1999 Fusion Summer Study
Energy Issues Working Group Subgroup B
Development Path Issues

Overall Summary

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Major Objectives and Organizing Principles

Some of the major objectives and organizing principles of this subgroup's discussion were:

1. The discussions in this subgroup fell in the intermediate ground between today's fusion status and experiments and the ultimate vision of a fusion reactor. We focussed on the problems of fusion energy development that might be taken up in the next 20 years.

2. The discussions were intended to provide an educational opportunity for the attendees to look longer term at what has to be done to actually move to fusion energy. The tasks that must be undertaken tend to evolve from today's largely scientific investigations to eventually nuclear technology issues.

3. The meetings were organized so that MFE and IFE people were able to discuss matters together and educate each other. This objective was largely met.

4. The meetings were organized so that everyone was able to hear every presentation and to discuss all the same questions.

5. The focus of the first two days was on overall forward looking roadmaps and the general issues of fusion development that lie ahead, in order to provide framework material for the second two days.

6. The second two days were devoted to discussions of specific machine proposals, examining them for what contributions they can make to fusion development and what research is needed to move them forward.

The prospectus for this subgroup's activities and the reading list of reference materials and background papers are included in the overall report of this group on the CD-ROM and can be found on the Web by following the trail: Energy Group Website, Hot Topics B, Prospectus, Reading List (http://fusion.gat.com/snowmass/energy/subgroup-b/reading-list-b.html

Overall Plan of First Week

	Tuesday July 13	Wednesday July 14	Thursday July 15	Friday July 16
First Half Session (starts1:30 PM)	Plenary Roadmaps, Generic Development Issues Framed	Plenary Discuss generic development issues	Plenary Specific Device Presentations 6 presentations	Plenary Specific Device Presentations 5 presentations
Break	3:20 – 3:35 PM	3:20 – 3:35	3:20 – 3:35	3:20 – 3:35
Second Half Session (ends 5:30 PM)	Plenary Discuss generic development issues	Plenary Discuss generic devopment path issues and roadmaps	Plenary Discuss above presentations	Plenary Discuss above presentations

Roadmaps

In the first session, Tuesday, July 13, in order to set some overall framework for the discussion of the generic issues of fusion development, review of existing roadmaps for fusion development over the next 20 years were given. J. Lindl gave a review of the IFE roadmap as recently developed by the IFE community and presented to FESAC and SEAB. G. Navratil gave a review of the MFE roadmap as it has emerged from the Madison forum and has been presented to FESAC and SEAB. R. Stambaugh presented a plan for a strong role for the spherical torus in MFE development. These presentations are represented in the summary set of files by either the transparencies used or papers which contain the speaker's essential content.

Issues of Fusion Development

The session convenors presented an introduction to the main issues of fusion development which were to be discussed in the subsequent sessions. Those issues are listed below immediately followed by the answers reached during discussion.

Q1) Burning Plasmas: Ignition and/or High Gain.

What is the importance of ignition/burn/high gain scientifically? What do we need to learn from a burning plasma experiment?

What is the importance of achieving ignition or burn in a larger sense? Must we demonstrate ignition to move fusion forward or should be look further ahead to the challenges of high time averaged power and neutron fluence? Participants in this discussion should be prepared to address these questions and to help hone the issue list below so we can well articulate the "yearn to burn."

MFE and IFE colleaques should be prepared to educate each other on the somewhat different burning plasma issues and objectives of their approaches.

Q1-MFE MFE BURNING PLASMA ISSUES AND QUESTIONS

Properties of DT plasmas (Isotope effects)
Confinement of alphas
Alpha heating
Alpha driven instabilities
Profile control in alpha heating dominated plasmas
Alpha heating effects on self-driven currents
Particle and power exhaust in alpha dominated plasmas (esp. He exhaust)
High gain burn control

WHY IS AN MFE BURNING PLASMA EXPERIMENT IMPORTANT?

