KRALL ASSOCIATES

DOE/ER/53280--T2

DE92 001777

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

**ANNUAL PERFORMANCE REPORT
FOR
"A PROGRAM OF FRC THEORY RESEARCH"**

Prepared by
Nicholas A. Krall

Prepared for
U.S. Department of Energy
Washington, D.C.

under
Grant No. DE-FG03-88ER53280

May 18, 1990

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

This report, required to be submitted with a renewal application, summarizes the research performed under Grant #DE-FG03-88ER53280 to date. Much of the current year research is still underway, including the calculation of nonlocal LFD stability. In this report, we describe the work which is more nearly complete.

The development of our model for turbulent transport in FRC, based on low frequency drift waves, is contained in the two published papers included as Appendix A and B. Appendix A (Phys. Fluids 30, 878 (1987)) is the stability theory on which the model is based. A crucial feature is that collisions cause the distribution to relax to a local distribution f_0 with strong gradients, rather than to a local Maxwellian f_M . Appendix B (Phys. Fluids B 1, 1811 (1989)) uses this stability theory to obtain loss rates, in agreement with experiment.

A side benefit of the LFD stability work was that it predicted stabilization of lower hybrid drift waves, if the LFD turbulence was sufficiently excited. This result is described in Appendix C (Phys. Fluids B 1, 2213 (1989)).

More recently, we have begun to study inclusion of LFD turbulence into MHD stability studies. Appendix D is an abstract recently submitted to the IAEA, describing this work. Another calculation, nonlocal stability of FRC to LFD waves, is underway; the results are not yet finished. We project that this calculation will be completed by mid-September.

Finally, a truly major effort was a review of the RFP physics data base as it relates to the ZTH experiment. That report, undertaken at the request of the DOE/OFE, is included as Appendix E of this report.

*reprints & preprints
included.
als*

APPENDIX E

**"AN ASSESSMENT OF THE RFP DATA BASE
AND THE ROLE OF THE ZTH EXPERIMENT**

AN ASSESSMENT OF THE RFP DATA BASE

AND THE ROLE OF THE ZTH EXPERIMENT

N. A. Krall (Chairman), Krall Associates
J. H. Harris, Oak Ridge National Laboratory
S. C. Prager, University of Wisconsin
R. D. Stambaugh, General Atomics
H. Weitzner, Courant Institute
M. C. Zarnstorff, Princeton University

March 5, 1990

ABSTRACT

At the request of the Office of Fusion Energy (Appendix A), a group of experts (Appendix B) was convened on February 6-8, 1990. This group met to assess the world data base on Reversed Field Pinch (RFP) physics, and, further, to assess the role of the ZTH experiment in providing reactor relevant physics understanding for that confinement geometry. This group met, analyzed some of the relevant literature (Appendix C), and heard extensive presentations (Appendix D) on the physics of the RFP and the plans for the ZTH and RFX devices. The conclusions of this group of experts are contained in this report.

1. EXECUTIVE SUMMARY

We conclude that in light of the international RFP data base, the state of RFP understanding, and the program plans for other RFP devices, the ZTH is an attractive experiment, with well posed scientific goals, in a highly interesting range of parameters and technology. It is well integrated into the world program. It is expected to operate in a parameter range which overlaps or exceeds other state-of-the-art experiments, but with unique features, specifically operation with a resistive shell and active equilibrium control, which are absolutely essential to the reactor embodiment of this concept, and may result in enhanced performance as well. The data base exists to virtually ensure startup and ramping to the design current. The resistive shell operation and aggressive choice of parameters will guarantee that the results obtained in ZTH and possible upgrades will be directly relevant to RFP-based reactor design.

We believe that with the ZTH and RFX (Padova, Italy) experiments, the RFP program will have matured to the point that it can and should be an important contributor to the rest of the toroidal physics community. To ensure that this happens, Los Alamos should take active steps to integrate their research with that community. To optimize their contributions, as well as to allow ZTH to achieve its scientific goals, we believe it essential that the experimental program be directly integrated with the theoretical and modelling efforts, particularly as to the choice and interpretation of the diagnostic array. In summary, we anticipate that the ZTH experiment will contribute uniquely both to the development of the RFP concept and to toroidal confinement physics in general.

