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Contract No. _____ 06-9349 _____

Contracting Officer _____ G. Yonas _____

Contracting Officer _____ M. Tobyas _____

Contracting Officer _____ 79-7044 _____

REF ID: A662-018

A TECHNICAL REVIEW OF THE SANDIA LABORATORIES'
PARTICLE BEAM FUSION PROGRAM

Prepared for:

Sandia Laboratories

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May 18, 1979

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PREFACE

On 30 November and 1 December 1978, a Technical Review of the Sandia Laboratories' Particle Beam Fusion Program was conducted at Sandia's Albuquerque facilities. This review was commissioned by Sandia Laboratories in part as a response to comments and recommendations made by the Ad Hoc Experts Group on Fusion in their Final Report submitted on June 7, 1978 to the Fusion Review Committee of the Research and Development Council of the U. S. Department of Energy. Those portions of the Ad Hoc Experts Group on Fusion Final Report that pertain to the Sandia Particle Beam Fusion Program are reproduced below:

IV. The Inertial Confinement Fusion (ICF) Program

5. The work at Sandia includes a set of approaches that are promising from the point of view of overall efficiency, but its underlying science is particularly complex. The work is valuable, but considerations of driver requirements and target coupling are not well integrated. This warrants a special review by a group that would include experts on the specifications of driver requirements and the technologies to be utilized. Management steps should be taken to ensure proper program integration and balance.

VII. Conclusions and Recommendations

3. Programs

B) Inertial Confinement

Observation:

The inertial confinement program is in a phase of rapid development with many driver-target options. This rapid change and the complications of classification form the basis for a set of specific suggestions.

Recommendations:

Operate, modify, and exploit current facilities, both existing and under construction to the greatest degree practical to obtain essential physics information.

Pursue the development of alternative drivers which offer the potential for achieving performance parameters required for eventual commercial use taking into account target coupling.

Review the objectives and technical status of the e-beam program at Sandia. Take management actions to assure program integration and balance.

These recommendations speak to both a technical and a programmatic review with consequent appropriate management action being taken to assure program integration and balance.

The purpose of the review that this report documents and summarizes was to focus on the technical aspects of the program and examine the program's initial goals, the progress made to date toward reaching those goals, and the future plans or methods of reaching those original or modified goals. The committee restricted its activities to an examination of the technical data base established by the particle beam fusion research work done to date, both of Sandia Laboratories and elsewhere in an attempt to determine if that data base was sound enough to justify Sandia's future program plans in this area. Although a technical review must eventually reduce to a set of conclusions/recommendations that have programmatic implications, the committee did not examine broad programmatic issues. Specifically, the programmatic issues related to an examination of particle beam fusion as a competitor to other inertial confinement techniques were avoided. Some issues that involved the internal characteristics and features of the Sandia program were considered.

The members of the review committee were selected on the basis of their theoretical/experimental experience and expertise in one or more of the various scientific/technical areas that comprise the Particle Beam Fusion Program at Sandia Laboratories. The committee was well balanced in the sense that there was at least one member of the committee that was currently working in, or had worked in, each program activity area. The members of the committee are listed below:

Richard E. Aamodt	Science Applications, Inc., Boulder, CO
Wayne Clark	Maxwell Laboratories, San Diego, CA
Damon Giovanelli	Los Alamos Scientific Laboratory, Los Alamos, NM

David A. Hammer	Cornell University, Ithaca, NY
Ray Pollock	Los Alamos Scientific Laboratory, Los Alamos, NM
Norman Rostoker	University of California, Irvine, CA
Ian D. Smith	Ian Smith, Inc. Alameda, CA
Derek A. Tidman	Institute for Physical Sciences and Technology, University of Maryland, College Park, MD
Alvin W. Trivelpiece	Science Applications, Inc., La Jolla, CA

The review consisted of a sequence of interactive presentations made by Gerold Yonas, Director, Pulsed Energy Programs Directorate; Glenn Kuswa, Department Manager, Particle Beam Fusion Research; Thomas Martin, Department Manager, Pulsed Power Systems; and members of the technical staff reporting to them. In addition, the committee held executive sessions, toured the facilities, and met privately with Dr. Yonas to discuss some special issues. The agenda for the review is reproduced at the end of this Preface.

During its executive sessions, the committee identified what it considered to be the critical issues that should be examined by the committee and discussed in the report. In effect, these critical issues and the analysis made with respect to them, were the main source for the conclusions and recommendations made with respect to the Sandia Particle Beam Fusion Program. Most of these critical issues did not involve classified matters. Those that did are contained in a separate classified report that deals with those aspects of this review.

The committee members greatly appreciated the effort that the members of the Sandia Particle Beam Fusion Program staff and management made to provide the committee with thorough and clear presentations of their programs, why they were doing what they were doing, and how that

fitted into their overall program. The committee was favorably impressed by the scope, depth, and quality of the work being done in this program and by the people doing it.

