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Report of the TMX-Upgrade Review Panel

May 1980

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Published November 1980

U.S. Department of Energy
Office of Fusion Energy
Division of Mirror Confinement Systems

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Prepared by the TMX-Upgrade Review Panel,
Edited by Robert Price, Chairman

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PREFACE

Within the last year, the thermal barrier tandem mirror (TBTM) concept has emerged as the primary area of research for the mirror program. Various deliberative committees, such as the Thermal Barrier Workshop (October 1979), the Mirror Senior Review Panel (MSRP) (January 1980), and the Fusion Power Coordinating Committee (FPCC) (February 1980), have identified the urgency to do physics and technology tests of the thermal barrier concept.

In response to this need, the Lawrence Livermore National Laboratory (LLNL) has approached the problem with vigor, carrying out extensive studies, and has submitted a plan to develop understanding of the TBTM concept as quickly as possible within the projected available funds. The general features of this plan were reviewed by the MSRP and the FPCC. A key element in the plan is to modify TMX in such a way that it will provide a definitive test of the thermal barrier and give data which can be used to increase the effectiveness of MFTF-B.

In May 1980, LLNL submitted a proposal to upgrade TMX. The new device is called TMX-Upgrade (TMX-U). A review panel was convened by the Division of Mirror Confinement Systems on May 22-23, 1980, to review the proposal and to make recommendations to the Office of Fusion Energy with respect to the proposal.

The TMX-U Review Panel met at Germantown, Maryland, on May 22-23, 1980. The Panel members were: Robert Price, Chairman, Stan Staten, and Warren Marton of OFE/Department of Energy; John Muhlestein, San Francisco Operations Office; Warren Quinn, Los Alamos Scientific Laboratory; Norm Lazar, TRW, Inc.; and Richard Post, University of Wisconsin. On May 22, the LLNL staff presented the details of the TMX-U proposal to the Panel. The Panel met in executive session on the evening of May 22, met again with the LLNL representatives on May 23 for further discussions and questions, and then returned to executive session where the findings and recommendations were discussed and this report drafted.

The TMX-U Review Panel has produced a thorough report, and I would like to take this opportunity to thank them for a job well done.

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THE TMX-UPGRADE (TMX-U) REVIEW PANEL

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I. INTRODUCTION

The Tandem Mirror Experiment Upgrade (TMX-U) Review Panel met at DOE Headquarters in Germantown, Maryland, on May 22 and 23, 1980. The principal objectives were to review and make recommendations to DOE with respect to the specific TMX-U project proposal. The letter addressing the charges and issues to the Panel is attached as Appendix A.

A. Charge to the Panel:

- Compare TMX-U as proposed by LLNL with the recommendations on TMX-U by the Mirror Senior Review Panel to determine if LLNL has responded to the Panel's recommendations.
- Determine if the machine, as proposed, will be a definitive TBTM test, and if the results will be applicable to MFTF-B.
- Decide if the engineering plans are compatible with the physics goals.
- Comment on the cost and fabrication time as to whether they are as small as possible considering the physics goals.

In addition, address the following questions:

1. Is the existing hardware being effectively used?
2. Are the diagnostics adequate?
3. Is the initial startup procedure reasonable?

B. Findings:

1. The TMX-U proposed design will provide for a TBTM test with results applicable to MFTF-B.
2. The changes in TMX-U over the version presented to the Mirror Senior Review Panel (MSRP) are reasonable and still within the recommendations made by the MSRP.
3. The engineering plans are compatible with the physics goals, and the two have been well coupled.
4. The existing TMX hardware is being effectively used.
5. The Panel believes that because of the several complex technologies that are being attempted for the first time in a tandem configuration (i.e. ion sloshing, ion pumping and ECRH), a significant amount of "debug" time may be anticipated on TMX-U before physics issues can be addressed.