The next Sections of this report document and provide the justification for the comments made in this Summary. The Appendices contain the charge on which this meeting was convened, a list of the experts who participated, a list of the primary literature examined, and the agenda of the February 6-8 meeting at LANL.

2. WHAT IS THE CURRENT UNDERSTANDING OF RFP CONFINEMENT PHYSICS?

An important question addressed at the meeting was the extent to which the properties and physical mechanisms of confinement in the RFP have been identified and are understood. It is clear that a consistent data base from experiments in many countries and laboratories has identified a number of distinct trends in RFP behavior. These trends include the robust and spontaneous formation of the reversed field state, the systematic increase of temperature with total plasma current when other parameters are held fixed, and the fact that all devices operate with a plasma beta of at least 8-10% over a wide range of confinement time and other parameters. It is inferred from these trends that the resistivity is comparable to classical in size and scaling, within a factor of 1-4, when the estimated impurity levels are included in "classical" resistivity. Further, the confinement improves with size and with total plasma current, very roughly as $\tau_E \sim I^{1.5} (1/na^2)^{1.5} a^2$ where n is the density. It is evident that these trends, if they continue (and are documented) as the current increases, would lead to an attractive RFP-based reactor.

These trends are found in experiments which at present vary in key parameters such as current, temperature, density, etc., by factors of less than ten, and with diagnostics which lack profile information required for an adequate description. Nevertheless, these trends are sufficiently well established to justify both an active search for further physics understanding and a program for experimental extrapolation of parameters and technology.

A number of observed phenomena are presently understood in terms of specific physics. These include the appearance of magnetic fluctuations in the core region, where the magnetic fields are apparently stochastic and confinement is poor; these fluctuations correlate with the theoretically expected $m = 1$ current driven MHD instability, although with fluctuation amplitudes somewhat less than expected. In the confinement region, an annulus of relatively well formed magnetic surfaces which surround the core, fluctuations are believed on theoretical grounds to arise from pressure driven instabilities, the so-called resistive-g modes. The transport from these modes is consistent with the observation of a fairly constant range of beta in the good regimes of operation. The observation of kinetic electrons in the confinement region is expected on theoretical grounds due to the stochastic nature of the magnetic fields in the

core and the magnetic flutter observed in the confinement region. Another phenomena, the control of plasma density by the injection of pellets, is understood by the results of detailed experiment and modelling.

The most ubiquitous aspect of the experiment is the dynamo effect which produces field reversal and controls the evolution of the magnetic profiles. It is generally agreed that the loop voltage applied to an RFP acts through the dynamo mechanism to maintain both the poloidal and toroidal magnetic fields against resistive losses. There is solid experimental evidence that the mean state of an RFP remains close to a zero beta Taylor state and prefers a state with particular values of the parameters F and θ . Turbulent processes are considered to be the mechanism for maintenance of the dynamo. By the very nature of the dynamo process, which breaks and reconnects magnetic lines, turbulence must also contribute to plasma heating and transport. Thus, any discussion of plasma confinement in an RFP must simultaneously consider "equilibrium" and energy balance questions. Hence, the problem of confinement in an RFP might be more challenging to analyze than in many other plasma systems, since one must create an integrated explanation for heating, equilibrium, and transport, and this explanation has at its core the notoriously difficult problem of turbulence.

There are many specific questions for which one would ideally like to have full answers. A few of particular significance include the following: much of the present thinking about RFP's is based on the hypothesized rough constancy of beta. One would very much like a convincing theoretical explanation validated by experimental observations based on profile diagnostics. A quantitative and predictive explanation of the dynamo effect, together with the ability to model and predict the mean state of an RFP would be very important for subsequent extrapolation of RFP's. Supported by a substantial world-wide effort, the Los Alamos Group has undertaken many experimental and coupled theoretical studies directed at these and other questions and they have tested their theoretical results against experimental observations. Their theories are able to explain some parts of their experimental observations quite successfully. Not surprisingly, they lack an integrated, coherent, and self-contained picture of RFP dynamics that is able to distinguish among the numerous competing theoretical models. Such a picture should be a long term goal of the

combined experimental and theoretical program. A sampling of various models and some of the consequences and relations to experiments follows.

