Summary Report of the Energy Issues Working Group

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1999 Fusion Summer Study

July 12-23, 1999, Snowmass, CO

Energy Working Group Web Site: http://aries.ucsd.edu/snowmass

Energy Issues WG has Two Subgroups

- **Subgroup A**: “Long-term Visions for Fusion Power”
  - Convenors: Jeffrey Freidberg,, Bill Nevins,
    John Perkins, **Don Steiner**

- **Subgroup B:** “Range of Steps Along Development Paths, Options, Directions, Accomplishments, & Decision Criteria”
  - Convenors: Wayne Meier, Gerald Navaratil,,
    Ron Stambaugh, Ned Sauthoff

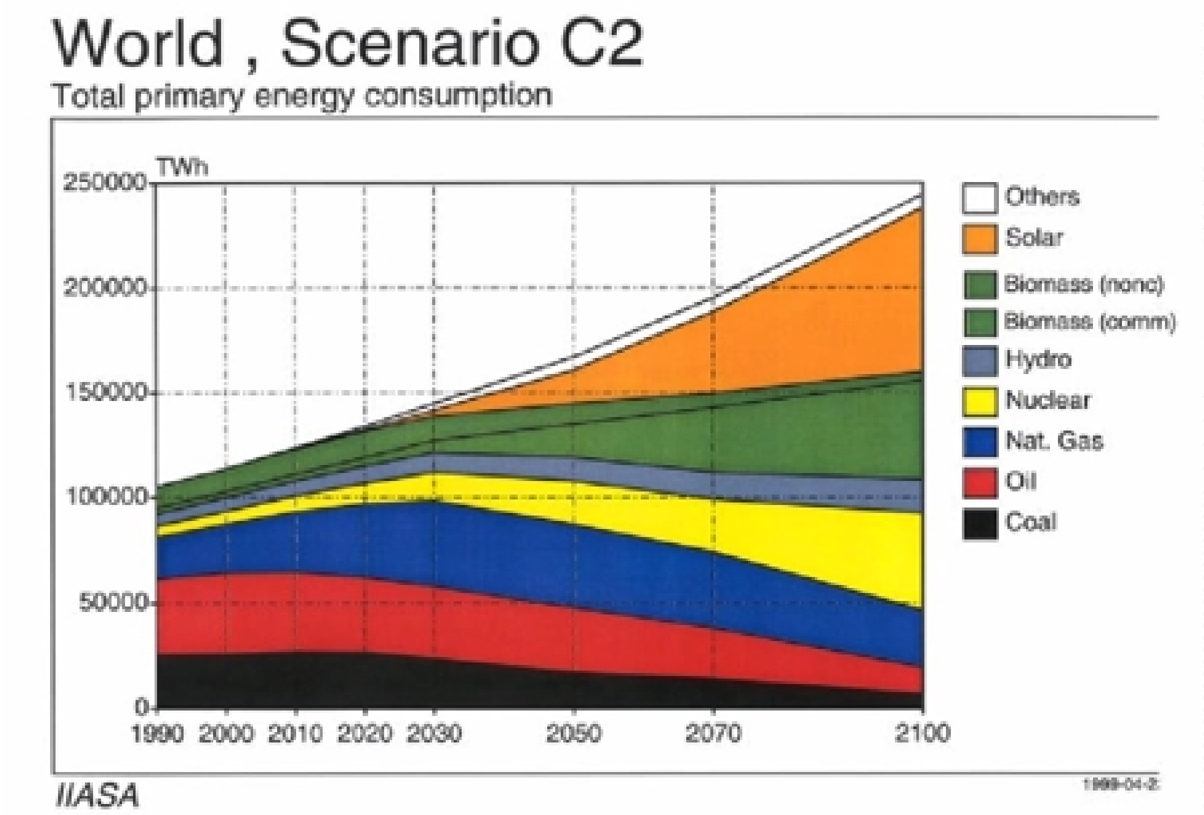
Subgroup A: "Long-term Visions for Fusion Power"

- What is the projected market for electrical energy production in the next century?
- What is Fusion's Potential for penetrating the energy market in the next century?
- Is there a potential role for advanced fusion fuels?
- What is Fusion's potential for applications other than conventional power plants?

Fusion Introduction into Energy Market

Observations:

- To meet the projected growing demand of electricity and to stabilize CO_2 concentration in atmosphere in 2050 and beyond, a large number of new power plants are required.



- This represents an opportunity for fusion energy development.

Opportunities for Fusion Development

- Our program strategy should continue to focus on scientific achievements and measured progress toward fusion energy goal.
- Moreover, we should also strive to gain broad acceptance of a plan to introduce commercial fusion energy by 2050 in order to be taken seriously by energy planners and forecasters.