6. The Panel believes that learning to apply ECRH effectively in a tandem mirror environment could be a lengthy process.
7. LLNL suggested several barrier start-up scenarios but a working computer simulation is not yet available to provide quantitative guidance. An optimum scenario will require a close interaction between simulation and experiment.
8. The initial diagnostics are adequate but significant improvements will be required as detailed measurements become necessary for improved understanding of the plasma behavior.
9. Additional theory support is needed.
10. The cost is reasonable, but the schedule is success oriented. Some delays could occur.
11. Neutral beam reliability is of concern for operating TMX-U. LLNL has a program in place for making the TMX neutral beams more reliable than they are now.
12. Radial transport could be a limiting factor on obtaining high Q's in TMR's. It is important for TMX-U to provide information on radial transport.
13. The TMX-U design was well done and LLNL is to be congratulated.
14. The magnets and vacuum tanks are the critical path items and should be started as soon as possible.

C. Recommendations:

- In agreement with the Mirror Senior Review Panel (MSRP), the TMX-U Review Panel recommends that TMX-U receive high priority in the fusion program. TMX-U will provide the first complete thermal barrier test, and important data in support of the MFTF-B project.
- The Panel recommends that DOE authorize the TMX-U project and that LLNL proceed to fabricate TMX-U as quickly as possible.
- The TMX-U program should focus first on the important physics issues--microstability, thermal barrier operation, and radial transport.
- The Panel recommends that serious consideration be given to an early test of the ECRH system into a plasma.
- In agreement with the MSRP, the TMX-U Review Panel recommends that theoretical studies of the TBTM should be increased to support the MSRP recommended larger role of mirrors in the fusion program.

- The Panel recommends an adequate FY 1983 operational budget to accommodate an expanded diagnostics set on TMX-U.
- The Panel generally agrees with the cost and schedule estimates for TMX-U as proposed by LLNL and reviewed in more detail by the DOE/SAN Office. The Panel agrees with the 20% contingency as recommended by LLNL.
- The Panel recommends that LLNL establish specific coordination channels between key TMX-U and MFTF-B personnel to ensure that a continuing exchange of information and decisions occurs between these two projects.

D. Report:

The remainder of this report is organized as follows. Section II discusses the history and background of the TBTM and relates to recent reviews of the concept. Also discussed are the MSRP's findings and recommendations. Section III contains a discussion of the findings and recommendations of this Panel. Section IV contains the summary.

II. THERMAL BARRIER TANDEM MIRROR BACKGROUND

In 1975-76, the 2XIIB mirror experiment at LLNL was very successful in that startup was achieved with a steady magnetic field, the ions in 2XIIB were heated to record temperatures (> 13 keV) for the magnetic fusion program, 2XIIB was MHD stable and showed improved confinement over smaller devices. Even though 2XIIB was successful in meeting its objectives, there was still a serious concern that the mirror program should be slowed or stopped because reactor projections were negative and a Q of about 1 was being projected for the mirror reactor. This led to four serious reviews--the 1976 Mirror Senior Review Panel, an FPCC Review, the MFTF Open System Technical Review Panel, and a Q Enhancement Workshop. It was the recommendation of these reviews that the mirror program should pursue with high priority a number of concepts to increase the mirror reactor Q. One of these concepts recommended by the Q Enhancement Workshop was tandem mirrors. The tandem mirror was independently invented in the U.S. (Dr. T. K. Fowler and Dr. B. Logan) and in the USSR (Dr. Dimov) in 1976, and gave promise of achieving a Q of 5 or more in a tandem mirror reactor (TMR). As a result of the four reviews, on March 25, 1977, LLNL proposed and DOE authorized a Tandem Mirror Experiment (TMX) at Lawrence Livermore Laboratory (LLNL). The TMX was planned as a cornerstone of the mirror program which would answer the basic physics issues of a TM configuration.

TMX was successfully operated as a tandem mirror in late 1979, and the results can be summarized as follows:

- The confinement of central-cell plasma is improved by the end plugs (up to 9-fold increase in $n\tau$ due to the electrostatic potential).
- Finite-beta central-cell plasmas have been produced and sustained by neutral beam injection (up to 10% without central-cell beam heating and up to 50% very locally with central-cell beam heating).
- Electron temperatures achieved in the TMX are higher than those observed in the 2XIIB (T_e up to 260 eV).