As a final note, some members of the committee were perplexed by the Ad Hoc Experts Group unqualified comment that "... its underlying science is particularly complex" in reference to the approaches being pursued in Sandia's Particle Beam Fusion Program. This comment creates the impression that it might be easier to ignite a pellet with a laser than with a particle beam. While this might be the case, that fact remains to be demonstrated in a scientifically acceptable manner. From a physics point of view, the use of electron beams or light ion beams to heat matter is no more or less intrinsically complex than the use of electromagnetic waves or heavy ions. From the point of view of pulse power and beam generation, components that are both efficient and repeatable, electron beams may be simpler and less complex. However, the physics of the final transport and the focussing of electron beams across acceptable standoff distances in present conceptual reactor designs is more difficult for e-beam than for lasers or heavy ions. The beam charge neutralization requires the use of a plasma channel or some other scheme. Each of the several inertial confinement concepts need to be understood in sufficient detail relative to their corresponding reactor designs that it is possible to compare the merits of the advantages each concept has.

SANDIA PARTICLE BEAM FUSION PROGRAM REVIEW SCHEDULE

Thursday, November 29, 1978
Building 802, Room 229

8:30 AM	Gerry Yonas	Charge to Overview Committee Program Overview Activities, schedules, rationale, budget, applications, organization
9:15	Glenn Kuswa	Goals, problems, approaches, inter-lab cooperation, introduction of speakers
9:45	Mel Widner	Target and Deposition Theory
10:05	Milton Clauser	Classified Target Theory
BREAK		
10:25	John Freeman	Plasma Theory
10:45	Paul Miller	Beam Experiments
11:45	Paul Mix	Diagnostics
12:00	Alan Toepfer	Target Experiments and Target Fabrication
12:30 - LUNCH		
1:15	Tom Martin	Overview, Fusion Accelerators
1:35	Pace VanDevender	Pulsed Power Research, Mite
2:10	Ken Prestwich	Rep Rate
2:45	Don Cook	Reactor Concepts
3:15	Steve Goldstein Gerry Barr	Area V Tour Area IV Tour

SUMMARY

The Sandia Laboratories' Particle Beam Fusion Program is dedicated to an effort that seeks to demonstrate that high voltage pulsed power generated high-current electron or light ion beams can be used to create conditions of temperature and density that will result in the fusion of light nuclei such as deuterium and tritium. The method by which they seek to accomplish this objective is to have such beam(s) impinge on a specially prepared pellet, causing it to implode and undergo thermonuclear burn. Further, Sandia seeks to demonstrate that this method of inducing a release of nuclear energy through the fusion of light nuclei can be developed into a practical energy delivery system capable of competing with other civilian power sources.

The electron beam-pellet implosion concepts had their origins in certain pulsed power technological developments that had taken place in DOE and DOD weapons simulation programs from the mid 1960's on. By the early 1970's, the pulse power technology and the related electron beam generation methods were developed to the point where exploratory research into their application to e-beam inertial confinement fusion seemed justified.

Recent developments have caused Sandia to place comparable or greater emphasis on a parallel exploration using the same pulsed power technology with light ions as the means of inducing pellet implosions to achieve an exothermic thermonuclear burn. This exploration, which is partially experimental, is based on and guided by the analytical scaling laws defining experiments that might scale to a reactor. Ion sources in this power range are only a few years old, but rapid progress has been made in terms of energy density. Experiment and analysis suggest that ion beams will scale to the conditions needed for a reactor.

Thus, initial efforts to demonstrate the focussing of an electron beam to current densities in excess of one megampere per square

centimeter, and the ability to deliver such beams to targets, led to an expanded program which has evolved into the present Sandia Laboratories Particle Beam Fusion Program. The principal new feature in the program is the Electron Beam Fusion Accelerator (EBFA) now under construction.

Sandia's Particle Beam Fusion Program has two main elements: Pulse Power Systems and Particle Beam Fusion Research. The Pulse Power Systems effort involves the research on and the operation of electrical systems to provide electron/ion beams with the characteristics required to induce desirable implosions. The Particle Beam Fusion Program Research effort involves theoretical and experimental research on the use of high-current electron/ion beams as fusion pellet drivers. There are several subelements to these activities, but listing them would not be useful in this summary. The main point is that these two main program elements must, and do, work together in a cooperative manner resulting in a generally balanced program.

In conducting its review, the committee was particularly concerned with the issue raised by others regarding the apparent diversity in the Sandia Particle Beam Fusion Program. In this committee's opinion, the program is not too diverse. Only a single approach is to be used in the design of EBFA. The polarity change needed between electron and ion experiments is easily carried out. Thus, several approaches of energy delivery to a pellet can be explored with this one generator. This flexibility is necessary since none of the energy convergence approaches presently being pursued is clearly superior, and much work remains to establish which is superior. This ability of the program to explore different methods of energy transport and confinement without having a corresponding diversity in energy generating technologies is clearly one of the strengths of the Sandia Particle Beam Fusion Program.

In general, the committee was favorably impressed by the technical presentations and by the high quality of the Sandia Particle Beam Fusion Program staff. However, the program is clearly resource limited and the program management is forced to make difficult choices in deciding

priorities. Their ability to make decisions is further complicated by what appears to the committee to be ambiguity in the national objectives to which Sandia's program is expected to be responsive. Namely, should the program become dedicated to civilian power or military applications? The emphasis on approaches that could lead to civilian power seems to be favored by the Sandia technical staff. The committee believes that this is the appropriate emphasis since significant military applications are likely to evolve automatically as a result of gaining an understanding of the implosion physics needed to develop inertial confinement fusion. However, a program that concentrated mostly on military applications would not likely yield civilian power applications.

