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WORKSHOP SUMMARIES FOR THE THIRD US/USSR SYMPOSIUM ON FUSION-FISSION REACTORS

EDITED BY:

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PLASMA PHYSICS LABORATORY

THIRD US/USSR SYMPOSIUM ON FUSION-FISSION REACTORS

PRINCETON, NEW JERSEY

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WORKSHOP SUMMARIES

	Title	Author
1.	External Factors	N. Amherd
2.	Plasma Engineering	R. Mills
3a.	ICF Hybrid Reactors-I	C. Nedoseev
3b.	ICF Hybrid Reactors-II	J. Maniscalco
4.	Blanket Design	K. Schultz
5.	Materials and Tritium	R. Krakowski
6.	Nuclear Data and Codes	D. Dudziak
7.	Blanket Engineering Development Requirements	K. Schultz

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PREFACE

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The Third US/USSR Symposium on Fusion-Fission Reactors was held at Princeton University in January 1979. Previous symposia in this series were held at the Kurchatov Institute of Atomic Energy in April 1977 and at the Lawrence Livermore Laboratory in July 1976. Each of the first four days of the Princeton Symposium was devoted to a single topic. Invited papers on that topic were followed by a workshop, which included contributed papers and extensive discussion. The fifth day was devoted to summaries of the workshops, prepared by the chairmen. All the participants in the symposium have had the opportunity to review the written summaries, which are compiled in this report.

An interesting feature of this symposium introduced by K. Schultz of General Atomic Company was a polling of the participants prior to the symposium on their views concerning blanket development requirements. The results of this polling are presented in K. Schultz's two summaries herein. It was widely agreed that polling on various technological issues should be continued and perhaps expanded in subsequent symposia on fusion-fission reactors and related topics. Separate polls may be advisable for magnetic confinement and inertial confinement specialists. Other workshop chairmen asked their participants to attempt to arrive at consenses on various issues; that technique proved to be effective in stimulating a great deal of debate.

The theme of most of the Princeton Symposium was the "Near-Term Development Requirements for Fusion-Fission (Hybrid) Reactors." It appears somewhat too early for agreement to be reached on any of the design features of the first hybrid test reactor, even if a particular fusion driver concept were to be specified. This uncertainty is consistent with the unlikelihood of a hybrid test reactor being authorized in the very near future. Nevertheless, it is expected that the generation of magnetic confinement reactors after TFTR, MFTF, etc., will be equipped with a large number of blanket test modules, of which several could be utilized for fissile breeding.

1. SUMMARY OF WORKSHOP ON EXTERNAL FACTORS

by

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SUMMARY OF WORKSHOP ON EXTERNAL FACTORS

by

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1. Introduction

How does the concept of fusion-fission hybrid systems interface with other planned or projected elements of the worldwide production of energy? This session, entitled External Factors, was planned to provide an updated discussion of some key relationships of hybrids to the external world and, in particular, to explore some suggestions about external impacts on fusion-fission hybrid development. For the purposes of this summary the session's presentations, whose titles and speakers are listed in Table 1, will be classified according to the following four categories: the role of fusion-fission hybrids in electric power production, fuel cycle issues associated with both the fission and fusion portions of the hybrid concept, the economic prospects for hybrids, and issues important in the development of hybrids. Brief descriptions for each of these categories will be given in the form of a synthesis of the major ideas presented by the speakers.

Table 1
Presentation Titles and Speakers for the Session on External Factors

1. Hybrid Reactors in the U.S. Energy Development Program, J. Clarke.
2. Role of Hybrid Reactors in Nuclear Power Production, Part 1, G. Shatalov; Part 2, I. Ganev.
3. The Hybrid Reactor: What is the Next Step?, W. Wolkenhauer, B. Jensen, and R. Huse.
4. Fusion-Fission Hybrids and Nonproliferating Fuel Cycles, H. Feiveson.
5. Coupling Between Hybrids and the Fusion Industry, S. Abdel-Khalik.
6. Fusion: The Ambient for the R&D and Commercialization, J. Simpson.
7. Status and Prospects of Advanced Fissile Fuel Breeders, R. Kostoff.
8. Economic Implications of Fusion-Fission Energy Systems, D. Deonigi.
9. The Effects of Fuel Cycles on Hybrid Performance, G. Woodruff.

2. On the Roles of Fusion-Fission Hybrids in Electric power Production

Fissile fuel production by hybrids for utilization in fission reactors continues to be an attractive prospect of fusion-fission hybrid concepts. The hybrid concept offers an alternative supply of fissile fuel that is bred from abundant resources of uranium and thorium, and, hence, can resolve the uncertainties in fuel supply due to varying ore grades and distributions of naturally occurring fissile material. The fuel produced, which can be either plutonium or U^{233}, can subsequently be used as necessary for the makeup or initial fuel loadings for present converter reactors, advanced converters, and fission breeder reactors.

Several attractive features of hybrids derive from the mode of operation in which one hybrid reactor facility has the capability of producing fissile fuel in quantities sufficient to support the makeup fuel requirements of 5 to 10 converter reactors. One important feature resulting from this fuel production rate is that a limited deployment rate of hybrids can have a magnified impact on the energy production capacity of nations. This occurs because the nuclear fission reactors, assumed to be an accepted and mature technology some time in the future, can be deployed at nearly unlimited rates to meet the existing energy demands. Hence, the fusion-fission hybrids can be expected to complement and support existing technology rather than replacing it. Other features of fuel producing hybrids include having a weakly felt effect on the cost of power due to uncertainties in cost or performance estimation and the potential for proliferation resistant operation through the use of the denatured U-233 fuel cycle, direct enrichment and re-enrichment of fission reactor fuel rod bundles, and the requirement for only a very small number of fuel producing sites to support a large fission power capacity. More will be described about proliferation in the fuel cycle section of the summary.

Other modes of operation of fusion-fission hybrids such as fission waste transmutation or placing an emphasis on electricity production bring a different set of hybrid system attributes. These may become important hybrid applications in the future but to date they do not appear to offer the advantageous deployment prospects of fissile fuel production. Electricity production from the hybrid improves the economics of the single device but may adversely affect its relationship with the other technical and financial elements of the energy producing sector. Further investigations are required to provide a clearer evaluation of the desirable fuel-to-power ratio for fusion-fission hybrids.

3. On the Fuel Cycle Issues Associated with both the Fission and Fusion Portions of the Hybrid Concept

Areas for improvements in the hybrid fuel cycle and hybrid impacts on the nuclear fission fuel cycle have been receiving detailed analyses. For example, hybrids offer the potential as an abundant supplier of U-233 without the need for an initial fissile-inventory. Hence, a large increase in the light water reactor conversion ratio, without significant redesign or development of the converter reactor, and economic use of the proliferation-resistant denatured-uranium fuel cycle could be achieved by the development of hybrids.

Direct enrichment and re-enrichment of fission reactor fuel bundles in the blanket of the hybrid appear technically feasible and proliferation resistant owing to the high level of radioactivity induced in the fuel rods. However, without reprocessing at some point in the cycle the support ratio is low and the associated economic penalty is high.

On the fusion side of the fuel cycle, some or all of the tritium might be obtained from other sources than the hybrid blanket. If so, then the global neutron and energy balances may be improved. Moreover, the hybrid cost and risk may be reduced through simplifications in the areas of blanket design, fabrication, and operation, and by increases in the fissile production rate of up to 2 to 3 times that when all the tritium is bred in situ. One source of tritium is the fission reactors served by the hybrid, but there arise potentially severe but unevaluated safety and licensing issues. Another possibility is operation of the hybrid on the D-D cycle in order to eliminate the tritium requirement altogether. There has been considerable controversy on these issues.

The hybrid fuel cycle is an area of work requiring considerably more attention in order to clarify the real operational and economic potentials of hybrids. Estimates of the hybrid cost, risk, and operational benefits arising from changes in the fuel cycle have not been characterized or quantified. Since the fuel cycle is the umbilical cord between the hybrid and the nuclear fission reactors, its characteristics will have a major role in determining the development goals for hybrids and possible modifications in the nuclear reactors to best utilize the characteristics of the fusion-fission hybrid.

4. On the Economic Prospects for Fusion-Fission Hybrids

The favorable economic prospects for fusion-fission hybrids continue to be shown from expanded and broader scope studies. Analyses of coupled hybrid-converter reactor models illustrate the opportunities for economic operation with hybrid reactor costs up to three times the cost of the converter reactor (of the same thermal power output), and with uranium prices consistent with turn-of-the-century projections.