At the same time that TMX was starting operation, a further improvement of the tandem mirror concept was invented at Livermore by Baldwin and Logan. The new concept was a thermal barrier, making it possible to heat electrons in the end plugs of a tandem mirror without heating the electrons in the center cell. The new configuration is called a Thermal Barrier Tandem Mirror (TBTM). TBTM results in potentially large improvements in TMR Q's, up to 20 or greater, possibly resulting in ignition in the center cell. TBTM also reduces the technology requirements of tandem mirrors.

Because of favorable TMX results, the invention of the TBTM, and the implications for MFTF, a comprehensive review of the mirror program was carried out. The review consisted of a SAN cost review of the MFTF-B proposal, the 1980 Mirror Senior Review Panel (MSRP), and a follow-on FPCC review. The MSRP made the following findings relative to TMX-U:

- The Panel (MSRP) commends the LLNL team for rapidly achieving successful operation of TMX, attaining the expected physics results, and developing the thermal barrier concept.
- TMX experimental results, in substantial agreement with expected performance, provide strong evidence for electrostatic reduction of end losses from a tandem mirror configuration without thermal barriers.
- The testing of thermal barrier physics in an integrated tandem mirror system (TMX-U) is a key experiment for verifying the total TBTM concept.
- Additional diagnostic capabilities are needed for the TMX and TMX-U experiments, and MFTF-B. In particular, the level of diagnostics required for the barrier regions will be similar to that for the plugs. Data acquisition and analysis capability may require strengthening.

In addition, the MSRP made the following recommendations toward TMX-U:

- The TMX-Upgrade experiment should be given a very high priority within the fusion program so that experimental verification of thermal barrier performance can be obtained at an early date.

- Additional diagnostic capabilities are recommended for TMX and TMX-U. Beyond techniques now in use on TMX, these capabilities should include time, space and ionization-state resolved spectroscopy, radiometry and x-ray diagnostics for determining the hot-electron distribution, microwave scattering $S(k, \omega)$ measurements, and surface-physics measurements for TMX. The inclusion of thermal barriers in TMX-U will increase the diagnostic requirements. Recognizing the urgency to establish a definitive thermal-barrier tandem-mirror experimental data base, the Panel urges that the funding for TMX-U be adequate to (1) enlarge the experimental staff, (2) increase the number of stations for present diagnostics and to introduce new diagnostic techniques, and (3) provide data acquisition and analysis capability commensurate with the increased complexity and sophistication of the required measurements.
- The Panel, recognizing strong benefits to be derived both for near-term TMX and TMX-U operations and for the longer-term MFTF-B applications, recommends that LLNL evaluate the immediate integration of MFTF data-acquisition capability with the TMX diagnostic effort.
- The Panel recommends not freezing the detailed MFTF-B design, particularly the thermal barrier cell, prematurely, in order to take maximum advantage of theoretical refinements, testing of MFTF components and systems, and preparations for TMX-U experiments.

At the time of the MSRP (January 1980), the TMX-U proposal was still in preparation; however, the goals of TMX-U spelled out in the MSRP report include: setting up thermal barriers using ion pumping and ECRH; investigating the microstability of the plug and outer cell; studying the MHD stability of the barrier-tandem configuration; investigating electron heating of the outer A-cell; investigating the establishment of an electron temperature difference across the thermal barrier region; and investigating the establishment of sloshing trapped ions in the barrier region.

Conversion of MFTF to MFTF-B was approved by the DOE in April 1980. The budget scenario approved calls for completion of construction for MFTF-B in September 1985. This completion date means that early TMX-U results, which would be the first complete test of a thermal barrier, could be used to improve the operation of MFTF-B. LLNL submitted the TMX-U proposal to DOE in early May 1980.