While emphasis on approaches for practical fusion reactors is appropriate, a demonstration of ignition would be extremely valuable for the confidence it would generate in the eventual success of the inertial confinement fusion program. Such a successful ignition experiment would provide a good basis for checking pellet designs and target theories. This consideration is apart from military applications. In view of the fixed resources, development work can be deferred in favor of research leading to ignition.

Thus, while efforts to ignite a pellet in a mode that has little hope of being extrapolated into a reactor should not occupy a central place in the program, some effort probably should be devoted to determining if there is an experiment that might produce a pellet ignition much sooner than one that is on a reactor development path. For example, it is possible that an electron beam driven experiment might produce ignition in the near term, but ion drivers might provide a better eventual path to a reactor. If this were the case, then electron drivers should be exploited to obtain ignition.

In establishing its program priorities, and as a result of external constraints, the Sandia program has become handicapped by a lack of in-house theoretical support in the area of pellet design and target interaction. Sandia management has recently made efforts to correct this weakness, but still more emphasis in this activity seems

called for. It is essential that the group developing the target designs capable of producing ignition under realistic conditions work closely with those who fabricate and use the pellets in experiments on the ignitors. Sandia is presently at a disadvantage in this activity with respect to the ICF programs at other laboratories. Under a fixed resource constraint, the remedy is not obvious, but the problem is. To make proper use of pulse power as a pellet driver, the effort in target design and fabrication at Sandia should be expanded and a higher level of support from appropriate groups at LLL or LASL should be guaranteed. The committee tends to favor increased effort at Sandia, because of close contact with experiments and because particle beam driven pellets are different from laser driven pellets.

Although Sandia has been successful in producing neutrons using a magnetically insulated pellet, there was concern expressed by the committee that this was not likely to be a fruitful approach for an eventual breakeven experiment. There was some disagreement between some members of the committee and some members of the Sandia technical staff on the physical models and the analysis that was used in an attempt to explain the magnetically insulated pellet results. The experimental results are important and interesting, and additional experimental work to determine how the results scale is warranted. However, the committee was not optimistic that the theoretically predicted lowering in ignition power would hold up once an adequate inclusion of 2D effects was made in the pellet models.

The rapid progress that has been made in the ability to produce light ion beams and the growing conviction among Sandia's staff that ion beams offer a more straight forward path to a fusion reactor is causing a problem in the Sandia Particle Beam Fusion Program. Namely, should they abandon electron beam drivers in favor of ion beam drivers? While the preliminary evidence seems to support the optimism about ion beams, there is a great deal yet to be learned by using electron beams as drivers for pellet/target experiments. Deciding in favor of one or the other is not a simple problem, and Sandia management and technical staff must face

up to this issue and make a decision as to the course they should follow, or at least specify a date and a technical path which will lead to a decision. The real danger is that an unstructured slow drift from a program that emphasizes electrons to one that emphasizes ions might take place in a manner that doesn't make best use of the technical resources and talent, and may neglect important physical considerations. The committee felt that immediate work should, and does, emphasize ions to the extent needed to determine critical information about transport and focussing; after that, a formal decision must be made among the several possible roles for each particle.

The Sandia pulsed power development program is appropriate in size and scope to the needs of the program for pulsed power drivers. The pulse power program has achieved reliable operation of up to 10 TW in the Proto II device which operates at 1-2 MV with a 40 ns pulse. The program has developed a technology that appears capable of being exploited in the large experimental facilities that are envisioned as being necessary to the overall Sandia Particle Beam Fusion Program. The designs that have evolved appear capable of scaling to power levels in the 100 TW range and beyond. There is no reason to believe that the pulse power development program will not be able to supply single pulse electricity on whatever basis is required by the fusion research component of the program.

For reactor development, there are the questions of repetitive pulse operation and long life. Repetitive pulse high average power systems need to be developed for Sandia's and several other applications. Sandia has correctly given this activity a lower priority in view of the budget limitations and assigned only a small fraction of its pulsed power effort to this activity. The committee believes that this course is appropriate considering the present size of the program, but notes that much effort will eventually be needed in repetitive pulse technology.

The well known success of the Sandia pulse power development program has caused the impression in some quarters that its Particle Beam Fusion Program is primarily a pulsed power technology development

program and secondarily a fusion research program. This image is not accurate and Sandia should take steps to dispell this image as much as possible. Since the fusion research portion of the Sandia effort is younger than the pulse power portion, it must be nurtured and developed to a fully competitive position.

While the program is not without problems, both managerially and technically, the overall impression of the committee concerning the Sandia Particle Beam Fusion Program was quite favorable. Sandia is aware of most of their internal problems and they seem to be moving in directions that will solve them. They have a soundly conceived research and development program that is structured to address the critical technical issues associated with the possible development of particle beam fusion into a practical civilian power source. This doesn't guarantee that they will be successful in this endeavor. The review committee did not identify any fatal technical flaws in the Sandia program as presented to them. The extrapolation from ignition to a practical fusion reactor requires solutions to many technical engineering and materials problems as well as economic and political issues that are beyond contemporary resolution. These problems are common with all other advanced energy generating technologies and are not appropriate issues for this review committee to address other than to state that particle beam fusion is probably on an equal footing with other technologies as far as such issues are concerned.

