. The surface temperature of the dump could be monitored with a matrix of thermocouples. However, it is not clear how one attaches a thermocouple to the front surface so that it is not destroyed by the beam. The minimum spacing of the thermocouple matrix depends on the anticipated size of a localized hot spot. This size in turn depends on specific details of the beam-dump design. A combination of pyrometric and radiometric techniques appears to be the most promising temperature-sensing method although further development is necessary before calibration problems can be resolved.

We do not have a reliable cost estimate for this temperature-sensing system because engineering effort is being directed toward an improved cost estimate of MFTF. However, our preliminary estimate for a system based on charge-coupled devices is \$6 thousand per ion dump. With 24 sustaining neutral beams, the cost for diagnostics for the ion dumps is $24 \times \$6 \text{ thousand} \approx \150 thousand (as noted in Table 3). The ion dumps absorb roughly 41% of the total

energy. Since each beam dump must be instrumented to protect against an up-to-water accident, the total cost of instrumentation is therefore approximately $150/0.41 \approx \$400$ thousand, without contingency or escalation.

5. Effects of Neutron Heating and Activation

The calculations of neutron activation and neutron heating of the superconductor in Ref. 1 are based on a 0.5-s pulse length and 100 shots per week. With $\beta = 0.5$, $\bar{E}_1 = 50$ keV, $B_0 = 2.0$ T, operation with deuterium yields an estimated neutron source strength of 2×10^{16} neutrons/s. The maximum heat transfer rate in the magnet due to the neutron load is 1.4×10^{-3} W/cm², well below the estimated permissible joule heating load of 0.25 W/cm². With this small heat load, the magnet will remain superconducting, allowing steady-state operation. Thus, neutron heating effects are not an important consideration for multisecond D-D operation with the above parameters. However, this heating effect can become a significant limitation for operation with plasma having higher density, higher ion energy, and larger volume.

As shown below, neutron activation effects will limit routine multisecond operation of the MFTF. To evaluate the activation problem, our analysis is based on the anticipated operating schedule sketched in Fig. 4. The machine cycle will be roughly periodic with period T. A fraction (f_{on}) of that time will be spent doing maintenance and making small changes in the machine. Personnel must spend a fraction (f) of the down time within the magnet structure. The average plasma on time (s/week) must then be kept low enough that the radiation received by these personnel is within safe limits. Entry within the magnet will not be possible for a certain time (δ) after the experimental run. The minimum value of δ is the time required to warm the magnet and is estimated to be 5 to 7 days.

To determine the dose received during a shut-down period, we use the following expression:

$$\text{Dose (K)} = 2.8 \times 10^{15} \text{ f } \bar{s} \sum_{i=1}^I \frac{1}{\gamma_i} \left(\frac{\text{Dose}}{n} \right)_i \left[1 - \exp(-\gamma_i f_{on} T) \right] \left\{ \exp(-\gamma_i \delta) - \exp[-\gamma_i (1-f_{on})T] \right\} \frac{1 - \exp(-\gamma_i K T)}{1 - \exp(-\gamma_i T)}$$

where f = fraction of the maintenance time spent within the magnet
 $\bar{s}$ = average plasma on time during the experimental period (s/week)

Fig. 4. Relationship between the anticipated machine operating cycle, the dose rate on the interior of the magnet consistent with that cycle, and the dose that can be accumulated by personnel entering the magnet after a given delay time. In this figure, δ is the delay time, T is the machine cycle time, s is the mean plasma on time, and f_{on} is the fraction of the cycle time during which plasma experiments are being conducted.

$(\text{dose}/n)_i$ = dose from isotope i per source neutron (rem/neutron)

γ_i = activation constant for isotope i (day^{-1})

T = machine cycle time

f_{on} = fraction of cycle time during which experiments are being conducted

δ = the period of time that elapses between the termination of an experimental run and the time that personnel can enter the magnet region.

K = the number of experimental periods that preceded the shutdown period for which the dose is being calculated.

The doses received for $T = 90$ and $T = 120$ from the five dominant activation products¹ are shown in Fig. 5. The dose saturates after approximately 1 year of operation. The dose accumulated by personnel working for 1 year at this saturation level is approximately $0.75 \bar{f}_s$ (rem) for both a 90-day and a 120-day cycle. Because the maximum allowable dose rate is 5 rem/year, plasma on time must be limited so that

$$\bar{f}_s < 6.7.$$

Fig. 5. Normalized dose accumulated by personnel working inside the magnet versus the number of machine cycles, where f is the fraction of the machine on time during which personnel work inside the magnet and s is the mean plasma on time. For the calculations in this figure, delay time (δ) = 7 days and the fraction of the cycle during which plasma experiments are being conducted (f_{on}) = 0.5.