There have been extensive resistive MHD studies, which range from full, three-dimensional, nonlinear simulations of RFP dynamics to simpler studies of linear stability of particular configurations. The simulations appear to be able to explain sawtooth-like behavior in high θ discharges as well as the continuous oscillatory behavior of low or normal θ RFP's. Resistive MHD instabilities are an outstanding candidate to generate the dynamo action. The observed spectrum of magnetic field fluctuations for low frequency matches the resistive MHD calculations, although the absolute magnitude of the fluctuations is poorly given.

Another, complementary, model for dynamo action relies on a kinetic dynamo. Transport of electrons along stochastic field lines is modelled by a semi-phenomenological kinetic equation. The transport is dependent on the mechanism of MHD turbulence to generate stochasticity. The model predicts reasonable current profiles and the distinctive experimentally observed, hot electron distribution function at the plasma edge. The close coupling between the resistive MHD model and the kinetic dynamo has not yet been explored.

With the plasma core being strongly turbulent, the confinement properties of the RFP are hypothesized to come from an outer region with good flux surfaces where resistive g modes dominate the transport processes. The predicted spectrum of resistive g modes appears to match the experimentally observed spectrum of magnetic fluctuations for moderately large mode numbers, assuming a linear relation between mode number and frequency. Estimates of transport from these modes also suggest that they may provide an explanation for the relative constancy of beta observed in the RFP.

Other modes may be present in an RFP and may contribute to the dynamo action and transport, but their significance and relevance is not at all clear. Many types of drift waves, as well as η_i and η_e modes, might also be important.

It should be clear that the entire fusion program stands to benefit substantially from the study of turbulent effects in an RFP, since exactly the same modes and phenomena occur quite generally. Correspondingly, non-RFP groups should be encouraged to participate in research on ZTH and in interpretation of their results.

3. WHAT PHYSICS BASE INSURES ZTH PERFORMANCE RELEVANT TO THE REACTOR REGIME?

Although the scaling trends described in Section 2 are favorable and general theoretical and empirical understanding is substantial, we attempted to identify the specific data base which will ensure that the ZTH will form and obtain its desired design point in a reactor relevant regime. As noted in the previous section, the data base is both worldwide and consistent, yet is limited in both parameter range and in the lack of profile diagnostics. The improvement of this data base should be a major expected contribution of next generation RFP's like ZTH. Despite these limitations, the existing data is sufficiently well based to ensure that the ZTH will start up and ramp to its design current, and that the design point will be the appropriate one to study confinement and control in a genuinely reactor-relevant regime.

The startup is ensured because similar experiments exist in regimes which overlap ZTH startup. Reactor relevance follows both from the thin shell operation and from the fact that the choice of design current and minor radius represent a substantial fraction of the distance between present parameters and those required for a reactor. Further, the significant dimensionless parameters of the device are qualitatively the same as they will have to be for a reactor, lessening the chance that new physics regimes will emerge in reactor prototype designs.

The projected ZTH parameters represent a large step toward the reactor regime. The plasma parameters are separable into two categories: those required for the physics goals to be addressed, and those which are the objects of investigation. Parameters which determine the magnetic configuration are of the first type. Thus, strict requirements are attached to the plasma current I and the time duration of flat top operation T . Achievement of specific values of I and T depends mainly on the plasma resistivity. Parameters which embody the new physics to be investigated include density, temperature, and energy confinement time (which depends upon β_p and resistance only). Although there are arguments to suggest that the high β_p values obtained in all past RFP devices will extend to high current, there is no need to provide a guarantee of this scaling as a requisite for carrying out the experiment. Indeed, a major

purpose of the experiment is to discover the values of these parameters in high current plasmas.

Predicting the I and T to be achieved in ZTH is complicated by the effect of the thin shell. With the exception of limited experiments on OHTE and HBTX-1C, all RFP devices have surrounded the plasma by a conducting shell whose skin time is long compared to the duration of the flat top current pulse. This is called thick shell operation, and though it is not consistent with reactor design (quasi steady state), it is expected to provide stability control. Let us first assess the case in which the thin shell is assumed to have no harmful effects compared to the more usual thick shell operation. For an assumed resistance, the achievement of parameter goals depends only upon the available toroidal volt-seconds and startup loop voltage. Considering the resistivity achieved in numerous RFP's (including the unoptimized initial MST operation of the same size), the committee has very high confidence that ZTH will attain its stated goal of 1.7 MA for 400 ms. With unipolar operation (at ~ 14 Volt-second), the flux swing is more than ample. The startup voltages are also sufficient (and similar to that used in MST). In fact, a target of 1.7 MA is conservative, and perhaps understates the machine capability. For an additional \$1-3 M, the plasma current can be extended to about 3 MA. Thus, for an extremely small increment in funding, the current can be increased substantially.