This question was discussed in both the Energy Subgroup B in the afternoon sessions and the Burning Plasma subgroup of MFE Concepts in the morning sessions. The two groups reached agreement on supporting the following statements:

The excitement of a magnetically-confined burning plasma experiment stems from the prospect of investigating and integrating frontier physics in the areas of energetic particles, transport, stability, and plasma control, in a relevant fusion energy regime. This is fundamental to the development of fusion energy.

Scientific understanding from a burning plasma experiment will benefit related confinement concepts, and technologies developed for and tested in such a facility will benefit nearly all approaches to magnetic fusion energy.

FRONTIER PHYSICS TO INVESTIGATE AND INTEGRATE IN A SELF-HEATED PLASMA

- **Energetic Particles**
  - Collective alpha-driven instabilities and associated alpha transport.
- **Transport**
  - Transport physics at dimensionless parameters relevant to a reactor regime (L/r_i)* scaling of microtubulence, effects on transport barriers…
- **Stability**
  - Non-ideal MHD effects at high L/r_i: resistive tearing modes, resistive wall modes, particle kinetic effects…
- **Plasma Control**
  - Wide range of time-scales: feedback control, burn dynamics, current profile evolution
- **Boundary Physics**

  Power and particle handling, coupling to core

***L/r_i is the system size divided by the Larmor radius.**

SCIENTIFIC TRANSFERABILITY

A general statement agreed to by the Energy Subgroup B in the afternoon sessions and the Burning Plasma subgroup of MFE Concepts in the morning sessions on the subject of how transferable the results of a burning plasma in one concept are to another concept follows:

A well-diagnosed, flexible burning plasma experiment will address a broad range of scientific issues and enable development and validation of theoretical understanding applicable in varying degrees to other magnetic fusion concepts

- Energetic particle density gradient driven instabilities
- Transport and burn control techniques
- Boundary Physics, power and particle handling issues

The Energy Subgroup B took up separately the question of how generic would the results from a tokamak burning plasma experiment be to other magnetic confinement approaches. The bottom line question was whether the achievement of some particular result in the tokamak would allow not building a separate burning plasma experiment in another concept. The status and expectation in regard to various burning plasma issues are summarized in the table below. As one proceeds down in the table, one moves from single particle physics to collective plasma physics effects. The last column reflects the views of Energy Subgroup B on how generic the results would be.

Burning Issue	Status, Expectation	Generic if Done in Tokamak?
DT Plasma Issues (Isotope Effects)	Varied results in TFTR and JET have plausible explanations.	Generic to other concepts
Alpha Transport and Slowing Down	Classical in TFTR and JET. Classical expectation	Generic to other concepts
Alpha Heating	Detected in TFTR and JET. Expected to be classical. Needs to be done Q>5.	Generic to other concepts
Alpha Driven Instabilities	Seen in TFTR and JET but no large effects.	The physics would be largely generic if the theory were confirmed in a tokamak.
Power and Particle Exhaust	Alpha ash behaves like thermal He. Hence one needs to understand reactor regime particle transport in general.	Generic to extent each concept understands its particle transport.
Reactor Plasma Transport	The need is to measure transport in reactor scale regimes and to use alpha heating to reach those regimes.	Generic in Tokamak and ST. Other concepts need burning plasma experiment.
High Gain Burn and Profile Control	Exciting challenge-Dynamics and interaction with thermal plasma transport and stability properties.	Generic in Tokamak and ST. Other concepts need burning plasma experiment.

TECHNOLOGY TRANSFERABILITY

The Energy Subgroup B also interacted with the Technology Groups meeting in the afternoon to examine the question of the transferability of technology results from a burning plasma experiment in one concept to another concept and the technology reasons for mounting burning plasma experiments. The technology reasons for burning plasma experiments depended a great deal on the pulse length of the burning plasma as shown in the table below. The Groups supported the following strong conclusion about technology transferability:

"The technologies developed for burning plasma experiments are in general applicable to all other magnetic fusion concepts and future magnetic fusion power systems."