III. DISCUSSION OF TMX-U REVIEW PANEL FINDINGS AND RECOMMENDATIONS

A. The TMX-U Proposal Addresses MSRP Recommendations:

Comparison of the proposed TMX-Upgrade (TMX-U) by LLNL with the recommendations on TMX-U by the MSRP shows that LLNL has responded to the Panel's recommendations. The present TMX-U design includes the following items that were specifically called out by the MSRP:

- thermal barrier end plugs
- ECRH heating of electrons in end plugs
- sloshing ion populations in end plugs
- barrier ion pumping in end plugs
- existing TMX neutral beams
- development of plasma diagnostics to determine physics of the TBTM configuration
- provision for careful alignment of magnets to minimize magnetic field errors.

The projected plasma parameters for TMX-U are essentially those listed by the MSRP. (See Table I.)

The goals of the TMX-U include those recommended by the MSRP:

- the setting up of thermal barriers using ECRH, ion pumping, and sloshing-ion populations
- investigation of microstability in the end plugs
- determination of the MHD stability of the barrier-tandem configuration, of the temperature difference across the thermal barrier region, and of the sloshing trapped ions in the barrier region
- study of radial transport in the central solenoid confinement region.

Differences between the present proposed TMX-U and the MSRP's recommendations are: (1) Because of the smaller physical size and low magnetic fields of TMX-U relative to MFTF-B, the A-cell end plug design of MFTF-B has been changed in TMX-U to a single mirror cell. This is provided by an elongated baseball-coil design with additional symmetrical coils, to enhance the mirror ratio, and two transition coils. This design satisfies the thermal barrier end plug physics requirements and appears simpler than the MFTF-B end plug design; and (2) As to the question of beta limits in a tandem mirror, the TMX-U may not have sufficient beam power in its initial phase of operation to test beta limits. However, provisions in the TMX-U design will allow additional neutral beams that are available from the Beta-II facility if needed.

The Panel recommends that the critical physics issues of microstability, thermal barriers and radial transport be pursued with highest priority in TMX-U. The Panel agrees that beta can be addressed on a longer time scale compared with the need for evaluating the above physics issues for MFTF-B.

B. TMX-U is a Definitive TBTM Test and will Provide Results Relevant to MFTF-B:

The TMX-U device proposed by LLNL contains all of the requisite elements of a thermal barrier tandem mirror. The recommended magnetic configuration combined with neutral beam injectors for ion sloshing and pumping and with gyrotrons for electron heating will provide a basic capability for performing definitive tests of the thermal barrier. An acceptable degree of flexibility to adjust magnet currents, angles and position of neutral beams and ECRH injection has been provided in order to adjust key parameters associated with establishing the barrier itself. All of the elements of the thermal barrier have been combined into each of the end cells. While this represents a departure from the present conceptual design of MFTF-B in which the barriers are located in the outboard plasma fan of each Yin-yang magnet set, LLNL presented results of their tradeoff analyses which justify their recommended TMX-U configuration. The critical parameter in creating an outboard barrier is the plasma fan thickness divided by the ion Larmor radius. If TMX-U were built like MFTF-B, the fans would be only two ion Larmor radii thick. For a device of the general size and magnetic field of TMX-U and with the necessity to maintain a collisionless plasma like that of MFTF-B, LLNL selected the proposed configuration which should be capable of testing the critical issues of microstability, radial transport and basic barrier operation in an axial and radial plasma geometry representative of that for MFTF-B. Accordingly, the Panel concluded that the results from TMX-U will be applicable to MFTF-B and should provide essential information related to establishment of the MFTF-B thermal barriers, i.e. angles and positions of neutral beams and ECRH to be used during final assembly of MFTF-B. While the goals of MFTF-B clearly extend beyond those of TMX-U and relate, in part, to the development of tandem mirror reactors, it will be important for the MFTF-B project to develop a final design which continues to maintain a sufficient degree of commonality with the TMX-U design so that TMX-U experimental data will be relevant to MFTF-B.

It is essential that LLNL establish specific coordination channels between key TMX-U and MFTF-B personnel to assure that a continuing exchange of information and decisions occurs between these two projects.