INTRODUCTION

The report "Particle Beam Fusion" prepared by Sandia Laboratories is an adequate introduction to the subject for those individuals reading this report who might not be familiar with the general features of the Sandia Particle Beam Fusion program. An article in Scientific American (Volume 239, pp. 50-61, November 1978) "Fusion Power With Particle Beams" by G. Yonas treats the same subject area on a broader basis. For greater details on specific program activities, Sandia Laboratory progress reports on "Electron Beam Fusion" are available.

However, something that is not adequately introduced or reviewed in the above mentioned items are the pulse power aspects of the program. The following material is a brief review and assessment of the Sandia Pulse Power Program. The subsequent section of the report deals with "critical issues" and the committee's analysis of them.

Pulse Power Program Status

For a single shot demonstration of useful energy gain, the pulse power requirements are from one hundred to a few hundred terawatts, depending on the efficiency of generating energy in the particular form (i.e., electrons or protons) and on the efficiency of transferring energy to the pellet. Pulse durations are in the range of tens of nanoseconds for electrons, and possibly as much as one hundred nanoseconds or more when positive ions are employed, because these can compress the energy pulse in time. Lower overall efficiencies for positive ions may be assumed to mean that in spite of the power gain of the pulse compression process, the powers needed will still be similar to that for electrons; the energies to be delivered will be somewhat larger. Voltages needed will be in the range of a few MV for electrons and of the order of 10 Mev for ions.

The Sandia pulse power development has achieved reliable operation at up to about 10TW in its largest operational facility, Proto II (1-2 MV, 40 ns). This consists of two annular water-dielectric pulse lines, one above the other, feeding radially inwards to two vacuum tubes that are back-to-back. The tubes each have a single, annular vacuum/solid interface; such a design is limited in capability, because of the tendency of the interface to flashover. Considering the limit to be one on (P/T) where P is the power and T the pulse duration, each side of Proto II achieves about 1×10^{20} W/s. This value of (P/T) is close to that of several other similar "state-of-the-art" singlemodule systems in the U.S.

Recognizing the above limitation, the Sandia program has pursued several alternative approaches and has achieved success in two of them. One approach is the use of magnetic fields to increase the flashover limit of the vacuum/solid interface. This requires small diameter interfaces, and results in the water dielectric just outside

the interface becoming the limiting point. Unless pulse compression allows quite long driving pulses to be used, this limit may be below the levels needed. However, the approach appears useful in allowing a substantial upgrade of Proto II into the range of 10's of TW; this is an important expansion of the developmental capabilities, considering that the wide range of sources and energy transport schemes will require many experiments to be done, and that the rate of performing experiments on the EBFA will likely be less than that of earlier facilities, because of its large scale.

The second approach is the use of multiple vacuum interfaces at larger distances from the load, transporting the energy beyond each interface in a self-magnetically insulated transmission line. Such lines work at very high electric fields (a few MV/cm) and can transport power in a matched-flow mode at densities of the order of 10TW/m^2 , with 100TW/m^2 possible in short inductive sections. The efficiency of energy transport is of the order of 70 to 90 percent for loads with stable impedance, though it may be somewhat lower for loads whose impedances change with time, such as diodes with decaying impedance.

Power may be extracted from the transmission lines in one of two ways. Each line may drive a separate particle beam load connected to the pellet by a transport system. Operation in this mode has been essentially demonstrated for a one TW module of the 30TW EBFA I, at least with negative output polarity, and should extend to most particle transport schemes now envisioned. The second mode is where line outputs connect in parallel at a load, as when very high current diode loads are used. This mode is also possible, but as yet undemonstrated. There may be problems preserving magnetic insulation in the parallel-connection and in achieving adequate synchronization.

The use of many parallel vacuum interfaces and magnetically insulated transmission lines removes the need to use electrical stresses in the water pulse-forming lines that are any higher than those in present single shot systems. At the same time, it brings a need for a

modular pulse-line technology reliable enough for systems with large numbers of discrete, synchronous outputs. Experience with Proto II can be regarded as a transition to this kind of operation. Each of the two annular water lines of Proto II has many of the properties of a system of separate lines, since the transit times around the circumferences of the lines greatly exceeds the pulse duration. Few nanosecond synchronization of the parts of the water lines has been achieved by a series of accurately synchronized gas switches that control the charging of the lines and a large number of self-closing low inductive water breakdown switches. Reliable operation of Proto II for about 2,500 shots, together with full power tests of an EBFA module, gives confidence that the required modular technology now exists.

In an effort somewhat distinct from the main thrust to develop large single-shot systems, work has been performed at the repetition rates of about 10pps that will be needed for a reactor. An oil-dielectric pulse line has been charged by a pulse transformer to voltages approaching 1MV and discharged into a dummy resistive load for up to about one million shots (7 hours) and for more limited numbers of shots into a vacuum tube. Both the pulse line and the capacitor driving the transformer are switched by gas spark gaps. Data have been collected on the reliability and stability of operation and on switch electrode erosion. These data are encouraging so far, though no water dielectric has been used and fields and currents are well below those in use in the larger Sandia pulse power systems.

Pulse Power Program Assessment

The Sandia pulse power program has developed a technology that appears capable of providing the large experimental facilities that are envisioned necessary by the overall Sandia Inertial Confinement Fusion program. The designs that have been evolved appear capable of scaling to power loads in the 100TW range.