AS BURNING PLASMAS MOVE TOWARD STEADY-STATE, THEIR TECHNOLOGY MOVES TOWARD FUSION ENERGY

Technology **Pulse Length**

Technology Developed	10 s	1000 s	Steady-state
Auxiliary Heating and Current Drive	+	+ + +	+ + +
Magnets	+	+ + +	+ + +
Plasma Facing Components	+	+ +	+ + +
Fueling and Exhaust	+	+ + +	+ + +
Remote Handling	+	+ +	+ + +
Materials	+	+ +	+ + +
Safety and Licensing			+ + +
Tritium Handling and Breeding	+	+ + +	+ + +

+ = Initial Work, ++ = Partial development, +++ = Complete development

BURNING PLASMA OPPORTUNITIES

The Energy Subgroup B in the afternoon sessions and the Burning Plasma subgroup of MFE Concepts in the morning sessions agreed on the following statements about burning plasma opportunities:

1. Burning plasma experiments are essential to the development of fusion.

2. The tokamak is technically ready for a high gain burning plasma experiment.

3. The US should actively seek opportunities to explore burning plasma physics by:

   (i) Pursuing burning plasma physics through collaboration on potential international facilities (JET Upgrade, IGNITOR and ITER-RC)

   (ii) Seeking a partnership position, should ITER-RC construction proceed

   (iii) Continued design/studies of moderate cost burning plasma experiments (e.g., FIRE) capable of exploring advanced regimes

   (iv) Exploiting the capability of existing and upgraded tokamaks to explore and develop advanced operating regimes suitable for burning plasma experiments.

Q1-IFE IFE BURNING PLASMA ISSUES AND QUESTIONS

Driver requirements (energy, pulse shape, uniformity)
Central ignition, Propagating burn, Fractional burnup
Gain, and its relation to driver efficiency and type

Q: To what extent must the issues below be answered for each different driver and target type in IFE? How generic are the results from NIF?

Concensus Answer: NIF will be able to do both direct and indirect drive. Different targets (with different expected gains) will be studied for laser and heavy ion direct and indirect drive. Because of this wide coverage, the burn physics from NIF will be generic to laser indirect and direct drive and heavy ion beam indirect drive. The exception is heavy ion direct drive. Without the exception, the NIF for burning plasma issues and the IRE for driver and chamber issues will provide an adequate basis to proceed to an ETR.

Q: What is meant in IFE by ignition, propogating burn, etc?

Answer: The driver creates a hot spot. Ignition means that hot spot propogates outward into the surrounding cold fuel and burns up as much fuel as is consistent with the dissassembly time of the target. (Typical fractional burnup is 20-30%). The burn physics event that will result in an important announcement from NIF will be Q = 1, defined as fusion energy divided by laser energy.

IFE INTEGRATED RESEARCH EXPERIMENTS (IREs)

- The IRE is a Program which includes chamber development and target fabrication and injection, as well as a driver. The IRE is the primary Performance Extension step in the IFE roadmap.

- Success in NIF and the IRE Program will be sufficient to proceed with the Engineering Test Facility (ETF).

- Candidate IRE driver concepts are heavy ion, diode pumped solid state lasers (DPSSL), and KrF lasers.

- IREs include tests of beam propagation through simulated chamber conditions and intercepting targets at high rep-rate (5-10 Hz).

ENGINEERING TEST FACILITY (ETF) FOR IFE

- The ETF is the primary Fusion Energy Development step on the IFE roadmap
- The ETF integrates all major systems needed for an IFE power plant (driver, chamber target production and injection, fusion chamber, and heat removal system)
- Objectives of the ETF demonstration of driver efficiency, high rep-rate operation, with capsule yields of 20-30 MJ with possible exporation of higher gain and yield.

AN ISSUE LEFT UNRESOLVED

The timing of initiation of the IRE with respect to NIF results.