Newly completed studies comparing hybrids based on different fusion confinement concepts are showing that more than one concept has the potential for economic operation, and that the cost estimates and cost insensitivities of hybrids appear advantageous compared to alternative breeders.

Suggestions have also been forwarded that hybrids producing chemical fuels in addition to fissile fuel have enhanced economic prospects while retaining the desirable hybrid feature of being neither a significant supplier nor consumer of electric energy.

5. On the Development of Fusion-Fission Hybrids

Establishment of a fusion-fission hybrid plan was a prominent suggestion throughout this session. Without it, key issues such as the timing for commercial-scale hybrid systems, guidance for energy system planners regarding the prospects and assurance of hybrids, and the setting of goals for hybrid R&D would all be lacking. External factors should play a role in the establishment of this plan. Pessimistic forecasts of energy supply should be used for planning purposes in order to stimulate the development of several practical alternatives. For example, the plan might be based on low to moderate estimates of economically constrained uranium resource such as 1.8×10^6 and 3.0×10^6 tonnes U_3O_8 for the US and the OECD nations respectively; restrictions on fossil fuel burning due to the reality of the CO_2 problem; severe competition for worldwide resources due to ambitious energy expectations of developing countries; and limitations of oil to transportation purposes only. Of course, a comprehensive long-range governmental energy policy is required in order to assess the roles of various nuclear fission and fusion options. Political issues such as proliferation, fission waste disposal, and the public view of fission reactor safety can have an impact on the timing and direction of future hybrid developments.

Independent of the existence of the hybrid development plan, several key near-term development requirements as listed in Table 2 were identified. The two far-reaching aspects of these requirements are the initiation of a hybrid experimental program and the search for hybrid systems with improved commerical-scale potential.

Table 2
Listing of Specific Recommendations of Near-Term Development Requirements for Fusion-Fission Hybrid Systems

- Initiate experimental activities to reduce uncertainties and to evaluate the performance of practical hybrid blanket concepts.
- Investigate the feasibility of obtaining useful hybrid blanket data from upcoming D-T fusion systems such as TFTR, Shiva Nova, JET, T-20, . . .
- Assess the economic impacts of fissile inventory charges for the hybrid.
- Attain reactor-level plasmas with $Q \sim 1$.
- Initiate studies to identify systems that can be optimized for commercial-scale use through potential
  - cost reductions
  - labor nonintensiveness
  - manufacturing compatibility
  - reliability
  - development with the least number of R&D stages
- Assess fuel & clad performance, especially for inertial confinement fusion blanket concepts.

6. Conclusions

External factors have been shown to impact the choices and directions available with fusion-fission hybrid concepts, primarily in terms of targets for potential commercial-scale hybrid systems but also in defining specific aspects of the near-term development programs. Fusion-fission hybrids, being but one choice of fusion energy system and having a dependence upon the character of nuclear fission developments, can benefit from the establishment of an energy plan and a hybrid R&D plan in order to identify, quantify, and test the hybrid's advantages and disadvantages compared to complementary and competing energy technologies. However, even without such plans, areas of work can be identified that improve the hybrid R&D program balance and offer significant extensions in the hybrid data base.

2. SUMMARY OF WORKSHOP ON PLASMA ENGINEERING

by

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[illegible] ENGINEERING

[illegible]

I. Introduction

In the workshop on so-called "plasma engineering," eight people made presentations: Messrs. Brooks, Gibson, Jassby, Moir, Rose, Shatalov, Tenney, and Teofilo. In addition, we had many comments from the audience, and I shall try to present a distillation of the accumulated wisdom of that large group.

II. Some Basic Quantities of Plasma Engineering

Let me start with three basic quantities of plasma engineering. First there is Q. That is defined a little bit differently by different people, but with broad brush it is simply the ratio of the energy out to the energy in. Early magnetic confinement machines could be categorized in two classes. There were high-Q devices, the closed toroidal machines, and there were low-Q devices, the classical mirrors with end losses. Today we are considering some intermediate-Q devices, for example, the tandem mirror (the end stoppered mirror) and the inertial confinement systems. As hypothetical reactor designs were developed, the very low-Q machines seemed to become more and more marginal, and now we believe we would have to be quite lucky to get a really low-Q system to work. Howeever, the intermediate-Q devices have gained in interest.

A second basic quantity very important to plasma engineering is our old friend, $n\tau$, the reactor parameter introduced by J. D. Lawson. This is really a go or no-go criterion. The inertial confinement people don't talk about seconds per cubic centimeter the way the magnetic confinement people do. They tend to talk in terms of grams per square centimeter, but it all comes down to $n\tau$. From the grams/cm^2 point of view, it is clear that success requires either getting very high pellet compression or very large pellets, requiring a great deal of energy. Or perhaps we must have both high compression and a large quantity of energy. The preference among the people who spoke on ICF was to assume that energies on target of something like a megajoule will be needed, and pellet gains of about

200 are assumed. The experimental results to date imply that this is indeed a difficult assignemnt. Much work is required.

A third basic quantity applies not to the inertial confinement systems, but only to the magnetic confinement systems. This is the familiar expression $\beta^2 B^4$. It is a measure of the power density you can produce in the system. It is also a key to some of the problems that face us in magnetic confinement. The toroids have traditionally been, and still are, believed to be essentially low-β machines. We are talking about less than 10%. We may get 10% or more on axis, but the average β will probably be less than that; in fact it may be quite a bit less. With the traditional mirror machines where advantage can be taken of the curvature of the confining field as well as the magnetic pressure, β may exceed one in the low-field region. On the other hand, for the tandem mirror, which has solenoidal confinement, β will drop below one to perhaps one half, but still giving a potentially substantial advantage over the toroids.

The B factor is interesting from a technological point of view because it has to do with what kinds of magnets we will have to build. The technological restriction, however, usually occurs at some point on the conductor. The useful magnetic field available to confine the plasma is a different question. In the toroids, since higher field exsits at the conductor than in the plasma due to the difference in major radius, there is a premium price for the space between the plasma and the coil. In machines with thick blankets and shields, there is a rather large reduction in field available for plasma confinement in a torus from that at the coil — a factor of at least two, perhaps as high as three. The tandem mirror has a similar problem because it must provide high-field magnetic end plugs, but it has a low-field solenoid. The ratios are a little less advantageous than in toroids, perhaps four or five, but the decrease in this B factor is compensated by the increase in β; so the overall $\beta^2 B^4$ in the tandem mirror and in toroids is somewhat similar.

We have problems to solve in technology and knowledge to gain of basic plasma physics that apply to these three basic quantities of importance.

III. Theoretical Guidance

What guidance do we have from theory for the values of these parameters that can be accomplished in various systems? In the old days, the early to mid-60's, we had a dilemma. Theory told us that in magnetic confinement as the temperature went up, the confinement should improve, whereas the experiments did exactly the reverse — the confinement went down as the temperature went up. This was very discouraging for those attempting to design realistic apparatus for reaching the necessary quantities. Then the happy days began with the results from the T-3 tokamak in Moscow and the subsequent events of the next seven or eight years. We seemed to turn the corner. The confinement improved as the temperature went up more or less in accordance with theory. It was predicted, however, by theory that along about the time we reached the conditions that we are now achieving in the laboratory, the confinement would turn around and go down. Well, now again we have reached a divergence between theory and experiment. As the temperature continues to rise, the confinement seems to go up instead of going down. Now that is a happier situation than the one we had earlier. It is much nicer to have theory say τ should go down while τ continues to increase. On the other hand it doesn't give us a great deal of confidence in the theoretical guidance we have been receiving, and it has led to a certain amount of empiricism as demonstrated by D. L. Jassby's talk at this meeting. Another example of empiricism is the so-called Alcator scaling where $n\tau$ is predicted to scale as n^2. It can't really, but so far the performance of various machines conforms to that fairly well. Jassby suggested another correlation of a figure of merit for neutron production that would scale with about the 3/2 power of the input energy. The empirical extrapolations are encouraging so far, and I suppose we should be grateful.

IV. Difficulties

A. Fundamental Problems

What are the difficulties that face us? Why can't we go ahead and build reactors? The fundamental problem is our lack of knowledge of reactor-grade plasma transport properties, what $n\tau$ has been achieved in magnetic systems and what we may expect — or the grams/cm^2 one may achieve in the ICF systems.