Confidence is particularly high as long as the modules of each system remain separate at the load region. In this case, operation in negative-output mode has been demonstrated suitable for greater than one terrawatt per module with good synchronization and ability to transport energy in an electromagnetic form in magnetically insulated transmission lined to within tens of centimeters of a central point. For positive output, the performance of the magnetically insulated lines and pulse forming circuits is not so well demonstrated, but it is likely at worst that their efficiency will be somewhat reduced, and that the pulse forming circuits will be somewhat de-rated or increased in size. It may well be that performance fully equal to that in negative output mode can be realized.

It seems possible that the choice or design of the source may require parallel connection of modules at the load. In this case more work remains, but still the Sandia approach of multiple vacuum interfaces and transmission lines seems to offer the best possibility of achieving the very large powers and currents required.

The technology also appears capable of being extended to longer pulses and to a combination of increased pulse duration and voltage, as may be needed for ions or foils.

Thus, there are no flaws or areas in need of re-evaluation that can be detected in the effort to develop large systems. The development of pulse power systems potentially scaleable to more than a hundred TW and to the regions $P/T \gg 10^{20}$ W/ns is in fact a major achievement of the Sandia program. The flexibility of the pulse power designs to be used with the several energy confining schemes and in both output polarities is encouraging and a commendable source of strength in the program.

For the application of a driver of a pellet with moderate or high gain, in either single shot or a repetitive reactor-like mode, significant advances have also been made. The magnetically insulated vacuum transmission lines have allowed the more sensitive

and expensive components of the pulse power system to be removed to a reasonable distance from the pellet. The voltage gradient achieved with these magnetically insulated lines exceeds 10^7 volts/cm. This is a spectacular technological achievement in its own right. The transmission lines are rugged and do not depend on a good surface finish so that they can probably survive reasonably close to the pellet; for single shot work they should certainly keep replacement costs down to an acceptable level. For a repetitive power reactor it seems unlikely that damaged transmission lines could be replaced with sufficiently high speed and low cost (although the Soviet electron beam ICF program appears to contemplate this kind of operation), so that some length of further energy transport with better properties in these respects still seems to be required. However, the vacuum lines should make it feasible to protect the sensitive vacuum interfaces from the effects of the pellet in multiple pulse operation.

The modular approach adopted by Sandia to the design of the pulse forming circuits favors the design of power reactors by simplifying maintenance and reducing fault modes. Work at Sandia has begun to demonstrate the capabilities of the pulse generating circuits to work repetitively for long periods. However, it is obvious that very little of the large amount of work needed in this area has been seriously addressed. The repetitive pulser now being tested at Sandia uses relatively low stresses in the dielectrics and vacuum interfaces. The degree of de-rating needed from the stresses now used in large single shot systems will strongly affect reactor design and cost...through the size of the water lines, the number of modules, the area of vacuum interfaces, their distance from the center, energy transport distances, transport losses, and so on. The de-rating question also applies to energy storage capacitors, which must probably be re-designed to operate below pulse corona threshold in order to achieve lifetimes of 10^8 - 10^{11} shots.

The Sandia repetitive pulser is also much lower in voltage and current than an EBFA module; the large systems at Sandia and elsewhere have all used liquid switches to cope with the higher currents and voltages, and since debris and shock makes these impractical for repetitive use, they must be replaced with low inductance gas switches or an as yet unidentified possible substitute for both. Lifetime and reliability of switches requires demonstration also.

CRITICAL ISSUES

This section of the report contains the summaries of the opinions expressed by the members of the committee with respect to a collection of critical issues they identified during an executive session following the formal presentation portion of the review. Although every member of the committee did not submit written comments on each issue, there were several opinions submitted on each issue. There was good agreement among those that chose to comment on a particular issue, and the material below contains a summation of the opinions expressed on each issue.

It is recognized that these opinions may not correctly reflect the actual situation in certain areas of the Sandia Particle Beam Fusion Program. Nevertheless, the opinions expressed were based on the impressions gained during the site visit presentation and on the experience and background knowledge each member had concerning the program. If the committee's impressions are incorrect, then perhaps it would be a good idea for the members of the Sandia Particle Beam Fusion Program to examine these opinions and develop an approach to describing their program that does not convey impressions they believe erroneous. These critical issues were identified and commented on in the spirit that they would be helpful and are not intended to condemn any aspect of the program, which in general the committee found to be quite healthy.

I. Should there be more in-house theoretical effort in support of pellet designs and target interactions?

There was general support among the committee for increased emphasis on in-house theoretical effort in pellet design and target analysis. However, it was recognized by the committee that the recent internal reorganization of the fusion group would result in increased activity in this area and that this had not yet had time to produce significant contributions. While this increased activity was generally applauded, it was felt by the committee that still more theoretical activity is going to be needed to match the experimental program. This is not to preclude continued and possibly expanded cooperation among theorists at Sandia and those at Livermore and Los Alamos.

Since much of the justification for the enthusiasm in the civilian particle beam program will rest on having believable target designs that produce ignition under realistic, attainable input conditions, it is essential to have a group capable of developing those designs working closely with those working on the ignitors. This is important since the actual pellets required for this program are likely to be different from those developed in the laser program. Sandia's small design group has relied rather heavily on LLL and LASL for support in target design work that involves the long range goal ignition targets optimized for high gain. This puts Sandia at somewhat of a disadvantage in the ICF program, especially since the other labs place emphasis on pellet concepts that are intended for use with high-power, short pulse drivers. However, the Sandia target design group has the capability to design the targets to be used in the experiments planned in the immediate future. Sandia plans to expand its target design effort.