Wait for NIF Results	Proceed in Parallel
• The timing of initiation of the IRE should be keyed to some initial results on NIF. • These results will validate the viability of IFE, for at most a 2-3 year delay. • Success on NIF would provide the financial support to pursue the IRE. • Results on NIF could affect the choice or metrics for the IRE driver(s).	• The IFE roadmap has a balanced porfolio of research elements at a reasonable cost. The plan requires results from NIF and the IRE to make the ETR decision. • Serializing the IFE efforts unreasonably delays the resolution of key issues. • The NIF and the IRE will work together to resolve the key issues for IFE.

The Challenge of Steady-state and High Time Average Power.

IFE High Time Average Power Issues
First wall and optics protection
Chamber clearing between shots
High rep-rate drivers (KrF, DPSSL, HIB)
Low cost target production and high rep-rate target insertion
Problems of heat removal

These issues are more pressing than burn issues for the ultimate success of IFE. Unfortunately, the group did not get to discuss these issues.

MFE High Time Average Power Issues
Non-inductive current drive and profile control in devices with current
Is a pulsed magnetic system acceptable?
Stellarators
The problems of fluence, erosion and codeposition
Problems of operational boundaries (e.g. disruptions)
Problems of heat exhaust (both MFE and IFE)

MFE HIGH TIME AVERAGE POWER ISSUES

The discussion revolved around:

1) whether the burning plasma experiment should be based on conventional or AT tokamak physics,
2) the extent to which AT physics should be explorable in the burning plasma experiment,
3) and whether it was more important to first achieve a steady-state AT tokamak and then take the burning plasma step with that AT.

The group reached concensus that:

A burning plasma experiment should be capable of Advanced Tokamak Research.

Proving a resolution of the disruption issue, providing adequate pulse length for blanket development, and providing enough fluence to surfaces to study the erosion, redeposition, and tritium retention problem requires a true steady-state machine that can have several hour to day long pulses at least and with a reasonable duty factor. JT-60SU has a plan for true steady-state operation, but a limited DT operation. Steady-state operation with high neutron wall loads has been proposed for an ST device in either VNS or FDF facilities. Maximum pulse lengths expected are 1 hour in LHD and W7-X and at low duty factor. ITER-RC may be able to pulse about one hour with a reasonable duty factor. KSTAR and HT-7U will have pulses in the 300 second range.

Q3) Nuclear Technology Development

These questions are largely common to MFE and IFE and can be profitably discussed together.

What is our plan to develop blanket technology?
What are the limits on MW/m^2 of neutrons or heat at the first wall?

How are we going to survive neutron damage? Typical fusion systems project the need to change the blanket components every two-four years.

Do we need both a point neutron source and a volume neutron source? Should we plan to learn by doing, e.g build and deploy blankets on a suitable source?

How important are low activation materials and how will we introduce them?

What do the MFE and IFE roadmaps envision for Tritium usage in the various stages of development? When must fusion energy make the transition from external Tritium supply to self-sufficiency?

How are we going to get an overall system TBR > 1? What are the Tritium inventory centers in MFE and IFE systems?

The group did not get to discussing these issues.

PRESENTATION AND DISCUSSIONS ON SPECIFIC DEVICE PROPOSALS

Thursday 7/15

D. Meade	FIRE
C. Gormezano	JET Upgrades
R. Stambaugh	ST in a Fusion Development Facility
R. Bangerter	IRE (introduction & HIB driver)
J. Sethian	IRE (KrF driver)
H. Powell	IRE (DPSSL driver)
W. Meier	IFE Engineering Test Facility

Friday 7/16

R. Parker	ITER-RC
K. Thomassen	Steady-state Tokamaks
N. Ohyabu	Stellarator
W. Hogan	NIF, LMJ, and Japan's ICF program
L. Sugiyama	Ignitor

The transparencies and/or papers containing the views of the above authors are included in the record of Energy Subgroup B for the Snowmass meeting.