Assumptions of what $n\tau$ will be achieved has a lot of leverage on what the prediction of hypothetical reactor studies will be. Fred Tenney emphasized this in his talk. The selling price for electric power is very dependent upon what $n\tau$ is going to be achieved — very dependent on the transport properties of the plasma, the things we don't yet know. In fact the economy of hypothetical successful systems will vary by a factor of two depending on what that quantity actually turns out to be. It is a little bit awkward to take too seriously today's detailed point models of the basic plasma physics for predicting the economics. We are uncertain by a factor to two, at least. The $n\tau$ value is closely related, of course, to the value of Q, and V. L. Teofilo in his presentation, as well as several other poeple during this conference, has shown the leverage that Q has on the economy of the final reactor.

B. Associated Engineering Difficulties

The above are fundamental plasma problems. There are also some associated engineering difficulties which really can be called plasma engineering. Dr. Shatalov, for example, talked about thermal cycling. This is indeed a severe problem. One thinks about thermal cycling when considering the fast theta pinches that we talked about more in the past. Thermal cycling certainly exists in the case of the ICF conditions. But thermal cycling also exists in terms of the quasi-steady state systems such as tokamaks. It would be much better to have a truly steady state system. The stellarator versions of the tokamak might be a better way to go if indeed they work as well. The tandem mirrors and classical mirrors as well have always been considered to be dc systems. The tandem mirror may have to be interrupted, however, the way the tokamak does because it may require unloading of debris. It seems that if it works well, it may work too well. It may be so excellent a confinement system that a slow increase in the effective Z of the plasma occurs as the fusion products or impurities build up. The classical mirror was a great ejector of impurities due to the same positive potential to be used as an end plug in the tandem mirror. That was a point in favor of the traditional mirror, and we shouldn't write it off. I mentioned that the traditional mirror was a low-Q device, but maybe low-Q devices can be important in fusion-fission systems. It may come back. The tandem mirror, if

It works well, may be much better, but it has to be interrupted just as the tokamak probably does. Furthermore, there are possibilities for extending a tokamak discharge. It may be possible to drive the current by an external means — by rf, for instance.

The thermal cycling problem that causes one to consider alternative approaches is a very important question. If you have to cycle a machine, you have to derate it. There is no question about that. Heavy machinery such as boilers, turbines, steel-making furnaces, [illegible] need to be brought up to temperature over periods of weeks and kept there forever, if possible. So we shouldn't take that problem too lightly.

Drs. Shatalov and Rose both emphasized the very important divertor problem. We are just beginning experiments on divertors but not necessarily on the pumping aspects of them. We are now more concerned with the impurity control aspects. The question of electrodes was mentioned by both Drs. Shatalov and Rose. Perhaps we cannot collect divertor effluent on electrodes. Perhaps it will be necessary to go to a deionization front, for example. These things need to be examined. The question of the type of divertor is important. Can a bundle divertor work on a large scale or is a poloidal divertor necessary? This has to do with the power density in the effluent from the plasma core. It was mentioned in one of the presentations that with a bundle divertor where all the effluent comes out in one place, there is an extraordinarily high power density in that effluent. We may have a problem similar to those of the neutral beam ducts where an excessive base pressure can lead to choking as well as to mechanical damage to the walls.

In the interest of time I am not going to summarize all the problems with the first wall. I think everyone here understands them very well and appreciates the problems of fueling. These are unsolved problems. Gordon Gibson from Westinghouse emphasized the role of the neutral beam in fueling. An assumption that a neutral beam injector could successfully fuel a tokamak is highly questionable to say the least, and would probably lead to a voltage problem. Neutral beams are a good way of heating. They are probably not a good way of fueling. So first wall problems, fueling, divertor problems, and thermal cycling are all associated with engineering difficulties that really must be solved before one can seriously consider true reactor operation.

Well, what should be done today? One thing, and this was mentioned by R. Moir, would be the development of neutral beams that are dependent on negative ion sources. This is important if we are going to be able to provide higher energy neutral beams at a reasonable efficiency. These beams are important for the end plugs of tandem mirrors. They may also be important for the suggested machines for the burning of deuterium rather than of D-T. As Dr. Shatalov emphasized, theory is inadequate, and experiment is required, not just for basic plasma physics, but also for study of the first wall, the divertor, and the technological problems mentioned above.

What is the role of the hybrid and the program it requires in the Department of Energy? I think the principal advantage of the hybrid is that it can shift the bulk of power generation from the plasma into the blanket. That is really the source of most of its advantages from the plasma engineering point of view. In this sense it may be able to save a marginal fusion system and make it a practical device because it multiplies the fusion power gain (although systems studies of the past few years indicate that $Q \geq 2$ is desirable). Secondarily, but almost as important, it eases some of the problems with the first wall and other power density problems, such as the divertor and other things we have mentioned, since the plasma part is a much smaller fraction of the total. Another consideration is the possibility that it might hasten the availability of practical application of the fusion program.

Finally, however, one should be a little bit cautious about leaping to the conclusion that hybrids could hasten fusion application greatly. We are still determining the transport properties of plasma. Whether we go on to pure fusion or hybrid fusion, we shall have to understand these things first. We are all very hopeful for the tandem mirror, for example, possibly a very attractive fusion core for a hybrid, but we still do not have a tandem mirror operating that demonstrates the basic principles, although perhaps we shall later this year.

Let me close by saying a little bit about the suggestions for the program that were made in the session. I shall make three points. First of all, I think the consensus was that hybrids should be taken seriously; they appear to be systems that can work. We ought not to relegate them to the classification of a curiosity. Secondly, the large machines that are being planned and designed and in some cases constructed today should be used for more hybrid-oriented experiments. It is up to the community to decide which ones make the most sense. Finally, and on this one there may be some dissension, I believe that the desirability of incorporating hybrid-oriented experiments in the new machines does not imply that there should be any large shift in the major goals or direction of the existing worldwide fusion energy program.

3a. SUMMARY OF WORKSHOP ON ICF HYBRID REACTORS-I

by

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SUMMARY OF WORKSHOP ON ICF HYBRID REACTORS-I

C. Nedoseev
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In comparison with the 1977 Symposium on Fission-Fusion Reactors in Moscow, we can see a significant increase in reports devoted to ICF hybrids. Five groups — three from the US and two from the USSR — have presented here the results of their work. Three groups use a laser as a driver and two use relativistic electron beams.

Main Parameters of ICF Hybrids

	Driver	Driver Energy (J)	Fusion Energy (J)	Rep. Rate (s^{-1})	Blanket Gain
LLL	laser	10^6	10^9	high (7-13)	2-8
Solase H	laser	$2 \cdot 10^6$	$3 \cdot 10^8$	4	2.5
LASL	laser	10^6	10^8	1-10	1.8
UBTAH	laser	10^6	low	high	100
Bechtel	REB	$6 \cdot 10^6$	$7 \cdot 10^8$	high (10)	
UAE	REB	$5 \cdot 10^6$	10^9	low (0.17)	2.3

All projects use approximately equal values of total delivered energy, but the values of repetition rate and blanket gain are very different. The principal reason for this difference is that very different driver systems are choosen in these projects. There are different lasers, and different systems for the electron beam transport and focusing. The main features of the drivers must be tested experimentally on large devices, which should be built in the near future.

When the total thermal energy of the system is fixed, the degradation of some reactor elements, and in particular in the hybrid blanket, depends essentially on repetition rate. For blankets the lowest value of the repetition rate is limited by the allowed temperature variations, which cause stresses in the cladding and fuel elements.

Taking this into account, we can say that the blanket designs and materials must be significantly different for ICF reactors with different repetition rates.

As the pellet gain can be smaller in hybrids, it seems to many participants that hybrid ICF reactors are more generally useful than "clean" ICF reactors. It is obvious that the energy multiplication given by the fuel production in a hybrid blanket gives us the possibility of decreasing the energy of the microexplosion, or of reducing the repetition rate. So in hybrids the problem of the lifetime of the driver and of other systems becomes easier.

The results of our discussions allow one to conclude that an important factor we need to take into account when choosing blanket concepts is the thermal stress. In any case, it will be necessary to do something to decrease the effect of thermal stress on blanket lifetime and reactor economics. Perhaps a liquid or solid moderator of the fast neutron spectrum, liquid fuel elements, or homogeneous mixtures of fuel and graphite can be attractive from this point of view.