Since the e-beam and ion beam drivers offer high energy at low cost and high efficiency, but not such high power and power densities as for lasers, Sandia should concentrate their target design effort on high energy targets. Presumably, given enough energy, the power deficiency can be overcome by the use of properly designed targets. Sandia is

already moving this way as evidenced by their interest in magnetic insulation. The target design effort should be strongly coupled with an experimental program aimed at quantifying absorption and redistribution of energy in the target, and verifying computer models. This effort could be accelerated by increased cooperation and involvement with the Livermore and/or Los Alamos design groups.

II. Is the Sandia Particle Beam Fusion Program too diverse?

The response by the committee was mixed in the reasoning and the rationales identified in forming individual conclusions. Nevertheless, there was uniformity in the sign of the collective response to the question posed. The answer is a simple no.

Sandia's Particle Beam Fusion Program is certainly not too diverse in terms of beam accelerator design. In fact, only a single approach is being considered for both EBFA I and EBFA II. Some important features of this machine design approach are being adopted from activities in progress on the most powerful machine at Sandia (Proto II). Other advances in accelerator and pulse power technology are also likely to be incorporated into the upgraded version of Proto II.

Even though only one machine design approach is being used, several approaches are being used to deliver generator energy to the pellet. This is appropriate since energy convergence is the least certain aspect of the Particle Beam Fusion Program. None of the energy convergence approaches presently being pursued is clearly superior and considerable work remains to be done to establish the best approach to follow. Most important is the fact that each of these approaches can be followed using essentially the same machine design. From a technical point of view, the ability of the program to use different forms of energy transport and confinement, without requiring a corresponding diversity in energy generating technologies, is clearly one of the strengths of the Sandia Particle Beam Fusion Program.

The elements of the Sandia Particle Beam Fusion Program appear to be the logical avenues of exploration for the use of pulse power for pellet fusion. The top identified program priorities of seeking to achieve increased electron power density and enhanced electron deposition, and of developing ion beam focussing and of transport are quite appropriate.

In part, the issue of diversity is one of appearance. The fact is that there is a common thread that links the activities that comprise

the Sandia Particle Beam Fusion Program. Careful examination of the Particle Beam Fusion Program reveals that all its activities really are directed toward identified goals. Unfortunately, this is not very obvious without some careful examination of the program. What is needed is to express a commitment to a few well identified, understandable goals and have those presented clearly to those outside of Sandia that have an interest in or some responsibility for the program. Then each aspect of the program could be shown to tie directly to that goal. The program is driven by the complex of goals that involve achieving appropriate pellet performance (net energy gain) with scalable geometries at modest cost. The more simply stated goal, appropriate in the near term, is that of achieving pellet ignition be the shortest route to a reactor. In addition, technically worthwhile intermediate goals should be identified (and updated as the physics warrants) for use as milestones by which the Particle Beam Fusion Program's progress can be measured.

The technical competence and free exchange of opinions evident at Sandia should provide all the input necessary for both a sound program and a clear presentation of it.

III. Is sufficient effort being devoted to quantitative studies on the focusing to determine minimum diameters of beams given the types of sources available and the existing pellet/target designs?

The consensus is no, but the details are a matter of degree and emphasis. In general, the opinions of the committee can be summarized as follows.

The central issue is focussing and transport. That is, can energy densities of $10^{13} - 10^{14}$ watts/cm² be achieved with electron or ion beams. Simple arguments have been made that 10^{13} W/cm² is accessible for electrons and 10^{14} W/cm² for ions. Even so, the committee feels that insufficient effort is being devoted to the development of analytic models that establish the relationship between beam brightness, beam emittance, beam convergence, source size, transport and focussing distances and channel properties for the various ion types being considered. More information on this subject than was presented to the committee probably exists, but since ion beam focussing is a relatively new activity and may be of even greater significance to Sandia's success in particle beam fusion, the greatest practical clarity and rigor in developing analytic models is felt to be desirable. More experimentation is needed, and is planned. Target parameter studies need to be done to determine the sensitivity of target performance to focussing conditions.

A related issue concerns the method of generating plasma channels to transport electrons or ions. Experiments have been done where an electron beam is propagated in an ionized channel created when a discharge is initiated by a fine wire by passing a large current through a background gas. The argument was made that similar transport could be achieved if a laser were used to create the ionized channel instead of an exploding wire. This should be demonstrated experimentally. The demonstration should include showing that the ablation of the target by the laser and/or the plasma channel can be small enough to be acceptable. If the required properties of the laser channel cannot be demonstrated, then some other method of beam transport, compatible with

delivering the required energy to an undamaged pellet should be developed. Whatever form of discharge channel is used, there are going to be nonuniformities due to effects such as sausage instabilities. In turn, this will result in a beam loss. It is necessary to determine if such channels can transport a beam without appreciable particle loss over the 3-5 meter distances that might be required for certain reactor concepts. Also, the successful overlap of the required number of beams on target needs to be demonstrated.

Also, the theoretical group effort needs to be strengthened in this area of beam transport and focussing. There is plenty of computer simulation effort, but insufficient analytical theory devoted to these two related subjects. There is the concern that in spite of the effort to date, it is not possible to prove theoretically whether or not e-beams can be focussed to intensities of 10^{14} watts/cm². Such knowledge would be of great value in determining whether or not to continue or discontinue the e-beam option.