When the possible effect of the thin shell is included, the time duration becomes an important object of study, rather than a parameter to be predicted. Determining and controlling thin shell behavior is a significant scientific goal of the ZTH. The empirical evidence is mixed. The OHTE experiment reported thin shell operation with little change in confinement parameters; when vertical magnetic fields were used and optimized to actively control the equilibrium, the pulse length actually exceeded that of thick shell operation. In contrast, HBTX-1C reported evidence of resistivity increasing with time, shortening the pulse. Field errors in HBTX-1C were an order of magnitude greater than in OHTE; from ZT-40M data, which showed fluctuations increasing with field error, this might contribute to the poor performance in HBTX-1C. In terms of startup, the only remaining parameter requiring specification with confidence is the current to which the experiment will ramp before flat top operation. All smaller thin

shell experiments (OHTE, HBTX-1C, REPUTE) have succeeded in establishing a plasma with I values equal to those obtained with thick shells, without excessive voltage consumption. In some cases the setting up time has been several shell times. From this empirical evidence, and considering the relatively long shell time of ZTH (50 ms), the committee has high confidence that the goals for ZTH startup and ramping to the design current will be achieved.

4. WHAT IS THE DATA BASE NEEDED TO EXTRAPOLATE TO AN RFP REACTOR?

There are at least three important issues in physics understanding required to confidently extrapolate from present devices to a RFP-based reactor. The first and most obvious is the issue of whether the behavior observed in present devices, i.e., that confinement improves with current and minor radius, and that beta is greater than 8-10% virtually independent of the other discharge parameters, will continue as the current is increased. In common with all fusion schemes, confinement scaling can only be confirmed by a set of scaling experiments of the ZTH type. In addition to this issue, operation with a resistive shell, i.e., with a shell whose time scale for magnetic penetration is shorter than the pulse length, is absolutely vital to ensure that the results of present experiments, including the RFX experiment at Padova, Italy, are relevant to the reactor regime. This is because a reactor is presumed to require quasi steady state operation, while present devices typically have pulse lengths short compared with the shell skin time. A third issue is that of current drive. This is also required for steady state operation. Although several possibilities have been proposed for current drive, as in other fusion devices, none has been convincingly demonstrated on a large scale RFP. Helicity injection has been demonstrated in a small way as a current drive technique, but the efficiency and other properties are far from being known at reactor relevant conditions. Finally, a technological issue that may have to be faced is that of a magnetic divertor, for wall protection or impurity control.

The ZTH design is well chosen as a very significant step along the path to a "compact" ($R \sim 4$ m) RFP fusion reactor (such as TITAN). The increase in size (factor ~ 1.5) and plasma current (factor $\sim 5-10$) over those of present devices place it in a much more reactor-like regime with regard to Lundquist number S and toroidal electric field factor E_ϕ/E_{cr} . The "thin shell" design in which the discharge length exceeds the time constant of the conducting stabilizing shell is a prototype of that required for a long pulse/steady state reactor. These basic features will make it possible to determine the behavior of the RFP configuration in more reactor-like conditions in which the relative time constants, instability drive, and fluctuation spectra may be significantly different than those seen in present RFP's.

The ZTH design has the important additional advantage of providing the flexibility and access to add additional, reactor-relevant capabilities as understanding grows. Chief among these potential additions are:

- (1) long-pulse (≥ 200 ms) 4 MA operation,
- (2) current drive (likely via helicity injection, F- θ pumping),
- (3) divertor (probably diverting the toroidal field).

While some preliminary concepts for these modifications exist, decisions on how, when, and with what priority to undertake these significant (10-20% of project scale) upgrades will properly depend on the understanding developed during initial operation with the nominal machine configuration.