It is necessary to do some experimental investigations to simulate thermal stresses and thermal cycling effects of short intense neutron pulses. Pulsed fast-neutron reactors may be useful for this purpose.

3b. SUMMARY OF WORKSHOP ON ICF HYBRID REACTORS-II

by

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[illegible]

A. Maniscalco

Exxon Research and Engineering Company, Linden, New Jersey [illegible] USA

The following set of questions was posed to workshop attendees

1. Does the relaxed fusion energy gain criteria (ηQ [illegible]) offer an opportunity for earlier development and deployment?
   A. Examples to consider: 1% driver with pellet gain of [illegible]
      2% driver with pellet gain of [illegible]
2. What are the major problems affecting the technical feasibility of an ICF hybrid?
   A. Are any of the problems significantly different for pure fusion?
3. What are the desirable features of an ETF which would deal with the major technical problems of an ICF hybrid?
   A. Are any of the features significantly different from those required for pure fusion?
4. What are the logical steps which should be taken to prepare for an ETF that deals with ICF hybrid engineering issues?
   A. Can we get good estimates of pulsed radiation [illegible] effects before we have a high fluence pulsed radiation source? Are they really necessary?
5. In comparison to MFE, what are the advantages and disadvantages of ICF as a platform for a hybrid?
6. Are liquid metal cooled blanket technologies most attractive for ICF systems? If so, should ICF hybrid development be focused on liquid metal cooled-steel systems?
7. Should tritium be bred in hybrid or elsewhere?
8. What materials problems are introduced in a hybrid which do not exist for pure fusion?

Although the time allotted to the workshop was insufficient to address each of these individually, a "soft consensus" was developed in subsequent discussion between individual participants. The answers, posed in the following sections, should not be interpreted as a group response, but rather as the informed opinion of some members.

Question #1: The relaxed fusion energy gain criteria does have potential to offer earlier development and deployment of ICF hybrids relative to pure fusion. The most important example would be a driver which was able to produce a high pellet gain but is limited in efficiency. In this case, a driver technology that is not acceptable for pure fusion can be viable in a hybrid system. The example of low gain but high driver efficiency is also important (e.g. CO_2 laser systems).

Question #2: The major technical problems affecting the technical feasibility of an ICF hybrid are basically the same as those of pure fusion devices. A possible exception favoring hybrids is discussed in question 1 above. The problem of pulsed hybrid fuel-clad interactions could be significant and requires further attention.

Question #3: An engineering test facility (ETF) for ICF hybrid reactors must be able to produce $\sim$1000 consecutive pulses of $\sim$1 Hz for operational testing of hybrid blanket modules. A materials test facility (MTF) requiring 10^{22} n/cm^2 total fluence per year must attain an average performance of $\sim$100MJ at $\sim$1 Hz. The MTF would logically follow the ETF. Both facilities would also be required for pure fusion development.

Question #4: The logical steps leading towards a commercial hybrid demonstration are given below.

Critical R&D and Commercial Milestones

Milestone	Facility	Cost	Date
Scientific feasibility (high gain Q 50)	80-300 TW irradiation facility (e.g., Shiva Nova, Antares)	\$200 M	1984
Commercial Pellet Development and Reactor Component Testing for Single Pulse Effects (Q 100)	Single Pulse Target Facility (e.g., Shiva Nova II Upgrade)	\$250 M	1986
High Repetition Rate Integration of Laser-Pellet-Tracking and Other Systems	Systems Integration Facility (no thermonuclear yield required)	\$100 M	1988
First Wall and Hybrid Blanket Module Qualification in pulsed radiation environment	Engineering Test Facility (must deliver 1000 consecutive pulses at 1 Hz)	\$350 M	1991
High duty factor, repetition rate, and fluence ($\sim 10^{22}$ n/cm^2) for materials qualification	Materials Test Facility ($\sim 10^5$ targets/day)	\$350 M	1995
Low duty factor hybrid plant integration (exluding on line target fabrication and electricity generation)	Experimental Hybrid Reactor ($\sim$300 MW$_t$)	\$800 M	1996
Commercial Demonstration (directly extrapolable to larger commercial systems)	Prototype Hybrid Reactor ($\sim$300 MWe)	\$1800 M	2001
First Commercial System	Laser Fusion Breeder (2300MW$_t$ thorium blanket)	\$2000*M	2010

*Fifth of a kind economic analysis

[illegible] doubtful that we can get good estimates of pulsed radiation damage effects before MTF results (1996). However, these might not be required for systems which preceed a prototype hybrid which accumulates fluence an order of magnitude faster than the MTF.

Question #5: In comparison with MFE the principal advantages of ICF as a hybrid platform are as follows:

- the driver is decoupled from the cavity-leading to more flexible geometry and higher overall performance
- the absence of magnetic fields allows the consideration of liquid metal coolants and ferritic steel structures. Liquid metal systems have good neutronic performance and are largely developed in the LMFBR program. Ferritic steels are more corrosion resistant cheaper, more available, and possibly more resistant to radiation damage than stainless steels
- less restrictive vacuum requirements mean that liquid metals and buffer gases can be used to reduce the radiation fluxes to the first wall

The principal disadvantages of ICF in comparison with MFE are as follows:

- the driver technology and pellet physics lag behind tokamak systems by five years or more
- the combination of cyclic stresses in the fuel clad and first wall structure presents a difficult instantaneous heating and stress problem that is several orders of magnitude more severe than for MFE systems. This problem is partially alleviated by the reduced vacuum requirements
- difficulties involving the mass production and positioning of targets remain to be resolved

Question #6: Liquid metal technologies are very attractive for ICF systems (see discussion above) and they should be emphasized early in the program.

Question #7: The question of where to breed tritium has not been resolved. However, because liquid lithium is an excellent coolant and thermal poison (i.e., so as not to burn bred plutonium and ^{233}U) it is likely that some, or all, tritium breeding will be done in the hybrid

Question #8: The principal materials problem which is unique to the hybrid concerns pulsed fuel clad interactions. Presently the actual magnitude of this problem has not been determined. Other problems associated with fission product contamination are also unique.

4. SUMMARY OF WORKSHOP ON BLANKET DESIGN

by

K. R. Schultz

General Atomic Company
San Diego, California

USA-USSR SYMPOSIUM ON FUSION-FISSION REACTORS

HYBRID BLANKET DESIGN WORKSHOP
WEDNESDAY, 1/25/79
K. R. Schultz - Chairman

BLANKET DESIGN WORKSHOP SUMMARY

1. Introduction

The Blanket Design Workshop was divided into two portions. Proponents of each of the four main hybrid blanket technologies were invited to discuss the advantages and disadvantages of that particular technology.

Liquid metal-cooled blankets - W. D. Allen
Water-cooled blankets - R. P. Rose
Molten salt-cooled blankets - J. D. Lee
Gas-cooled blankets - K. R. Schultz

As written summaries of these presentations are included in these proceedings, they will not be discussed in any depth here. Following these invited presentations the results of the Blanket Design Workshop questionnaire were presented and discussed. The questionnaire was sent or given to all USSR/USA Hybrid Symposium participants prior to the workshop and thus should reflect the opinions of the hybrid development community before any significant discussion or interaction on the questionnaire occurred. For future workshops, it may be valuable to have the questionnaire completed after the workshop as the discussions may have clarified the intent of the questionnaire, raised issues not previously considered, or even changed minds.

The intent of the workshop on hybrid blanket development was to try to determine if the hybrid design community (including the research funding and direction agencies DOE and EPRI, the blanket design and development groups, and the potential utility users of hybrids) felt that the depth and breadth of work done to date was sufficient to allow design efforts to be focused and directed towards general design concepts and which general design concepts should be selected.

2. Blanket Technologies

W. Allen of Bechtel National Corp. presented a summary of liquid metal cooled blankets. He suggested that sodium or lithium could be excellent coolants for inertial fusion systems but that magnetic effects probably ruled them out for magnetic fusion. Liquid metal coolant allows good neutronic performance, good heat transfer and can take advantage of the LMFBR development program.