C. The Engineering Plans are Compatible with Physics Goals:

The physics goals of TMX-U are to investigate the following:

- Microstability of the plug plasma.
- Heating of plug electrons.
- Establishment of a thermal barrier.
- Radial transport.
- MHD stability of the TBTM configuration.

LLNL has carefully developed an engineering design with these physics goals setting many of the design criteria. The design of the magnets was determined by the radial thickness of the fans. The magnet size and shape was set by the availability of neutral beams to create sloshing ions, compatibility with the available 28 GHz gyrotrons, adiabaticity of injected ions, ion drift surface closure and the capability to have access to inject neutral beams. The decision to increase the operating pulse length of the machine was based on the startup time and expected confinement time. The pulse length time of 75 msec is approximately two startup times and two expected confinement times, and allows for some uncertainty in the two times. The upper limit on machine pulse length is set by neutral beam and gyrotron power supplies and the limitation of the vacuum pumps to maintain the vacuum during a plasma experimental shot. The central cell size and magnetic field were chosen to confine neutral beam injected ions and to match with the end cells. The total length of TMX-U was chosen to test the physics but limited by the building. Any additional increased length beyond the limitations of the building would be very costly.

In general, the Panel feels that the engineering goals set by LLNL will provide a timely test of the physics goals. One area of concern expressed by the Panel was that the normally available neutral beam current would not be enough to drive a TB TMX-U. However, LLNL has a program in place to increase the available current by increasing the reliability of the neutral beams by: (1) using lower voltage, and (2) identifying and fixing particularly troublesome areas in electrical distribution systems and power supplies. In addition, the neutral beams from Beta II are available as is the ICRF system being used on TMX.

D. The Existing Hardware is being Used Effectively:

The TMX-U as proposed uses many parts from the existing TMX. The end cell vacuum tanks will be modified and used; the neutral beams, upgraded to longer pulse length, will be used; the control and diagnostic systems will be upgraded and re-used; and the various substations and magnet power supplies will be re-used.

LLNL expended a considerable effort to find a way to utilize the existing TMX baseball coils. Only after this effort proved unsuccessful did they design an entirely new end cell magnet set. The six central cell coils of TMX are re-used solenoid coils fabricated for 2XII. The TMX-U central cell, being larger than that of TMX, will use these six coils as well as four more that are presently on the neutral beam test stand.

The central control system will utilize the existing computer control system from TMX, expanded and upgraded somewhat to accommodate the added data acquisition channels required for TMX-U.

The neutral beam systems will use an improved modulator tube and more energy storage for the longer pulse length, but will otherwise be much the same as presently in use on TMX. There is an activity in place on TMX to determine and improve those areas where failures are most frequent and will have the largest impact on neutral beam availability.

The central cell vacuum tank of TMX-U will be larger in diameter and longer than that of TMX because of the increased length of the experiment and the increased vacuum pumping required by the longer pulse length. This step necessitated the fabrication of new vacuum vessel sections to mate with the existing end cell tanks that will be re-used.

E. Initiation of the Experimental Program on TMX-U:

TMX-U contains new technical and physics challenges over TMX. On the technical side, there are new ECRH systems which have to be added. The neutral beam pulse length will have to be increased, and neutral beam reliability needs to be further improved to provide, during operation, the large beam current requirement of TMX-U. These technical issues are being aggressively addressed by LLNL. However, it is clear that due to this increased technical program, a significant amount of checkout and startup time will be required to bring up TMX-U to the level where physics issues can be addressed. The Panel believes that a checkout and startup time on the order of nine (9) months could be expected after completion of construction, corresponding to initial physics experiments in the spring of 1981.

The physics objectives are also more complex than in TMX. New diagnostics will be incorporated for analysis of the barrier, warm electrons, and sloshing ions. The time required to verify the sloshing ion concept, barrier pumping with associated plug microstability, hot electron barrier suppression of passing electrons and the production of a warm electron population will be substantially greater than the time required for the initial confirmation of the basic tandem mirror concept in TMX. Only under favorable circumstances could this be accomplished in a one-year period after startup, and it is reasonable to expect more effort to be required.