ZTH physics studies in regimes of greatly improved parameters will allow and require improved diagnostic efforts to accurately determine RFP confinement properties. Especially important among these are the interrelated issues of β_θ "constancy," the dependence of T_e on plasma current, and the global energy confinement time. Improved characterization of confinement and the underlying plasma physics will make extrapolation to the reactor regime more reliable.

5. CAN THIS DATA BASE BE OBTAINED ON EXISTING DEVICES OR IS ZTH ESSENTIAL?

The question was discussed of whether these physics issues can be addressed by ZTH or instead can be studied on other devices such as the RFX experiment in Padova, Italy. We concluded that there is an excellent complementarity between ZTH and RFX in terms of scientific objectives. The RFX device will operate at a plasma current and minor radius which represents a substantial and exciting step beyond the parameter range of present devices. To be certain of accessing this aggressive parameter range, the device will use conservative technology, in that it will operate with a conducting shell whose time constant is long compared with the pulse length of the plasma current. This will ensure that the physics of equilibrium control and wall stabilization are the same as in experiments such as ZT-40M, concentrating instead on the confinement properties of the high current regime. The ZTH, while operating in a baseline parameter range similar to RFX and designed to accommodate a number of possible upgrades, will instead use a thin shell, with τ -shell $\ll \tau$ -pulse, and employ active magnetic control of the equilibrium. This type of operation is considered absolutely essential to reactor operation. Together with RFX (as well as the MST experiment at the University of Wisconsin), this will help separate the effects of the high current and large size operation from the effects of active control, thin shell operation. At the same time, reactor relevance clearly requires that this thin shell be studied in the high current regime addressed by ZTH and RFX. At present, the RFX program has no plans to study thin shell operation, concentrating instead on confinement scaling with current. Thus ZTH will be the only platform from which this information can be reached. It should be mentioned that in addition to being necessary for a reactor, it is possible that active control of the equilibrium will also result in better performance, based on limited tests on the OHTE experiment which obtained a longer pulse with little change in other parameters when a conducting shell was replaced by a thin shell and vertical magnetic fields were programmed for equilibrium control.

We also note that a program with more than one active laboratory gains strength from both competition and mutual interaction, and that the scientific output is determined as much by diagnostic design and theory support as it is

by parameter selection. Therefore, the operation of ZTH and RFX in similar parameter ranges, but with complementary scientific goals, is a strength of the world-wide program. Further, the breadth and depth of the physics issues of the RFP warrants more than one multi-megampere experiment.

The focus of the initial ZTH experiments will be to investigate RFP stability, confinement, and operation with a thin shell. As mentioned repeatedly in this report, this configuration is required for a viable reactor and may lead to enhanced performance due to reduced field errors and improved active equilibrium control. As presently planned, this configuration will not be studied on other RFP experiments. The ZTH design also allows natural future upgrades (if warranted) to higher current and to investigate the (potentially) reactor-critical issues of current drive and active impurity control via a magnetic divertor. There are no plans to investigate these issues in other RFP experiments.

We caution however that while the existing data base is adequate for supporting the present round of experiments, a substantially more detailed base will be required to extrapolate to a reactor. The proposed diagnostic array in ZTH can accomplish this, if it is properly integrated with the theoretical studies, and if it is augmented by diagnostics adequate to study ion energy balance. The planned profile measurements will be valuable in answering questions about the actual beta values achieved as well as about transport. Previous experiments worldwide have suffered from a minimal set of diagnostics, and this would be fatal for achieving the desired reactor relevant results from ZTH. Similarly, coupling of the diagnostic plan with theory will be essential for the success of these experiments, as in other toroidal physics efforts. We consider the existence of both theoretical and modelling capabilities at LANL to be a strong feature of the ZTH program; the utilization and integration of these capabilities must be made an active goal of the program. If the results of the ZTH and RFX experiments are consistently favorable, it will still almost certainly require this sort of interplay between diagnostics and theory to understand how to scale to a reactor.