R. Rose of Westinghouse Electric Corp. presented a summary of water-cooled blankets. He suggested that water cooling has the greatest operating and development experience and should be useful for near-term machines. The performance obtained to date in US studies has been quite modest. The presence of water appears to degrade the blanket nuclear performance by about 30% compared to gas-cooled designs. The presentation of G. Shatalov of a boiling water blanket design developed for the tandem mirror hybrid reactor at Kurchatov Institute, however, indicates that performance of water blankets may be quite acceptable. A degradation of only 10 to 15% compared to gas-cooled blankets was observed. These results are expected to be quite design-dependent. Further study appears to be needed to resolve the questions of nuclear performance in water-cooled blankets.

J. D. Lee of Lawrence Livermore Laboratory presented a discussion of a fission-suppressed molten salt blanket. Using Be for neutron multiplication, the breeding rate is excellent and because of low multiplication, the support ratio is quite large. He noted materials and process development needs.

K. Schultz of General Atomic presented arguments for gas-cooled blankets. Helium is inert and concerns about chemical, nuclear, gravity, magnetic and electrical interactions are minimized. The low volumetric heat capacity, however, requires design attention to obtain good thermal/hydraulic behavior. Maintenance advantages appear good.

3. Blanket Design Questionnaire

The results of the blanket development questionnaire are shown in Table 1. These results were discussed and the results and consensus from these discussions are presented below.

1. Should hybrid blanket development efforts be focused on one (or a few) design concepts?: Yes - 50% No - 45%.
   There was strong polarization on this issue. Some people felt that we should focus because of a sense of urgency: "Time is running out - we have to do something, therefore we should concentrate our resources." Others felt, equally strongly, that we haven't done enough to choose, that fusion is different from fission in that the driver could be developed and many blanket options tried in one driver, and that we should not focus for fear of missing the "optimum" blanket concept.

2. Are we ready to focus blanket development efforts at this time? Yes - 43% No - 58%.
   Despite the sense of urgency on the part of some participants, the sense that we must do something, the consensus of the group was that we do not yet agree on the best blankets or operating modes for hybrids and thus cannot focus efforts yet. It was the consensus of the workshop that several blanket options must be carried into the serious blanket development phase before these issues will be sufficiently understood to allow recommendations to be made.

3. Rank the blanket selection criteria in order of importance:
   Performance: 1.2
   Technical simplicity: 2.5
   Fuel cycle technology: 3.1

Existing reactor experience: 3.3
Safety and environmental concerns: 3.7
Proliferation/diversion concerns: 6.1

While the criterion of performance was regarded as having paramount importance, there was strong feeling that all the other criteria are important and all should be given careful consideration. Relatively less interest was expressed in the importance of proliferation/diversion aspects. It was felt that hybrids could offer unique advantages in this area but that this was an external factor over which we had little control. Concern was expressed that the selection criteria list suggested may not be complete and, in many cases, the suggested criteria were not unique. A more detailed list must be developed.

4. Which blanket technology should be selected for further development?
   A. Fuel cycle: Uranium/Plutonium 80%, Thorium/Uranium 66%
   B. Technology:

Water-cooled	58%
Steam-cooled	35%
Helium-cooled/graphite	35%
Helium-cooled/metal clad	75%
Molten-salt	28%
Liquid-metal-cooled	30%
Other	0%

There was no consensus for selection of one or a few concepts, although the helium-cooled/metal clad blanket seemed most popular. Each of the technologies had strong supporters and no widespread adamant opposition to any concept emerged. C. Nedoseev reported that similar lack of consensus appeared to be the case for the USSR hybrid program blanket design efforts too.

There was strong opposition to proceeding with serious development work on any design concept until further studies had shown that the concept led to an attractive commercial reactor system. Heated discussion occurred regarding the current understanding of water-cooling and the relative importance of performance potential versus the current status of development and experience.

It was the consensus of the group (with several people strongly dissenting) that the proper role of the hybrid blanket was fuel production. Fissile fuel should not be intentionally consumed in the hybrid blanket. No such agreement occurred on the question of suppressing fast fission of the fertile material. Advocates for both fast fission blankets and fission-suppressed blankets stated their opinions but no agreement was reached. It was felt that more in-depth design studies and more general economics consideration would have to be made to try to resolve this question.

[illegible]. Nedoseev pointed out, and all participants agreed, that because of the significantly different operating characteristics of the various fusion drivers, the "best" blanket option will depend strongly upon the driver chosen. Four general categories were identified:

Continuous operation (e.g., mirrors)
Long pulse (e.g., tokamak)
Short pulse, [illegible] 1 Hz (e.g., small pellet inertial)
Short pulse, [illegible] 1 Hz (e.g., large pellet inertial)

It was noted that the relatively small support for liquid metal-cooled blankets was probably due to the small number of ICF representatives compared to magnetic fusion representatives. It appeared to be the consensus that liquid metal coolants were not desirable for magnetic confinement fusion hybrids. Liquid metal cooling has strong support for ICF hybrids.

In summary, the Blanket Design Workshop concluded that further scoping studies were needed to identify promising blanket concepts. Further, that more in-depth analysis was needed of concepts that appeared to be interesting in order to verify their performance and design characteristics and potential. And finally, that serious blanket development efforts on a given concept should not be pursued until serious design studies had been done to show the ultimate potential of that concept. It was the opinion of the group that several technologies did meet that criteria and that several others had the potential to do so. Thus the opportunities available for development of hybrid fusion blankets with excellent design and performance characteristics appear promising.

TABLE 1
3rd US/USSR SYMPOSIUM ON FUSION-FISSION REACTORS
BLANKET DESIGN WORKSHOP QUESTIONNAIRE RESULTS

1. Should hybrid blanket development efforts be focused on one or a few design concepts?
   Yes 55%
   No 45%

2. Are we ready to focus blanket development efforts at this time?
   Yes 43%
   No 56%

3. Rank the following aspects of blanket concepts in terms of importance to selection for further development. Rank each 1 to 10; 1 is most important, 10 is least important.

1.	Blanket performance (fuel and/or energy production)	1.2
2.	Existing fission reactor experience	3.3
3.	Safety and environmental aspects	3.7
4.	Proliferation/diversion aspects	6.1
5.	Technological simplicity/feasibility	2.5
6.	Fuel cycle and reprocessing technology	3.1

4. Which blanket technologies should be selected for further development?

   A. Fuel cycle

   Uranium cycle - 80%
   Thorium cycle - 66%

   B. Technology

   Water-cooled (LWR) - 58%
   Steam-cooled - 35%
   Helium-cooled, graphite (HTGR) - 35%
   Helium-cooled, metal clad (GCFR) - 75%
   Molten-salt - 28%
   Liquid metal-cooled (LMFBR) - 30%
   Other - 0%

(Consider blankets for both magnetic and inertial confinement)

5. SUMMARY OF WORKSHOP ON MATERIALS AND TRITIUM

by

R. A. Krakowski

Los Alamos Scientific Laboratory
Los Alamos, New Mexico

SUMMARY OF WORKSHOP ON MATERIALS AND [illegible] FOR HYBRID REACTORS

R. A. Krakowski

Participants: D. Berwald (Exxon Research and Energy Company)
A. Dubberley (General Electric, Sunnyvale)
R. Krakowski (Los Alamos Scientific Laboratory)
F. Tenney (Princeton Plasma Physics Laboratory)
V. Vasiliev (Institute for Inorganic Materials, Moscow)

The charter of this workshop was to examine the materials problems anticipated for the hybrid approach that appeared to be uniquely related to or exacerbated by the fusion-fission application. In addressing these issues a 31 by 18 matrix of materials-related issues presented in a systems or functional ordering versus critical materials properties was constructed. As expected, when auxiliary constraints of hybrid operating mode (power versus fuel production), characteristics of the fusion driver, and specific candidates and combinations of blanket components (structure, coolant, fissile/fertile fuel, tritium breeder, etc.) were enforced, even a partial attack on this 558 element matrix proved impossible on the 1-1/2 hour time scale allowed for the workshop. This materials matrix, nevertheless, is included for reference and (hopefully) future implementation.

The workshop group adopted a second approach at this point which simply called for all workshop participants to list materials-related issues/questions associated with their perceived hybrid approach. A list of such issues/questions follows.

1. Is the existing/developing (materials) data base adequate for purposes of a DEMO design?
2. Is the existing/developing (materials) data base adequate for purposes of licensing?
3. Is the perceived materials requirement resolved to an extent such that:
   a) existing experience could be used?
   b) new blanket concepts should be designed/developed?
4. Can a self-consistent set of blanket materials be identified such that a hybrid blanket can be built with little or no new materials development?