We can expect a good physics base from TMX-U to begin to emerge in the summer of 1982 and to continue to develop for some time thereafter. Although this data base will not be available in time to influence major hardware designs for MFTF-B, it may lead to minor hardware changes and will have a significant impact on operation and analysis.

F. ECRH Plasma Experiments:

Both the Panel and LLNL recognized that limited experience among the LLNL staff in the application of ECRH (electron cyclotron heating) in energetic plasmas must be rapidly overcome in order to implement the thermal barrier

concept expeditiously in TMX-U. Although intensive engineering tests of the microwave components (gyrotrons, power supplies, microwave distribution system hardware) are planned by the LLNL staff, both LLNL and the Panel understand these tests would not satisfy the need for predictable heating behavior in TMX-U. Both the Panel and LLNL, therefore, recognize the desirability of early implementation of ECRH in a plasma experiment and heating rate measurements. The Panel agrees with LLNL that the Laboratory staff is best able to determine if a suitable facility in which to carry out preliminary ECRH studies can be found at LLNL. The Panel finding is influenced by the recognition that these ECRH heating studies could, in fact, be programmed to take place during the startup time in TMX-U facility itself. The Panel, nevertheless, recommends that LLNL seriously evaluate the possibility of carrying out ECRH plasma experiments in one of their existing facilities during the fabrication and assembly period in order to develop expertise and experience in this technology at the earliest time.

G. Diagnostics:

The Panel finds the project diagnostics included in the LLNL proposal combined with the basic diagnostics which will be available during the first year of operation of TMX-U, will be adequate to:

- determine the microstability of the end plugs;
- confirm the anticipated qualitative improvement in plasma confinement;
- permit an evaluation of the plasma evolution in the end plugs during the plasma startup period. These observations are required for the development of a startup scenario which would assure that the plasma evolves into the desired overall equilibrium.

The thermal barrier/electrostatic end plug conceptual design described in the LLNL proposal requires a detailed matching along the axis of energy and velocity space distributions of both ions and electrons, including those magnetically trapped as well as those streaming through the end cell. The burden on the TMX-U experimental team will be to obtain sufficient information from the diagnostic system to permit an evaluation of the degree that the plasma distributions are consistent with theoretical models. The Panel finds that with the proposed basic diagnostics, the TMX-U team could determine the end plug ion and electron energy and the ion velocity space distributions. However, the Panel finds upgrading of these diagnostics will be necessary if detailed radial or axial profiles of these distribution functions are required to understand the behavior of the thermal barrier. The Panel also recognizes that space and time resolved plasma potential measurements may become necessary if the plasma behavior does not conform in detail to expectations. Potential measurements can probably best be carried out with heavy ion beam probes, systems that will require significant development.

The Panel was led to recognize the importance of radial transport in the plasma equilibrium anticipated for TMX-U. The average lifetimes calculated from axial and radial transport of particles in the central cell reported in the LLNL proposal are 50 and 25 msec respectively. During the technical presentations, it was pointed out that the radial transport estimates were highly dependent on the model for the equilibrium radial density profile. The radial profile will adjust itself self-consistently to conform to the required axial loss rates, presumably by forming radial electric fields which, in turn, would modify the calculated distributions. The overall self-consistent equilibrium, including the effects of electric fields on the drift orbits, has not yet been calculated by LLNL, although they have computer codes which are presently being used to attempt to model various aspects of this complex equilibrium. A concern exists, which is recognized by LLNL, the MSRP and this Review Panel, that radial energy transport could require additional controls over the thermal barrier (e.g., by requiring a radial heating rate profile to compensate the higher thermal losses along certain field lines). The self-consistent radial electric fields would also influence the ion and electron drift orbits in the plugs possibly influencing the mapping of the barrier cross-section into orbits in the central cell. The Panel found that the basic diagnostics would have to be augmented if detailed radial profile data becomes necessary to understand the plasma confinement.