The group of experts also considered the question of what other physics can be expected from the ZTH program. Clearly, if the parameters expected from present confinement results persist to the high current regime, the RFP will

have the potential to be a major contributor to the study of the toroidal physics of moderate beta devices, including general topics of stability, turbulence, and transport. Some of the topics which might be addressed include the theory of the η_i mode, the interplay of kinetic and MHD effects in controlling the nonlinear behavior of a core of stochastic magnetic fluctuations, the development of the kinetic electron energy distribution in a stochastic magnetic field, and other related topics. Equally important might be the general study of active control of a hot plasma by magnetic control systems, which is important in many different fusion reactor scenarios, and the study of the effect and control of magnetic field errors in toroidal experiments.

Thus we conclude that ZTH, with its base diagnostic set augmented by T_i profile measurements, and the other new RFP experiments (RFX, MST), will solidify and greatly extend the RFP confinement data base. The thin shell data obtained by ZTH will be required to be able to project to a reactor. In addition, the ZTH experiment is required so that the RFP program have sufficient breadth and depth to give confidence in projecting to any following experiment.

6. WHAT IS THE SCIENTIFIC BASIS AND TECHNICAL PATH FOR ZTH UPGRADES?

The potential of the ZTH for various upgrades is an attractive feature of this relatively flexible device. Because of its contributions to the study of confinement in high current regimes, of the behavior of thin shell operation, and of the study of magnetic control systems and field error control, this experiment stands on its own as an experiment of physics behavior in the reactor relevant regime. But upgrades involving higher current operation and current drive can increase the useful scientific lifetime of this device. The scientific basis for upgrades should be predicated on the performance of the baseline experiment, in terms of parameters, research output, and control. The results of these studies will determine the priority to be assigned to various possibilities, including modest upgrade to 2-3 MA current, more expensive upgrade to 4 MA operation, and incorporation of current drive into the design. The technical path for the higher current options is already in place; preliminary studies of current drive experiments have been done, and room for the hardware is present in the baseline device.

We find that the operation and study of 2 MA RFP's (ZTH and RFX) is an appropriate scaling step in the development of the RFP. The 2 MA plasma will have sufficient opacity to neutrals to remove atomic physics from the reversal (confinement) layer and so enable a clear examination of RFP confinement. The Lundquist parameter S will be increased by over two orders of magnitude from present devices. The ZTH seems well positioned in time scales, with the shell time comparable to the Taylor relaxation time to give high confidence of reaching the reversed state, a discharge time about six shell times to investigate thin shell physics, and $\omega\tau_{\text{wall}}$ very large to possibly minimize resistive wall instabilities. The 2 MA plasmas should be a good environment in which to study the dynamo and confinement physics.

An extension to 4 MA operation later in the ZTH program should be examined in light of progress at 2 MA and the weighing of other options. Such an upgrade to 4 MA could be an important additional step for the RFP. The Lundquist number S and confinement time τ_E are projected to increase another factor of 5; the plasmas would move more solidly into the reactor relevant regime in which the species are closely coupled ($\tau_{ei}/\tau_E < 1$). These

improvements are, however, incremental in parameters rather than providing entry to a significantly new regime.

The upgrade to 4 MA does not appear pressing in light of the presently authorized capabilities of ZTH. However, with modest near term additional expenditures in the range of \$1 M to \$3 M, it appears $I_\phi \sim 3$ MA can be reached with a flat top duration sufficient to evaluate the confinement. These near term capabilities should maintain ZTH in a competitive position with regard to RFX (2 MA).

Our present thinking, subject to review of the results from RFX and ZTH, is as follows. The upgrade to 4 MA should be considered as part of a priority ordered sequence of research program steps:

- (1) Thin shell operation
- (2) Power handling and wall conditioning development at 2 MA
- (3) Detailed study of the physics of basic RFP processes at 2 MA
  - Dynamo mechanism
  - Confinement
  - Resistivity verification
- (4) Current drive and/or upgrades to 3 MA
- (5) 4 MA upgrade
- (6) Divertor tests

The first two items are crucial to operating the baseline device successfully and creating the plasmas suitable for the studies called for in Item (3). As in all long pulse experiments, impurity control will be an important issue in achieving the experimental goals. The planned use of gettering, carbon walls, etc., shows that LANL appreciates this important issue. As stated above, besides the thin shell physics, current drive is the other key technical development needed to progress toward a reactor. The 2 MA plasmas should be sufficient for current drive studies. The 4 MA upgrade, preceded by the more modestly priced upgrade to 3 MA, would provide further support for the confinement scaling. The divertor option should wait on an assessment of the results of Item (2) in the baseline experiment. The committee believes a

revised but workable schedule for ZTH research can be made based on the above sequence of objectives.