5. Will rate effects lead to significantly different radiation damage in highly-pulsed (ICF) systems as compared to long-pulsed MFE systems?
6. Most near-term hybrids will be pulsed to varying extents (ideally, TMR would not). What are the special thermal and mechanical problems expected to occur within the fissile/fertile fuels, and can satisfactory design solutions be found?
7. A serious lack of radiation damage information exists for (ICF) systems that propose the use of ferritic steels.
8. Corrosion data for liquid-metal systems (other than Na/St.St.) is sorely lacking. Liquid lithium at high temperature presents a difficult problem (except, perhaps, for TZM).
9. Molten salt systems, lithium salt systems will probably be first used. Electrochemical/corrosion effects in molten salts forced to flow across magnetic fields must be resolved. Permissible voltages of 200 mV may seriously limit flow velocities.
10. The materials data base for solid lithium breeding compounds is quite sparse. Data is needed on thermophysical properties, chemical reaction effects, tritium retention, and radiation damage.
11. Pulsed heating, thermal shocks, cyclic stresses, stress corrosion (particularly as related to fission-product/clad interaction), and the cyclic mechanical interaction between cladding and fissile-fertile fuel, to varying degrees (ICF most serious, long-pulsed tokamak less serious) will present a unique problem to hybrids, particularly for the refresh cycle.
12. The modeling and understanding of both tritium and fission product transport in most hybrid blanket configurations requires further development.
13. The spatial and time variation of neutron fluxes, dpa, gas (T, H, He) production, fissile fuel generation, fission power and fission product density, as well as associated effects (heating, swelling, loss of ductility, embrittlement, fertile-fuel buildup and burnup, etc.) can be serious considerations. Some of these effects can be ameliorated by clever design and

system operation (fuel shuffling). The impact of such spatial effects on blanket life, fuel reprocessing, usability of final product, tritium recovery/inventory, etc., cannot be resolved because computations of adequate depth have not been made.

14. The chemistry and exreactor manipulations associated with the $^{233}U/^{232}Th$ fuel cycle are considerably different (and in some instances more difficult) than for the $^{233}Pu/^{238}U$ fuel cycle. Considerable work has been done on ^{233}U fuel development, reprocessing and core design at ORNL and GA, much of which would be applicable to other reactor technologies. Nevertheless, the $^{233}U/^{232}Th$ cycle may, in fact, not be developed for fission power *per se*. Acceptance and introduction of the $^{233}U/^{232}Th$ hybrid and the associated impetus to utilize this fuel cycle in fission burners may lead to the unusual result that the hybrid concept may drive research needs in all aspects of the $^{233}U/^{232}Th$ technologies.

An attempt was made, *vis a vis* the fourth point raised above, to identify a "most probable" blanket concept according to structure, coolant, fissile/fertile fuel, fusile fuel breeder, cladding materials. It became apparent that even this task was too broad for the workshop. The overall state of ignorance or lack of consensus did not permit a specific blanket onto which crucial materials issues could be focused and specific research needs could be specified.

In an effort to resolve these issues, at least in a broad sense, it was noted that a materials program was in place for both the LWR and the FBR, as well as a strong materials data base associated with these fission systems. Furthermore, a programmed but very low-level materials plan exists for the development of pure fusion, and a comprehensive assessment of materials needs for pure fusion has been made over the past decade. Consequently, the materials workshop adopted the thesis that:

> "Materials problems for hybrids appear no more severe than for pure fusion and/or fission (MSBP, LWR, FBR) power, and materials programs are (have been, will be) planned and/or are in place for the latter systems."

In a "roll-back" fashion the hybrid reactor materials workshop directed attention to the identification of obvious exceptions to this oversimplified statement in order to identify special requirements of hybrid materials requirements. Some of these exceptions and/or caveats are listed below.

1. For the hybrid, pulsed heating of the fertile/fissile fuel pins is expected for a number of cycles that far exceeds that for fission systems.
2. If molten-salt coolants/fuel are used, fluid flow in the presence of magnetic fields will lead to voltages, electrochemical breakdown, and unique corrosion mechanisms.
3. If molten salts are used, the chemistry of such coolants/fuels in the hybrid systems will be sufficiently unique (i.e., lithium bearing) to warrant different consideration of chemistry, corrosion, stress-corrosion cracking, reprocessing, etc.
4. Fissile/fertile chemistry will be different in so far as fission-product and actinide content are concerned, perhaps leading to somewhat different reprocessing considerations, fuel-cladding (chemical) interactions, fission-product transport, etc.
5. Because the neutron spectrum will be a mixture of fusion and fission spectra, radiation damage effects and transmutation effects will be different from those for either pure fusion or pure fission. Such effects and the degree to which they can be related to either limit will vary spatially and in time.
6. If the hybrid system operates with low plasma Q, fusion driver systems <u>external</u> to the blanket may demand materials-related development that normally would not be required (at least in degree) by a pure fusion ignited reactor:
   - higher heat/particle flux to divertors,
   - higher heat/particle flux to first walls,
   - higher neutron fluences in neutral beam injectors,
   - higher average power density at direct convertors.
7. The hybrid reactor appears to exhibit more design, construction and operational flexibility compared with a pure fusion device or a pure fission device:

- The hybrid system operates apart from the electrical grid.
- The hybrid system generally has and can afford a lower thermal power density within the blanket, as compared to fission systems. This situation leads to a more open system that is less prone to hotspots, thermal stresses, crucial operating constraints.
- The hybrid system can afford to make serious, but costly, mistakes in blanket design (i.e., materials selection, coolant configurations, fissile/fertile fuel arrangement, neutron moderation, etc.), simply because retrofitting of different blanket systems can be made without affecting a major part of the plant (and capital cost). This advantage is unique to driven systems (unlike a fission reactor) where the neutron source is separated distinctly from the breeding and cooling system. This characteristic, when coupled with an off-grid operation, may permit a trial-and-error, but educated selection of materials for the hybrid without a profound and separate materials testing program; the hybrid itself could serve as a materials testing facility.

In conclusion, a number of issues prevented a comprehensive assessment of the materials problems anticipated for hybrid reactors, not the least of which were the limited time available and the still poorly defined role of hybrid systems. The question of hybrid materials needs, nonetheless, must be addressed more squarely in the near future, and will play an important role in focusing onto a specific hybrid reactor blanket scheme.

FUNCTIONAL ORDERING OF MATERIALS ISSUES / CRITICAL PROPERTIES	1. Mechanical Properties	1.1 Creep Strength	1.2 Ductility	1.3 Cyclic Fatigue	1.4 Fracture Toughness	1.5 Erosion	2. Chemical	2.1 Corrosion/Matl. Loss	2.2 Stress Corrosion Cracking	2.3 Compatibility/Transport	2.4 Tritium Transport	2.5 Transmutations	3. Fabrication	3.1 Joining/Forming	3.2 Cost/Resource	3.3 Remote Maintenance	4. Radiation Effects	4.1 Bulk Effects	4.1.1 Swelling	4.1.2 Embrittlement	4.1.3 Physical Property Changes	4.2 Surface Effects
1. Plasma/Structure Interface																					
1.1 First-Wall/Vac																					
1.2 Divertors																					
1.3 Direct Convertors & Ends (Mirror)																					
2. Plasma Heaters																					
2.1 Neutral Beams																					
2.2 RF																					
2.3 Lasers																					
2.4 Ohmic Heating																					
2.5 Compression																					
3. Plasma Fueling																					
3.1 Neutral Beams																					
3.2 Gas Blankets																					
3.3 Pellet Injectors																					
3.4 Other (Plasma Beams, Liquid Jets, etc.)																					
3.5 Target Pellets																					
4. Fertile/Fissile Fuels																					
4.1 Metal Alloys																					
4.2 Ceramics																					
4.3 Fluids																					
4.4 Reprocessing																					
5. Fertile/Fissile Fuel Clad																					
6. Blanket Structure																					
7. Coolants																					
7.1 Water (Liquid, Liquid/Vapor, Vapor)																					
7.2 He																					
7.3 Molten Salts																					
7.4 Liquid Metals																					
7.5 Falling Beds, etc.																					
8. Tritium Breeders																					
8.1 Liquids																					
8.2 Solids																					
9. Tritium																					
9.1 Injection																					
9.2 Recovery																					
10. Shields (Magnet, Bulk)																					
10.1 Structure																					
10.2 Bulk																					
10.3 Cooling																					

Fig. 5-1.