During the second year of TMX-U operation, it is not apparent to the Panel that sufficient funds are available to provide for the possible requirements of upgraded diagnostics. The Panel therefore recommends that DOE make available additional funds in FY 1983 to take account of these possible additional diagnostic needs.

H. Startup:

Startup of TMX-U is expected to be more complicated than TMX due primarily to the barrier pumping and generation of hot electron population. If the central cell plasma is too collisional, the barrier will fill up fast so that it cannot be pumped with available pump beam current. LLNL has begun to examine various startup possibilities as well as the development of a startup code which will permit a more quantitative evaluation of startup requirements. With the additional capabilities of central cell ion heating by ICRF and low energy neutral beams coupled with microstable end plugs, satisfactory startup should be possible even though a detailed time dependent scenario is not yet available. Further work is needed and is already well under way. Optimum startup scenarios will undoubtedly not be found without considerable experimentation.

I. Additional Theory Support Needed:

The TMX-U Review Panel would like to emphasize the recommendation made by the MSRP as to a strengthening of theoretical thermal barrier studies. With a large program like MFTF-B also dependent on thermal barriers, there must be theoretical models available which will permit understanding of the TMX-U data. Additional theory funding will aid in having the appropriate numerical models available in time to coincide with TMX-U results and to be applied to last minute changes in MFTF-B, i.e. neutral beam injection angles, ECRH injection, etc.

J. The Cost and Schedule are Reasonable:

The Panel concludes that the cost estimate to construct TMX-U is generally acceptable as a total amount, and is based upon accepted estimating practices.

The Work Breakdown Structure as presented is excellent and forms a sound basis for estimating costs and establishing schedule baselines.

The 10% escalation rate on total costs with FY 1980 as the base year appears reasonable when consideration is given to the 18-month schedule.

Based upon experience LLNL has gained from the original TMX construction, the Panel believes that the 20% contingency estimate for the project appears reasonable. In agreeing with 20% contingency, the Panel recognizes that current FY 1981/82 budget limitations for TMX-U have placed constraints on funding profiles.

The schedule for completion of the TMX-U is success oriented. Procurement cycles and assembly schedules are optimistic and will require close project management.

The DOE/SAN Office reviewed the detailed schedule and cost estimates at LLNL on May 12 and 13, 1980. Subsequent to the SAN review, additional cost information from LLNL was received at the meeting held at Germantown HQ on May 22 and 23, 1980, which clarified the SAN analysis and led to the Panel's recommendations as here presented.

IV. SUMMARY

The Review Panel was favorably impressed with the LLNL presentation, and commends LLNL for a job well done. Several issues were discussed at the review, but the Panel feels that there are no issues so insurmountable that TMX-U would not succeed in testing a thermal barrier. LLNL was already aware of the issues, and where funds permitted, incorporated features into the TMX-U program to make sure that TMX-U will succeed. In light of this very positive review, the driving need for a test of a thermal barrier in the mirror program, and the recommendation of the MSRP, this Review Panel strongly recommends to DOE that TMX-U be approved and fabrication begin as soon as possible.

Signature Page
TMX-U Review Panel

Dr. Robert E. Price, Chairman
DOE Headquarters
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TABLE I

TMX-U Parameters

<u>Center Cell</u>	<u>Presented to MSRP</u>	<u>Proposal</u>
$n(\text{cm}^{-3})$	4×10^{13}	2×10^{13}
$T_e(\text{kw})$	1.0	0.6
$T_i(\text{keV})$	1.0	0.9
$n\tau(\text{cm}^{-3}\text{sec})$	$2 \times 10^{11}-10^{12}$	$5 \times 10^{11}-10^{12}$
β	0.36	0.25
$\phi(\text{kV})$	4	2.2
$L(\text{m})$	5.5	8.0
<u>Plugs</u>		
$n(\text{cm}^{-3})$		7×10^{12}
$T_e(\text{kw})$		1 & 4
β	0.7	0.33
$\phi(\text{kV})$	4	4.8
<u>Barrier</u>		
n	1×10^{13}	5×10^{12}
β	0.1	
ϕ	6.0	0.8