The maximum value of f for a person working a 40-h week is $40/(7 \times 24) = 0.24$, but it is highly unlikely that a person will be required to spend 40 h/week within the magnet structure. Because the only reason for entering the magnet is either to remove something attached to the warm liner or to install something on it, a reasonable estimate for the time spent within the magnet is 4 h/week or $f \approx 0.02$. This value of f implies that the maximum value of $\bar{s}$ is about 300 s/week for either a 120-day or a 90-day cycle. This means that 30-s operation will be limited to about 10 shots/week. This estimate is considered a minimum because the magnet geometry assumed in Ref. 1 is spherical and hence ignores the fact that approximately 50% of the fusion neutrons do not interact with the coil structure. Considering this effect, operation with 30-s pulses is limited to about 20 shots/week. This restriction does not appear too severe for the first stages of 30-s MFTF operation.

To avoid damage, we plan to proceed cautiously with 30-s operation until we have determined the behavior of the facility. Thus, for the first series of shots, the pulse length will be significantly less than 30 s. When it has been determined to be safe, full 30-s operation will be undertaken. Only when 30-s operation becomes routine will induced radiation within the vacuum vessel reach levels that pose a potential personnel hazards problem. Because we calculate that the radiation level outside the vacuum vessel will be several orders of magnitude less than that inside the vessel, we do not expect radiation external to the vacuum vessel to be a problem.

Maintenance of internal structures can be divided into two categories: those requiring extensive work within the magnet cavity, and those requiring limited entry within the vacuum vessel. Experiments in which we investigate vacuum phenomena associated with the wall surrounding the plasma will undoubtedly require modifications within the magnet. However, other issues addressed by 30-s operation are mainly technological problems involving operation of steady-state beam dumps, plasma diagnostics, etc. that will require only limited entry into the magnet to remove the required parts. Hence, the time spent in the higher-radiation areas for facility modifications can be significantly reduced. In addition, facility modifications made between experiments will be scheduled so that those modifications requiring access into the magnet are done last; i.e., δ can be made longer. For example, an operating cycle with $T = 90$ days, $f_{on} = 0.6$, $\delta = 15$ days, and $f = 0.01$ will permit us to operate the facility at about 60 30-s shots per week.

In summary, any increase in the plasma density, ion energy, or plasma volume will increase the radiation problem. However, although the radiation hazard will require changes in the operating cycle, it does not appear to pose any insurmountable problems.

6. Extensions of Diagnostic Data System

Extending the pulse length to 30 s is a step toward steady-state operation and will increase the diagnostic data requirements. However, although memory requirements will increase, they will not scale linearly with increase in pulse length. Also, it will not be necessary to obtain all plasma diagnostic data with high bandwidth throughout the period of operation. Two data-acquisition modes are anticipated:

- (A) A variable bandwidth in which the data are sampled at fixed intervals, but are only recorded when changes are noted.
- (B) A predetermined bandwidth variation in which data are taken at 100 kHz for 10 ms, 50 kHz for 20 ms, 10 kHz for 470 ms, and 100 Hz for 29.5 s.

The expected increase in the number of data words created by going from 0.5-s to 30-s pulse length is tabulated in Tables 5 and 6 for the primary and secondary diagnostics. Primary diagnostics are those considered necessary to tune up a machine for a run; secondary diagnostics are those added to enhance understanding of the nature of a particular experiment. The increases for data-acquisition modes (A) and (B) are included. The first number for mode A is the fixed-interval count from 0.5 to 30 s at a 100-Hz rate (2.95 K/channel), and the second number is the estimate for the increase in the data count. Table 7 is a summary of the supervisory data system for 30-s operation.

These estimates indicate that the primary impact on the data base system is the increase in bulk storage requirements at the various levels of the system. There is, consequently, a concomitant increase in the total amount of intrasystem traffic; however, the required bandwidth of these circuits does not appear to be any greater than that necessary for 0.5-s operation. Throughout the diagnostic subsystem, and more particularly throughout the neutral-beam and machine control subsystems, there will be an increased requirement for real-time data handling.

The effect of 30-s operation on the supervisory and diagnostic software effort is minimal. For the most part, the routines necessary for 0.5-s operation will handle 30-s operation with a few procedural changes. Nevertheless,

Table 5. MFTF primary diagnostic data, showing the increase in data memory for extending the pulse duration from 0.5 s to 30 s.

Name	Source system	Channels	Acquisition mode		Ratio of 30-s data to 0.5-s data	
			A	B	A	B
Neutral analyzer	Diagnostics	16	47.2K/188K	47.2K	1.59/1.59	1.59
2-mm interferometer	Diagnostics	4	11.8K/47.2K	11.8K	1.59/1.59	1.59
Beam Attenuation: radial/axial	Diagnostics	20	59K/236K	59K	1.59/1.59	1.59
Neutrons	Diagnostics	2	5.9K/23.6K	5.9K	1.59/1.59	1.59
Thomson scattering	Diagnostics	24	~1440	~1440	3.88	3.88
Diagnostic loop	Diagnostics	1	2.95K/11.8K	2.95K	1.59/1.59	1.59
Startup neutral beam (I/E)	N/A+					
Sustaining neutral beam (I/E)	Neutral beams	48		283K		2.18
Target streams	N/A+					
Stabilizing streams	Machine control	14-50	41.3K-147.5K 165K-590K	41.3K to 147.5K	6.9/6.9	6.9
Laser forward scattering	Diagnostics	8	23.6K/94.4K	23.6K	1.59/1.59	1.59
Vacuum	Machine control	3	90	90	30	30
Neutral-beam status	Neutral beam	2	No change+			
Facility status	Machine control	1	6K	6K	30	30
Totals:			482K-588.4K 766K-1191K	482K- 588.4K	2.6-2.8/ 11.6-19	1.57

Table 6. MFTF secondary diagnostic data, showing the increase in data memory for extending the pulse duration from 0.5 s to 30 s.