Matrix of Materials-Related Issues

6. SUMMARY OF WORKSHOP ON NUCLEAR DATA AND CODES

by

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NUCLEAR DATA & CODES WORKING GROUP

D. J. DUDZIAK, CHAIRMAN

PARTICIPANTS

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G. E. Shatalov, USSR
R. P. Rose, Westinghouse
Noel Amherd, EPRI
Gregory Moses, Univ. of Wisconsin
David Chapin, Westinghouse
G. L. Woodruff, Univ. of Washington
Bruno W. Augenstein, Rand Corp
J. D. Lee, LLL

INTRODUCTION

The Nuclear Data and Codes Working Group met for about two hours on Thursday, 25 January 1979. There was clearly no time for an indepth discussion of any topic within the Working Group's purview, so it was decided to skim lightly over all pertinent nucleonics needs. Of the topics considered, most discussion centered on the appropriateness of performing blanket experiments in the TFTR.

As a starting point, the Working Group used the paper by D. Chapin on "Tokamak Blanket Neutronics Requirements." Also, a draft table of nuclear data needs as devised by a working group at the IAEA Advisory Group on Nuclear Data for Fusion Reactor Technology (18-22 DEC 78), was distributed by the Chairman. The discussions were then structured around four main topics:

1) Methods and Codes
2) Nuclear Data
3) Calculational Benchmarks
4) TFTR Blanket Experimental Possibilities

METHODS and CODES

1. BURN-UP CAPABILITY USING TRANSPORT THEORY.

A concern was expressed by several participants that code systems are required to compute fertile/fissile materials "burn-up" in cases where only transport theory (as opposed to diffusion theory) is adequate to determine neutron flux distributions. While little new basic methods development is required, significant code development effort is necessary. This is particularly true for 2-dimensional (2-D) neutronics models. Presently an ANISN-CINDER link exists at Westinghouse (Chapin) for 1-dimensional analysis. Also, the ORIGEN burn-up code is being placed on the NMFECC computer by LLL (Lee). Discussions revealed that there are still serious limitations to these codes for fusion applications; e.g., do not include n, 3n reactions.

The need to provide a 2-D transport capability, preferably fast running, to an adequate burn-up code, was stressed.

2. RUN TIME FOR 2-D TRANSPORT CALCULATIONS.

A general concern was expressed with the long running times of 2-D transport calculations for multiplying systems. Numbers quoted were "about a factor of 3" longer running than pure fusion calculations, which require only one outer iteration. No firm conclusions or recommendations were arrived at. However, the Chairman noted that TWOTRAN-DA, to be released ∼ Oct 79, is usually a factor of ∼ 4 to 10 times faster than other 2-D transport codes for a variety of fast reactor calculations*, and should show promise of alleviating run-time problems for hybrid calculations.

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*Ref. report LA-UR-79-38 by W. F. Miller <u>et al</u> (1979).

CORE STORAGE and DATA MANAGEMENT.

The Working Group could do little more than identify this problem area as needing attention in 2-D transport codes, as applied to hybrid reactor calculations. Designers are experiencing problems in these areas as related to both the size of problem allowable and the running times. A side discussion ensued as to the feasibility of meaningful neutronics calculations to compare with TFTR module experiments. Several participants voiced the opinion that the codes were inadequate to treat the complexity of such a module, while others pointed to the need to test the codes this way sometime soon.

4. STREAMING

There was a general consensus that 3-D streaming problems can be handled with existing Monte Carlo codes, including toroidal-geometries in the MCNP code (which resides on the NMFECC). Specific difficulties and/or needs for improvement in the Monte Carlo codes were not discussed. It was noted in passing by the Chairman that research in deterministic streaming methods for 2-D S_n codes was just commencing at LASL.

5. TIME-DEPENDENT TRANSPORT

Difficulties with negative scalar fluxes in the TDA code were noted at the Univ. of Wisconsin (Moses). A question remained as to the adequacy of S_n codes (no problems have been identified with TIMEX as applied to pure fusion reactors), and could not be resolved by the Working Group. No problems were identified for time-dependent transport calculations using Monte Carlo methods, which appear adequate.

6. SENSITIVITY METHODS & CODES

A need for cross-section and secondary energy/angle distribution sensitivity studies was agreed upon. The methods for such studies are available, but code development is needed mainly to implement secondary distribution sensitivity theory. No time was available to discuss covariance-data formulation, evaluation, processing, etc. Calculational-methods sensitivity was not discussed at all by the Working Group.

RESONANCE SELF-SHIEDING

Methods in current use were reviewed. They include a probability-table method used successfully with multipgroup Monte Carlo at LLL (Lee, Hanson), but with a caution regarding sensitivity to group structure (Hanson). An alternative method for S_n calculations, using the Bondarenko formalism, has been used successfully in the code systems AMPX at ORNL and MINX and NJOY at LASL*. Good results were found by Westinghouse (Chapin) in applying 27-group Bondarenko factors in analysis of $Th:H_2O$ lattice experiments.

The NJOY-produced MATXS library is at the NMFECC. The AMPX-produced library VITAMIN-C is available from ORNL.

NUCLEAR DATA

A very brief discussion of nuclear data concentrated on needs unique to hybrids. Topics such as activation cross-sections, covariance data, fissile-fuel production cross sections, and even fission-product cross sections were not considered.

The USSR delegate (Shatalov) noted severe deficiencies in secondary-distribution data; e.g., for Pb, Th and other heavy metals. These were discussed in Dr. Shatalov's paper earlier.

The sensitivity of hybrid blanket neutronic parameters to the $\chi(E)$ data for high-energy fission was considered to be an open question. Speculation by some participants was that the effect is not important, especially to integral quantities of current interest in hybrid blankets.

Data for ^{232}Th gamma production are not in ENDF/IV but may be in ENDF/V. An unresolved question remained on this matter, because the Vienna Working Group draft table lists these data as "S" for satisfactory.* Gamma-production data for ^{231}Pa and ^{232}U are in ENDF/V and the multigroup data can be made available on the MATXS file at the MFECC.

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* Note added in report: ^{232}Th gamma-production data are not in the <u>preliminary</u> ENDF/V data, but according to CSEWG sources will be in the final ENDF/V file.

CALCULATIONS BENCHMARKS

The USSR [illegible]talov) uses S_n and Monte Carlo methods of calculation, and Dr. Shatalov feels strongly that benchmarks, experimental and calculational, are necessary for hybrid reactor calculations. Such benchmarks should include some toroidal-geometry configurations.

While no time existed at the Working Group meeting to specifically define appropriate calculational benchmarks, it was agreed that doing so in the near future is extremely important. Accordingly, the Working Group urges participants in future US/USSR Hybrid Reactor Symposia to bring to the meeting a complete written definition of (at first) a 1-D calculational benchmark hybrid-reactor model. Preferably some results for the desired calculated parameters should be included. Specifically, Dr. Shatalov volunteered to document a proposal of one such benchmark for the next US/USSR Symposium.

The term "calculational benchmarks" as used herein means models of hybrid blanket systems, not so-called "clean" integral experiments. The latter class of experiments are also of considerable interest for testing of data and methods, but were not considered under this topic.

TFTR BLANKET EXPERIMENTAL POSSIBILITIES

Considerable discussion occurred concerning the possibilities of performing blanket module integral experiments in TFTR. However, most participants were not familiar with the specific proposal for such experiments until the day of the Working Group meeting. Therefore, difficulties occurred in focusing discussion on technical aspects of potential specific experiments, or in drawing definitive conclusions. However, the Working Group agreed upon the following statement:

STATEMENT ON TFTR EXPERIMENT POSSIBILITIES

Availability of D-T burning in the TFTR in the mid-1980's may provide one important set of opportunities in pure fusion and hybrid fusion-fission systems for integral experiments, for verifications of benchmarking theoretical [illegible] and for added operational experience in realistic problems of blanket module design, engineering, fabrication, diagnostics, and handling; perhaps as a multination effort.

These opportunities with an actual toroidal plasma, complex geometries, and heterogeneous materials can be effectively realized and fully exploited only by accompanying additional intensive programs securing improved nuclear data by employment of simpler, more readily interpretable experiments, by progress in other fusion machine programs, and by continuing development or verification of analysis tools for performance predictions of more realistic blanket modules, tools whose adequacy may be established with additional confidence by TFTR experience.