The key contributions of ZTH must come in the thin shell physics and the understanding of the dynamo and transport processes. Diagnostic resources and operating time must be provided to meet these goals. Upgrades should be examined based on the progress toward these key goals.

APPENDIX A. ESTABLISHMENT OF A MEETING OF EXPERTS

Department of Energy
Washington, DC 20545

JAN 18 1990

Dr. Nicholas A. Krall, Vice President
Krall Associates
1070 America Way
Del Mar, California 92014

Dear Dr. Krall:

The Confinement Physics Research Facility is presently under construction at Los Alamos for the purpose of investigating alternate plasma confinement lines. The first use of the facility will be to study ZT-H, a high-performance reversed field pinch (RFP) experiment. This facility has been reviewed in the past, and found to provide an important step in the development of the RFP.

Within the context of requiring a strong physics basis for advancement of any magnetic fusion plasma confinement line, and in view of the question regarding ZT-H raised by the MFAC letter to Dr. Hunter dated June 7, I request that you review the current physics basis and research prospects for the ZT-H planned for the Confinement Physics Research Facility.

Please convene a meeting of experts (names enclosed) to prepare an assessment of the current status of RFP research worldwide that is sufficient to judge the technical value of the ZT-H. Please address the following questions:

1. Is the present basis of understanding of RFP physics adequate to ensure formation of the configuration in ZT-H for the time duration and at the plasma parameters (temperature and density) required to study confinement physics in a reactor-relevant regime?
2. To what extent are the physical mechanisms of confinement in RFPs understood? What information will be required to confidently predict confinement in reactor-scale RFPs? Can this physics understanding be established with present facilities or on the RFX device nearing completion at Padova, Italy? Are the features of ZT-H and the planned diagnostics appropriate and adequate for addressing this issue?
3. In comparison with the RFX device, will the nominal 2-MA ZT-H provide significant scientific progress on topics other than confinement?
4. What scientific basis is appropriate to justify and to provide a clear technical path to enhance the capability of ZT-H from the planned nominal 2MA performance to 3 or 4MA?

Please understand that we are not requesting and cannot accept advice on how to structure and fund the U.S. magnetic fusion program. We do need the best possible technical information on the current status of RFP research to support our fusion program management plans and to optimize the technical implementation of the ZT-H research program.

I and my staff, specifically, William Dove and David Crandall, will provide additional background materials and procedural assistance. We need a report of your factual findings by the end of February 1990, if possible.

Sincerely,

N. Anne Davies
Acting Associate Director
for Fusion Energy
Office of Energy Research

Enclosure

APPENDIX B. LIST OF EXPERT PARTICIPANTS

SUGGESTED CPRF/ZT-H REVIEWERS

Dr. Stewart C. Prager
Department of Physics
University of Wisconsin
3287 Chamberlin Hall
1150 University Avenue
Madison, WI 53706

Dr. Harold Weitzner
Courant Institute of Mathematical Sciences
New York University
251 Mercer Street
New York, NY 10012

torff
Dr. Michael Zarnsdorf
Plasma Physics Laboratory
Princeton University
P.O. Box 451
Princeton, NJ 08543

Dr. Jeffrey H. Harris
Fusion Energy Division
Oak Ridge National Laboratory
P.O. Box 2009
Oak Ridge, TN 37831

Dr. Ronald D. Stambaugh
General Atomics
Fusion and Advanced Technology
P.O. Box ~~86508~~ 85608
San Diego, CA 92138-5608