IV. Are the projected improvements and optimism concerning the performance of magnetically insulated pellets realistic?

The optimism concerning the use of magnetically insulated central ignition regions appears to be based on models that omit several two-dimensional hydrodynamic effects due to the nonspherically symmetric transport produced by the B-field in magnetically insulated pellets. The committee feels that the calculated gain that results in a reduction of nearly one order of magnitude in ignition power requirements will shrink considerably when these effects are included in the model. Clearly, the calculation of the expected performance of such pellets is difficult, and extensive experimentation will be needed to verify the magnitude of any improvements in fuel heating. Although it was felt that no convincing arguments or designs of magnetically insulated pellets were presented, one related aspect has to be taken seriously. That is, the "wagon wheel" beam configuration which Sandia uses in some of its reactor designs is likely to result in some current-induced magnetic fields at least in the surface regions of targets. This will likely result in deposition asymmetries, the magnitude of which will depend on magnetic field penetration times. There will also be additional complexities introduced by the turbulence associated with the magnetized plasma. Thus, the investigation of magnetically insulated pellets and the general area of fields in pellets should be continued to establish a useful data base. This investigation will likely remain primarily experimental until a useful theoretical model can be established. This means any near term estimates of scaling are likely to be empirical.

V. Should the Sandia Laboratories Particle Beam Fusion Program emphasize the use of electron beams or ion beams as the principal method for the delivery of energy to the pellet/target?

This was an unexpected issue that became apparent to members of the committee during the course of the review. Simply stated, it appears that some members of the Sandia technical staff seem to favor dropping electron beams and pursuing ion beams as the primary method to be used to deliver energy to suitable targets. This was not an open issue in that there was no one who vigorously advocated one position versus the other. Rather, it was evidenced by an obvious undercurrent of attitudes that showed up in technical and social ways during the review.

The committee members generally expressed the thought that light ion drivers do look attractive on the basis of present knowledge. If the expectation that ions can be transported at high power density with bunching then overlapped at a pellet is realized, then the problem of power density is essentially solved; the basis for standoff in a reactor exists; the pulse power requirements are greatly eased from previous estimates by the reduction of power and current at the diode; and the need for anomalous deposition is removed.

Given these potential gains, and considering that transport at high energy density has not been attempted yet, emphasis on light ions to characterize the transport aspect seems well justified. This emphasis, which is already in effect, should continue until preliminary experiments have enabled first assessments of high energy density transport and overlap to be made. (Demonstration of improved focussing and a degree of bunching are also desirable during this period, but these may be considered less risky aspects at present.) The end of this assessment phase should be an important program milestone at which the relative role of ions and electrons in future research and in EBFA experiments is determined by Sandia management.

The possibilities of relative emphasis might be described as follows, in accordance with decreasing degrees of success in the ion assessment.

- (a) Cease all electron development. This appears an undesirable decision in any case.
- (b) Complete planned Proto II experiments on overlap of transported electron beams and any other development needed to ensure an electron capability for EBFA I. Plan to operate EBFA I in positive ion mode. Reserving electron mode as a backup. Plan target experiments and development around ions.
- (c) Plan EBFA I to operate mainly in positive ion mode, but plan specific target experiments at whatever level Proto II experiments indicate is feasible.
- (d) Emphasize electrons and ions equally, with increased effort to understand limits of electron beam convergence or the Rudakov "in-diode" approach, etc.

For electrons, some of the key technical issues are:

Can electron beams be focused/transported at 10^{14} watts/cm²?

Can the necessary current-densities be achieved after transport using high voltage or energy channels or tapered channels, even though these are not considered extendable to a reactor?

Can convergence and overlap in transport channels be demonstrated?

What deposition physics is required for the Rudakov approach to work?

For ions, one of the key technical issues is:

Can ion beams be formed and focused with the necessary angular divergence to deliver the proper energy to a target to achieve ignition?

There is also the issue of the deposition physics for both ions and electrons, and the kind of target convergence that might be realized.

Obviously, it is not the committee's business to identify all the technical considerations that bear on this issue. The Sandia staff members are in a better position to do that. Sandia should confront the ions vs. electrons issue and develop a basis for deciding the technical issue in a way that they and their management agree on. That is, should they emphasize one approach over the other, or continue both until a better data base is established.

Again, not wishing to tip the scales in either direction, the committee members generally expressed the thought that light ion drivers do look attractive on the basis of present knowledge.

VI. Is ignition, even under circumstances that are not applicable to a reactor, an important goal for inertial confinement fusion reactor development?

The answer is a qualified yes. There was not a uniformity of limiting qualifications expressed by the committee. The thoughts expressed are contained in the following summary.

An ignition demonstration experiment would be useful, particularly if it can be achieved in advance of the earliest date that a reactor compatible experiment is likely to achieve the same result. Such a result would be of benefit to the entire ICF program by virtue of the credence it would give to the idea that pellets can be ignited. An ignition experiment would provide a better basis to check pellet design calculations and investigate aspects of the physics of burning plasmas than are now available. The effort to ignite a pellet in a mode that doesn't lead to a reactor should not occupy a central place in the program, but should be pursued at a balanced and realistic level. The driver should be developed with some of the key reactor compatible characteristics, for instance, the single-pulse energy delivery mode and time scale should be comparable to that of a reactor driver.