IFE Development Roadmap - Summary

- Current development strategy is based primarily on two approaches
  - Indirect-drive targets driven by ion beams with a liquid wall chamber
  - Direct-drive targets driven by lasers with dry wall chambers

- Future development could change these combinations or concept exploration level ideas (e.g., fast ignitor or z-pinch) could prove superior

- Metrics and goals are being established for advancement to each successive level of development. Competitive COE for power plants and affordable development steps are essential.

- There is high confidence that predicted target performance will be achieved on NIF.

IFE Integrated Research Experiments (IREs)

- The IRE is the primary Performance Extension step in the IFE roadmap
- It is argued that NIF results plus successful IRE plus success in chamber and target technology programs will be sufficient to proceed with the Engineering Test Facility (ETF)
- IRE concepts for heavy ion, diode pumped solid state lasers (DPSSL), and KrF lasers were presented
- Total IRE beam energy is based on characteristics of particular driver technology – need demonstration technology to allow scale up to ETF driver
- IREs include tests of beam propagation through simulated chamber conditions and intercepting targets at high rep-rate (5-10 Hz)

ENGINEERING TEST FACILITY (ETF) FOR IFE

- The ETF is the primary "Fusion Energy Development" step on the IFE roadmap
- The ETF integrates all major systems needed for an IFE power plant (driver, chamber target production and injection, fusion chamber, and heat removal system)
- Objectives of the ETF demonstration of driver efficiency, high gain, high yield, high rep-rate operation, and safety.

THE ETF CAN BE A COST EFFECTIVE STEP IN DEVELOPMENT OF IFE

- 1-2 MJ driver may be adequate
- Single driver used to optimize target designs and test one or more chamber designs
- Chambers can be tested at small scale (10% of full-scale cost)
- Heat transfer components tested at 10% of full scale, electric power production not necessary
- Target technologies continue to leverage off ICF Program where possible

NIF, LMJ, AND JAPAN'S ICF PROGRAM

- NIF in the US, LMJ in France and Japan's ICF program are oriented toward target physics and based upon the same Nd:glass laser technology
- NIF with 192 beams and LMJ with 240 have same performance specifications
- Target ignition and gains of 1-10 are the goals of both NIF and LMJ
- Japan's program is not likely to seek larger machine until after NIF and LMJ succeed
- Experimental program for IFE on NIF will include:
  - loci of gain curves for a variety of target types
  - gain degradation vs manufacturing and driver specifications
  - studies of first wall materials for ETF
- NIF also requires development of technology and manufacturing techniques that makes solid state lasers more credible as an IFE driver
- Controversial issue raised during discussion: should IFE roadmap show commitment to IRE's before or after ignition is achieved on NIF — what info will NIF give that will affect design of IRE's?

NEXT STEP OPTIONS FOR MAGNETIC FUSION ENERGY DEVELOPMENT

- **THREE GENERAL CLASSES OF MFE STEPS WERE DISCUSSED:**
  - + **Burning Plasma Devices**

    ITER-RC, FIRE, IGNITOR, DTST, JET-Upgrade
  - + **Long Pulse Æ Steady-State Devices**

    LHD, KSTAR, JT-60SU, ITER-RC, ST-VNS, FIRE
  - + **Nuclear Technology Devices**

    ITER-RC, ST-FDF
- **THE FOLLOWING 5 QUESTIONS WERE DISCUSSED FOR EACH:**
  1) **Technical issues addressed by each step? What critical issues are not addressed?**
  2) **Technical risk and schedule and is this schedule achievable? What supporting work is required?**
  3) **Opportunity to reduce the development cost?**
  4) **Opportunity for significant international participation?**
  5) **If successful, position to move to next step beyond?**

BURNING PLASMA DEVICES

	Q	τ_{pulse}	SS	ρ^*/ρ^*_r	β/β_r	Cost
JET-U	2	10 s	< skin-time	3	1	0.1 B$

- Can be pursued in next few years
- Will not explore regime of strong self-heating