APPENDIX C. LITERATURE SURVEYED

- "RFP Experiments: Results from ZT-40M and ZT-P," G. A. Wurden et al., Varenna, 1987.
- "Refueling and Density Control in the ZT-40M Reversed Field Pinch," G. A. Wurden, P. G. Weber, R. G. Watt, C. P. Munson, T. E. Cayton, and K. Buchl, Varenna, 1987.
- "Confinement Dynamics and Boundary Condition Studies in the Reversed Field Pinch," K. F. Schoenberg et al., IAEA-CN-50/C-II-1, Nice, 1988.
- "The Titan Reversed-Field-Pinch Fusion Reactor Study," R. W. Conn, F. Najmabadi, R. A. Krakowski, K. R. Schultz, D. Steiner, and the Titan Research Group, IAEA-CN-50/G-1-4, Nice, 1988; 15th Symposium on Fusion Technology, Utrecht, 1988.
- "The Reversed-Field Pinch: From Experiment to Reactor," H. A. B. Bodin, R. A. Krakowski, and S. Ortolani, Fusion Technology, Vol. 10, p. 307, 1986.
- "Workshop Report on the Status of the RFP Edge Plasma," K. F. Schoenberg et al., July 1989.
- "Hall Effects on Magnetic Relaxation," L. Turner, IEEE Trans. Plasma Sci., Vol. PS-14, No. 6, 1986.
- "Reversed Field Pinch Confinement Physics," S. Ortolani, Controlled Fusion and Plasma Physics, 16th European Physical Society Plasma Physics Division Conf., March 1989.
- "Transport in RFP's," H. Strauss, L. Turner, M. Bevir, K. Kusano, and A. Yoshizawa, Ad Hoc RFP Research Committee, IEA, 1990.
- "Los Alamos RFP Program Plans and Projected Needs," P. G. Weber, MFAC Summer Study, 1988.
- "Short Summary of Reversed Field Pinch (FRP), Background and Status," P. G. Weber, MFAC Panel 22, 1989.
- "Report of the Review Committee on the LANL ZT-H Proposal," P. Diamond et al., 1985.
- "FRC Research Program," submitted to MFAC Panel IX, May, 1984.
- "Reversed Field Pinch Program," submitted to MFAC PQ2 Review Panel, LA-UR-82-2089, July, 1982.

APPENDIX D. AGENDA OF PRESENTATIONS

2/5/90

AGENDA

ZTH Physics Base Review SM-100 Conference Room (Old Cafeteria) Los Alamos National Laboratory

1st Day (2/6/90) Tuesday

8:30	Organizational Session	Experts & DOE Visitors
9:00	Welcome/Comments	John Whetten
		Dave Crandall
9:15	Introduction	Rulon Linford
9:45	Status of ZTH	Phil Thullen
10:15	Coffee Break	
10:30	RFP Overview	Kurt Schoenberg
	<u>Formation and Sustainment</u>	
11:30	MHD Theory of Sustainment	Richard Nebel
12:00	Working Lunch (SM-100)	Experts, DOE & Padova visitors, LANL Staff (by invitation)
1:00	RFP Start-Up	Carter Munson
1:30	Density Control & Sustainment	Glen Wurden
2:00	Kinetic Dynamo Theory & Summary	Dan Barnes
	<u>Shell Thickness and MHD Response</u>	
2:20	Thin Shell Issues	Joe DiMarco
2:50	Thin Shell Theory	Richard Nebel
3:30	Coffee Break	
	<u>Transport</u>	
3:45	Fluctuations & Confinement	Paul Weber
4:30	Physics Base for RFP Confinement	Dan Barnes
5:30	Adjourn	
	Dinner (Katherine's)	Experts, DOE & Padova visitors, LANL Staff (by invitation)

Second Day (2/7/90) Wednesday

	<u>Next Generation RFPs: Features and Programs</u>	
8:30	ZTH Design Features & Goals	Joe DiMarco
9:00	ZTH Program Plan	Paul Weber
9:30	RFX	Sergio Ortolani
10:30	Coffee Break	
10:45	Roles of ZTH & RFX	Joe DiMarco
11:15	Tour of CPRF/ZTH	Phil Thullen
12:30	Executive Working Lunch (SM-100)	Experts
1:30	Summary	Dick Siemon
2:30	Executive Session	Experts
5:00	Discussion/Request for Further Input	Experts, DOE & Padova visitors, Linford, Siemon, DiMarco, Barnes, Sherwood, Schoenberg
6:00	Dinner	

Third Day (2/8/90) Thursday

8:30	Executive Session	Experts
12:00	Lunch (Cafeteria Side Room A)	Experts, DOE & Padova visitors, LANL Staff (by invitation)
1:00	Executive Session	Experts

END

**DATE
FILMED**

11/14/191