While it is premature to decide now on the precise form or priority ranking of several possible TFTR blanket module experiments, the TFTR program sponsor should consider authorizing and reserving space for such module experiments, making necessary arrangements for a broad fusion community involvement in early TFTR module design planning and experiment scheduling, providing for maximum module experiment flexibility and for appropriate system upgrading, and setting up mechanisms by which the essential concurrent efforts noted above can be fully utilized.

An ambitious common goal of these parallel complementary streams of research and engineering efforts should be the gathering of significantly higher confidence in design and performance engineering knowledge, substantially facilitating construction of ETR-scale machines for both pure fusion systems and hybrid system development.

7. SUMMARY OF WORKSHOP ON BLANKET ENGINEERING DEVELOPMENT REQUIREMENTS

by

K. R. Schultz

General Atomic Company
San Diego, California

[illegible] FUSION-FISSION REACTORS
[illegible], January [illegible], 1979
[illegible] - Chairman

7. ENGINEERING DEVELOPMENT REQUIREMENTS WORKSHOP

1. [illegible]

The purpose of this workshop was to discuss the blanket engineering [illegible] requirements of [illegible] one of three parallel [illegible]. The other two were concerned with blanket neutronics development requirements, [illegible], and blanket materials development requirements, chaired by R. Krakowski of LASL. The discussions were focused on the engineering aspects of blanket development requirements such as thermal-hydraulics, mechanical design, stress analysis, systems engineering and systems integration to avoid overlap with the neutronics and materials development requirements discussions. It was found that these three areas are not really separable and many of the engineering development requirements are, in fact, related to neutronics or materials development needs.

The three blanket workshops jointly discussed the proposal for hybrid blanket module tests in TFTR presented by D. Jassby of PPPL. The three groups then separated and discussions in this workshop on engineering development requirements focused on the blanket engineering questionnaire sent out prior to the symposium. The questionnaire was returned before the workshop discussions and the results therefore do not necessarily reflect consensus developed during the workshop.

2. TFTR Hybrid Module Test Proposal

The TFTR Hybrid Module Test proposal presented earlier in the day by D. Jassby of PPPL was discussed jointly with the other two blanket development requirement workshops. There appeared to be considerable enthusiasm

[illegible]

[illegible]

3. Engineering Development Requirements

The results of the blanket engineering development requirements questionnaire are shown in Table 1. The questions posed and responses received, [illegible] this question area dominated the workshop.

3.1 Development Requirements. The point was made by [illegible] Institute, and generally agreed to by all, that it is difficult or even impossible to specify generic blanket development requirements since the blanket designs depend strongly on the driver operating regime and the chosen role of the hybrid (i.e., fuel vs. energy production). He suggested that the four driver regimes discussed in the Blanket Design Workshop on Wednesday could be used to further refine and separate blanket development requirements as each regime is expected to have unique development concerns. It appeared to be the consensus of the workshop that although the question on blanket development requirements was well intended and a good start on trying to define and prioritize development requirements, significant improvement, catagorization and expansion of the questionnaire would be [illegible] significant development [illegible] alternatives [illegible] [illegible] with [illegible]

The [illegible] to the question on blanket testing [illegible] is shown in Table 1. Subject to the caveat above, the workshop generally agreed that [illegible] significant need for development in the areas of first wall, fuel [illegible] irradiation behavior, blanket design work, remote maintenance, [illegible] It was noted that all blanket types require core [illegible] work [illegible] these [illegible] significantly more than [illegible] of [illegible] suggested that [illegible] requirements [illegible] separated by venue, that is, [illegible] facilities required. [illegible] addressed by out-of-pile work, [illegible] would need at least fission reactor irradiation tests, and [illegible] require a fusion hybrid test reactor to accomplish. A consensus was [illegible] at by the group and is noted in Table 1.

The statement was made by R. Moir of LLL and supported by J. Maniscalo of Exxon and K. Schultz of GA, that materials demands in hybrids should be less than those of pure fusion or fast breeder fission reactors because of lower fluence requirements than fusion and lower burnup requirements than fast breeders. J. Chi and J. Kelly of Westinghouse cautioned that the hybrid, however, has extra degrees of freedom and the design choices and tradeoffs are more diverse, complex and difficult. J. Maniscalo of Exxon suggested that because the hybrid can potentially provide fuel to a large number of relatively inexpensive fission burner reactors, it can perhaps afford to use blanket design options that are not pushed to their limits to obtain optimum performance.

There was strong input that the best way to proceed with hybrid blanket design is to do some power module tests. It appeared to be the consensus of the workshop that we need to choose several blanket options for further development and get on with design, construction and testing rather than just continue to study the problem in an abstract way.

[illegible] Development needs, by individuals in the [illegible] the following (random order):

- Irradiation of [illegible] and Th
- [illegible]/metallic compatibility
- [illegible] stainless steel compatibility
- [illegible] techniques and data
- [illegible] fertile material and lithium [illegible]
- [illegible] blanket design
- [illegible] designs to satisfy near-term designs
- Seal designs for reliable remote vacuum and pressure seals
- Safety evaluations and comparison
- Consideration of interaction with E&B fields
- Blanket instrumentation designs
- Fast fission high power density cooling designs
- Plus a physics confirmation that the driver will work!

[illegible] Next Development Steps. The blanket engineering development questionnaire results shown on Table 1 indicate strong support for [illegible] design and analysis of selected concepts followed by hybrid module experiments. The workshop expressed caution in that the question is loosely worded and does not ask for prioritization of the response. The consensus of the workshop, however, supported the results shown in Table 1, question [illegible].

There was strong support from the ICF representatives for the suggestion by [illegible] of Kurchatov that experiments in fast pulse fission reactors could contribute significantly to the development of ICF blanket designs.

Specific suggestions by individuals in the workshop included the following (random order):

- Develop a hybrid blanket development plan
- Start now on long lead time activities
- A TFTR test module
- Liquid lithium test loops
- Shiva/Nova module tests
- A hybrid module test facility to build and test modules (out-of-pile)
- Fast spectrum neutronics benchmark experiments
- A hybrid Engineering Test Facility (HETF) for in-pile testing
- Test hybrid modules in the Large Coil Test Facility or in TFTR to observe impact of E&B fields
- Proceed with out-of-pile tests to narrow the field of candidates

3. Closing Comments

The workshops on hybird blanket development appear to have taken the initial steps towards formulating a consensus from the energy research and development agencies, the hybrid design community, and the electric utilities on some of the steps that need to be taken as part of a hybrid reactor development program. Although further work, further interaction, and further discussion will be needed to develop and clarify this consensus, these initial steps are a necessary and noteworthy event.

TABLE 1

3rd US/USSR SYMPOSIUM ON FUSION-FISSION REACTORS
BLANKET ENGINEERING DEVELOPMENT QUESTIONNAIRE RESULTS

1. What are the development requirements for your preferred blanket? Indicate "developed" if you feel sufficient information is available from the fission program or elsewhere to proceed with reasonable confidence, "being developed" if the needed information is expected to be provided by an existing program or "needs development" if work will have to be done specifically for hybrids.

Development Requirements	Developed	Being Developed	Needs Development	[illegible]*
Fuel Fabrication	71	--	29	
Fuel Irradiation Capability	6	18	76	[illegible]
Fuel Reprocessing	59	6	[illegible]	[illegible]
Fuel-Clad Interaction	41	6	41	[illegible]
Clad Irradiation Capability	18	6	76	[illegible]
Clad-Coolant Interaction	35%	12%	53%	[illegible]
Coolant Chemistry	47%	18%	41%	[illegible]
Coolant Thermal-Hydraulics	47%	6	[illegible]	[illegible]
Blanket Designs	6	6	[illegible]	[illegible]
Remote Handling and Maintenance	18	--	82	
Power Conversion System	76	6	24	O
Waste Handling and Disposal	47%	6%	47	O
Safety Aspects	18	6	76	O

*O = Out-of-Pile, F = Fission reactor, H = Hybrid reactor.

2. What are the logical next steps for hybrid reactor blanket development?

1. Further scoping and exploratory studies	44%
2. More detailed blanket design and analysis of selected concepts	83%
3. Irradiation experiments in fission reactors	50%
4. Hybrid modules in T20 or TFTR	61%
5. Hybrid modules in ETF	61%
6. A hybrid ETF	44%