VII. Is sufficient effort being devoted to quantitative evaluation of target characteristics based on available theoretical models/codes and analytical studies?

No clear unequivocal answers to this question were developed by the committee. The feeling most strongly expressed was that with the recent increase in staff and the additional computer codes available for target design, there should be a significant increase in the quantitative theoretical output. However, accurate theoretical descriptions will not be possible without increased experimentation. This is where sufficient resources do not appear to exist. Thus, there is a premium on making a careful choice of which experiment to do. In any event, more experiments are necessary, and as time passes, Sandia's weakness in in-house target fabrication capability is bound to become more troublesome. Unless steps are taken to remedy this situation, there could be a serious impact on the EBFA I program.

VIII. Did the members of the Sandia Laboratories staff working in the Particle Beam Fusion Program make clear presentations of how they plan to coordinate their activities so as to make progress toward identified goals on a realistic schedule, taking key issues into account?

The individual presentations were clear and unambiguous and there were many beneficial interactions between the presentors and the audience. The review committee found the presentation well matched to its needs. Even so, some of the committee members were especially mindful that the Sandia Particle Beam Fusion Program appears to suffer from an image that it is primarily a pulse power technology development program, and secondarily a fusion research program with a clear sense of purpose. This problem, which manifested itself in the comments and recommendations made by the Ad Hoc Experts Group on Fusion is due to the impressions gained by scientists and administrators involved in or responsible for inertial confinement fusion research. Considering this, it is probably true that insufficient emphasis was given in the presentations to target work (both experimental and theoretical) in comparison to that devoted to driver development.

In general, if some confusion exists outside of Sandia as to what the program's goals are, then perhaps some changes in choice of material and method of presentation might be called for. First, there should be a clear commitment to a few simple goals that can be stated in terms understood by staff, management and outsiders with an interest/involvement in the Particle Beam Fusion Program. Next, those things that can be scheduled should be identified, e.g., the EBFA construction project schedule has been known for some time. Then those areas that involve unknowns should be clearly shown along with the methods of attack to find the answers. When decision points can be identified, such as the choice between electrons or ions, the avenue leading to that decision point should be laid out. Recognizing that such plans are not unalterable, but rather are plausible scenarios based on the

latest understanding, they should be updated periodically. If properly done, such planning will lend confidence to those examining the program, and will provide a means for measuring its progress. The plans should be formulated so that they also benefit the management, helping it to keep each segment of the program progressing toward its goal, and at the same time allow for rapid identification of deviations in the path which are dictated by the physics.

In the future, it might be better to have a few key members of the technical staff make tailored summary presentations rather than having several of them talk about their own contributions to the program. Scientific conferences offer adequate opportunities for detailed technical expositions. Even excellent scientists do not always give the kinds of balanced presentations that are appropriately matched to the needs of certain kinds of audiences--those for whom it is necessary to communicate the results of a considerable effort such as Sandia's Particle Beam Fusion Program in simple narrative terms that highlight key features rather than exposing technical details. The responsibility for clearly and unequivocally presenting the viewpoints, goals and triumphs of the program lies squarely with all the active participants, but most notably with the top management.

CONCLUSIONS

Some of the more salient points registered by the committee are repeated or summarized here. First, the committee was pleased to find a vigorous and healthy research and development program at Sandia staffed with capable individuals throughout. The program is reasonably well structured, but some effort should be devoted to the development of technical goals and objectives with identified milestones. This would help dispell the notion that the Sandia Program is too diverse. This is discussed in the Critical Issues section.

The committee concluded that the theoretical effort should be given greater emphasis. Particularly, the analytic theory dealing with beam transport, focussing and target designs.

The rate of improvement of beam power density with ion drivers is faster than that being realized with electron beams. As a result, there is the temptation to drop electron beam drivers in favor of ion beam drivers. The committee believes that it would be premature to take this step as there is much to be learned from electron beam systems. Sandia should establish a means by which this issue of electrons vs. ions can be addressed objectively.

The Sandia Pulse Power Program is a valuable and cost-effective part of the whole ICF Program. The availability of large energies at low cost make it unique among existing pellet drives. It is also cost-effective because, with one technology and essentially the same hardware, several forms of energy can be delivered to a pellet. These factors have allowed impressive progress to be made for a small part of the total ICF budget. An auxiliary benefit is that pulse power developments at Sandia help all other potential ICF drivers except RF ion accelerators, since all use pulse power technology in some form.

The weakest aspect of the Pulse Power Program is the less well developed ability to concentrate energy to high densities under conditions involving repetitive operation as needed for a reactor. In other respects

pulse power is compatible with repetitive operation for a reactor, though since today's large systems were developed for single shot applications much work is needed to determine how best to achieve this. The high efficiency particle beam drivers is an obvious asset, and makes plausible smaller reactors that can be considered with any other present driver candidate.

Thus, the committee is led to express optimism about eventual reactor application, and to assert that in any case pulse power has a very important part to play in high energy pellet experiments to check pellet design and, if these are successful, to study the effects of the explosions.

Finally, Sandia should continue to take advantage of efforts at NRL, Cornell and at DNA operated facilities. The cooperation and stimulation resulting from contact with individuals outside is a useful adjunct to the program. This includes expanding the cooperative target design efforts at Livermore and Los Alamos.