TABLE II

Comparison of Center Cell Confinement of Various Tandem Mirror Devices

	<u>TMX</u>	<u>TMX-U</u>	<u>MFTF-B</u>
$n(\text{cm}^{-3})$	1×10^{13}	2×10^{13}	2×10^{13}
$T_i (\text{kw})$	0.1	0.9	15
$r_{\text{plasma}} (\text{m})$	0.2	0.2	0.7
$L (\text{m})$	5.5	8.0	3.0
$B_c (\text{T})$	0.1	0.3	30
$n\tau (\text{cm}^{-3} \text{sec})$	10^{11}	$2 \times 10^{11} - 10^{12}$	5×10^{13}
β	0.15	0.36	0.2

Department of Energy
Washington, D.C. 20545

May 8, 1980

To The TMX-Upgrade Review Panel

Dear Colleagues,

I would like to thank you for serving on the TMX-Upgrade (TMX-U) Review Panel, which I will chair. The review will be held on May 22 and 23, 1980, in Room G-207 at DOE, Germantown. A copy of the Major Device Fabrication (MDF) proposal will be mailed to you from LLNL on or before May 12.

TMX-U is a very important experiment for the mirror program. It will be the first complete test of a thermal barrier tandem mirror (TBTM). Earlier this year an assessment of the U.S. mirror program was conducted by the Mirror Senior Review Panel, and the report of that Panel is enclosed so that you can read the findings and recommendations of that panel with respect to TMX-U. The Mirror Senior Review Panel stated that TMX-U is a key experiment for verifying the total TBTM concept and should be given a very high priority within the fusion program so that experimental verification of thermal barrier performance can be obtained at an early date. I would like to point out that the Mirror Senior Review Panel endorsed the idea of TMX-U as a TBTM, but did not have a specific proposal to review. Our review panel should proceed from the point of view that approval already exists for doing a TBTM upgrade to TMX, but that a hard look needs to be given to the particular route proposed, including costs, schedule, physics goals, diagnostics, relevance for MFTF-B, etc.

Since the Mirror Senior Review Panel assessment was made, the Department of Energy has approved plans to convert MFTF into a thermal barrier tandem mirror (MFTF-B), which will be completed in the FY 1984-1985 time frame. This means that there will now be time for TMX-U results to be used to improve the operation of MFTF-B. That is, when TMX-U operates (FY 1982), there will still be time to make minor changes in MFTF-B. Because of this, it is even more critical that the review of TMX-U be thoroughly done, and I know that this committee will do a thorough job. DOE wants to be satisfied that TMX-U will test the thermal barrier concept, and that its costs are as small as possible for the job being done and the fabrication schedule is as tight as possible.

Therefore, the tasks that we must address in the review are:

- Compare TMX-U as proposed by LLNL with the recommendations on TMX-U by the Mirror Senior Review Panel to determine if LLNL has responded to the Panel's recommendations.

- Determine if the machine, as proposed, will be a definitive TBDM test, and if the results will be applicable to MFTF-B.
- Decide if the engineering plans are compatible with the physics goals.
- Comment on the cost and fabrication time as to whether they are as small as possible considering the physics goals.

In addition, we will need to review and comment on the following questions:

- (1) Is the existing hardware being effectively used?
- (2) Are the diagnostics adequate?
- (3) Is the initial start-up procedure reasonable?

A tentative schedule is as follows. The committee will caucus on Thursday, May 12, at 8:30AM. From 9:00AM until 3:00PM, LLNL will make its formal presentation with appropriate breaks for coffee and lunch. At 3:00PM the committee will caucus and then ask questions of LLNL until 5:00PM. The following day, Friday, the committee will write its report and recommendations. The key people from LLNL should be available for questions on Friday. If necessary, we can extend into Thursday evening, Friday evening, or even Saturday, although I hope to finish on Friday. If you have any questions, please call me.

Sincerely,

Robert E. Price
Division of Mirror Confinement Systems
Office of Fusion Energy

Enclosure

cc:

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