Name	Channels	Acquisition mode		Ratio of 30-s data to 0.5-s data	
		A	B	A	B
rf probes (amplitudes)	8	23.6K/94.4K	23.6K	1.59/1.59K	1.59
rf probes (HF records)	8	32K-64K	32K-64K	2.0	2.0
B-field probes	10-20	29.5K-59K/ 118K-236K	29.5K-59K	1.59/1.59	1.59
End-loss analyzer	15	44.3K/177K	44.3K	1.59/1.59	1.59
End-loss probes	10	29.5K/118K	29.5K	1.59/1.59	1.59
Line density (HCN laser)	6	17.7K/70.8K	17.7K	1.59/1.59	1.59
Faraday rotation (HCN laser)	2	5.9K/23.6K	5.9K	1.59/1.59	1.59
Soft x-rays	4	11.8K/47.2K	11.8K	1.59/1.59	1.59
Axial & ends interferometers	4	11.8K/47.2K	11.8K	1.59/1.59	1.59
Local magnetic field	4	11.8K/47.2K	11.8K	1.59/1.59	1.59
Neutron camera	10	29.5K/11.8K	29.5K	1.59/1.59	1.59
Fusion product	4	11.8K/47.2K	11.8K	1.59/1.59	1.59
Totals:		259.2K-320K/ 908K-1026K	259K to 320K	1.62-1.71/ 1.54	1.40 to 1.42

Table 7. MFTF data base summary: supervisory data for 30-s operation.

A. Overall:

No. of files = No change from 0.5 s
 No. of subfiles = Same
 No. of data records = Same
 No. of data words = $26 \times 384 + 2.3M - 4.74M/\text{file}$
 Ratio of 30-s to 0.5-s data base = 1.53 - 1.69

B. Subsystem breakdown:

System	Subfiles	Data words	Ratio of 30-s to 0.5-s data
Diagnostics	19	1.08M/4.2M	1.61/1.64
Neutral beam	3	317K/417K	9.3/3.11
Machine control	4	51.3K/184K, 205K-710K	5.73-6.03/5.13-5.92

C. Traffic scheduling: (Urgent, Priority, Routine)

Source system	Records			Data words			Ratio of 30-s to 0.5-s data		
	U	P	R	U	P	R	U	P	R
Diagnostics		75	206		407K	4.2M		1.60	1.64
Neutral beam	2	48	48	500	316K	134K	N/C	9.40	1.00
Mach. control	4	44-100		203	51K-178K	211K-716K	N/C	5.1-5.9	5.28-5.97

D. Machine control diagnostics

System	Subfiles	Data words	Ratio of 30-s to 0.5-s data
Diagnostics	3	55.7K-76.7K	1.59-1.37
Neutral beam	3	317K-619K	9.3-1.84
Machine control	4	77.5K-454K	2.57-1.51

some attention should be paid to these changes in procedure since there will be a greater interleaving of acquisition, archiving, and processing. Data analysis, as differentiated from processing or conversion, probably does not change. There will be more emphasis on real-time data handling; but this is more a re-alignment of effort than a large increase.

It appears that a 0.5-s system can be designed initially that can be extended to 30-s operation at a later date. Moreover, if allowances are made for this operation from the beginning, the hardware and software costs should be moderate.

7. Summary and Conclusion

Excluding the neutral-beam modules themselves, the most expensive items required for multisecond operation are the beam dumps required to handle the increased power loads. The maximum practical pulse lengths with inertially cooled dumps will be about 1.6 s. Steady-state dumps are required for longer pulse lengths. The cost of such dumps, including the necessary high-purity water system, is about \$10 million. Additional costs may be accrued because of necessary instrumentation; the beam dumps must be instrumented to prevent an up-to-water accident. Possible instrumentation techniques have been considered, but no detailed design exists.

Thermal radiation from the beam dumps to the cryogenic surfaces does not appear to present any major difficulty in multisecond operation. The energy can be absorbed by boil-off of liquid nitrogen. Additional radiation shields may be required to prevent boil off of gas from the LN chevrons.

Finally, on the basis of the point design operating conditions, it appears that

- Neutron activation and heating will not add any significant cost to multisecond operation of the MFTF, and
- Neutron activation will limit routine multisecond operation.

Further study is required to determine the magnitude of these effects under other conditions.

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