	Q	τ_{pulse}	SS	ρ^*/ρ^*_r	β/β_r	Cost
DTST	$1 \rightarrow 10$	60 s	> skin-time	1	1	~0.5 B$

- Start of sequence of ST steps towards VNS and/or FDF
- Requires successful PoP results from NSTX (2003-2004)

	Q	τ_{pulse}	SS	ρ^*/ρ^*_r	β/β_r	Cost
IGNITOR	$10 \rightarrow \infty$	5-10 s	~ skin time	2	< 1	~0.5 B$

- Design complete and based on present tokamak physics
- Base regime is low-β aimed away from AT plasma & has no divertor

	Q	τ_{pulse}	SS	ρ^*/ρ^*_r	β/β_r	Cost
FIRE	$5 \rightarrow \infty$	20 s	> skin-time	2	1	~1 B$

- Base performance uses existing tokamak physics basis
- Pulse extension beyond 20 s at $Q \geq 5$ may be possible
- May require AT data to design PB/AT operating mode (2003-2004)

	Q	τ_{pulse}	SS	ρ^*/ρ^*_r	β/β_r	Cost
ITER-RC	$5 \rightarrow \infty$	500 s	Yes	1	1	~4 B$

- Complete integration of BP physics, long-pulse, and technology
- Has capability to explore AT in Steady-State with $Q \geq 5$

LONG PULSE → STEADY-STATE DEVICES

	τ_{pulse}	SS	ρ^*/ρ^*_r	β/β_r	Cost
LHD	20 s → 1 hr	~ skin-time	3	0.5	~1 B$
• Superconducting stellarator operating now					
KSTAR	20 → 300 s	> skin-time	3	1	~0.5 B$
• Will explore AT regime in long pulse H and D plasma					
• Presently under construction; first plasma in 2002-2003					
JT-60SU	> 50 s	Yes	2	< 1	~2 B$
• Near-reactor regime AT physics in SS DD plasma					
• Full complement of current-drive profile control tools					
ITER-RC	500 s → 1 hr	Yes	1	1	~4 B$
• Base performance uses existing tokamak physics basis					
• Capability for SS in AT plasma with DT at $Q \geq 5$					
ST-VNS	1000s → SS	Yes	1	1	~1 B$
• Requires ST physics basis including BP physics base					
• Test materials, blankets at moderate neutron fluence					
FIRE	20 s	> skin-time	2	1	~1 B$
• Aimed at exploration of AT physics in DT at $Q \geq 5$					

NUCLEAR TECHNOLOGY DEVICES

	τ_{pulse}	SS	ρ^*/ρ^*_r	β/β_r	Cost
ITER-RC	500 s → 1 hr	Yes	1	1	~4 B$

- Base performance uses existing tokamak physics basis
- Complete integration of BP physics, long-pulse, and technology
- Can support tests of heat extraction and tritium blanket modules at about 1 MW/m^2 neutron flux
- Capability for SS in AT plasma with DT at $Q \geq 5$

	τ_{pulse}	SS	ρ^*/ρ^*_r	β/β_r	Cost
ST-FDF	1000s → SS	Yes	1	1	~1 B$

- Requires ST physics basis including BP physics base
- Complete integration of BP physics, long-pulse, and technology
- Can support tests of heat extraction and tritium blanket modules
- Aimed at 8 MW/m^2 neutron flux for materials testing

Summary
Energy Development Path

- The IFE Program is presently engaged in Proof-of-Principle Research on various drivers. IFE will carry out its burning plasma research on the NIF and plans to carry out its high time-average power research in an Integrated Research Experiment Program comprised of high rep rate driver, chamber, and target research.

- Research in MFE is presently carried out with a portfolio of concepts extending up to the Performance Extension stage. MFE has opportunities to carry out its burning plasma research in either an integrated or pulsed tokamak experiment, its steady-state research in long pulse tokamaks and stellarators, and its nuclear technology development in an integrated tokamak experiment or the spherical torus.