Achieving the Safety and Environmental Potential of Fusion is Essential to its Competitiveness*

Metric	**Goal**
Cost of Electricity	5-6 c/kWh (1998$)
Accident dose limit	No public evacuation (<1 rem at site boundary)
Rad. Waste disposal criterion	Class C or better
Fuel cycle closed on site	Yes
Atmospheric pollutants (CO_2, SO_2, NO_X)	Negligible
Occupational dose to a worker	< 5 rem/yr
Capacity factor	> 80%
Major unscheduled shutdowns	< 0.1 per year

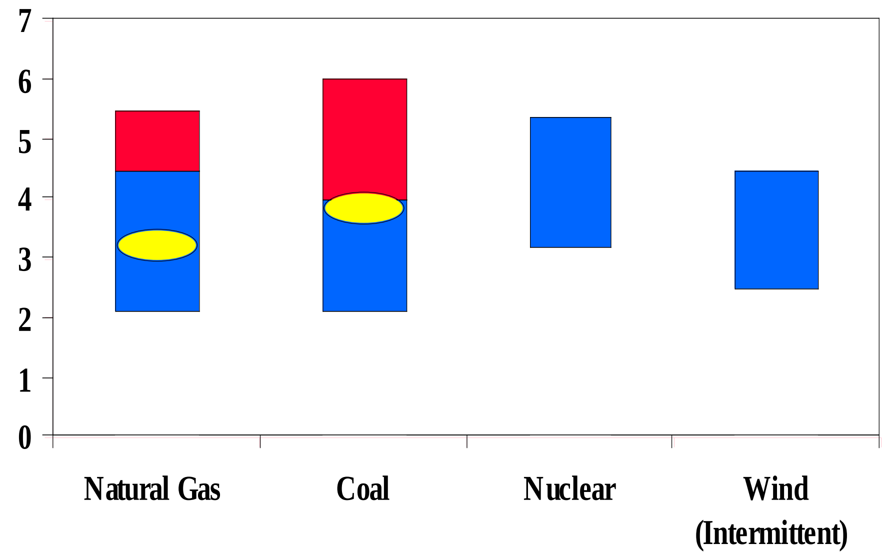
* FESAC Panel on program balance, metrics, and goals (draft report).

Projected COE for Future Energy Sources

Observations:

- Future energy sources (C-sequestered fossil, fission, ...) projected to be in the COE range 3-6 c/kWh.
- Design studies show that fusion can compete if its full safety, environmental, and waste potential is realized.
- Fusion development should continue to pursue physics, engineering, & technology improvements/innovations to further reduce projected COE

Estimated range of COE for 2020
EPRI Electric Supply Roadmap (1/99)



Impact of $100/ton carbon tax.

Other Estimates from Energy Information Agency Annual Energy Outlook 1999.

Fusion Power Plant Attractiveness, Technical Risk, and Balance

Observations:

- Tokamaks could lead to an attractive power plant.
- Stellarator, ST, and IFE concepts could also lead to attractive power plants, but at this point, are behind in demonstrated performance.
- Emerging concepts may lead to improvements in power plant attractiveness but they should be evaluated mainly on the basis of physics credibility.

Opportunity/Issue:

- It is too early to narrow down to one option and a balanced program is essential.
- As concepts move through the stages of development, power plant attractiveness and development cost and time frame, should be an

Advanced Fuels (D-^{3}He)
Summary of Assessment, Issues, & Opportunities

Issue	**Metric**	**Goal**	**Opportunities**
Energy confinement	$n_e \tau_E T$	~10^{23}keV-s/m^3	To be addressed by Physics program
α/p -ash	τ_p^* / τ_E	≤ 3	"
Power density	βB^2	? 12 T^2	"
Synchrotron radiation	Power loss fraction	<< fusion power	Develop tools for accurate calculation
Safety & environment	Activation	Reduced waste volume	Build on ongoing engineering efforts
Operation	Radiation lifetime	Plant lifetime	"
Direct conversion	Efficiency	60%–70%	Small-scale tests
^{3}He fuel supply	Accessibility & cost	$500/g	〈 Lunar mining 〈 Breeding

Advanced Fuels (D-^{3}He)
Summary of Assessment, Issues, & Opportunities

Challenges:

- Large physics extrapolation with respect to DT fuel:
  (factors of ~ 50 in $n_e \tau_E T$, ~5 in βB^2, and ~2-5 in τ_p^* / τ_E)
- Large heat flux on in-vessel components and/or efficient direct conversion.
- ^{3}He fuel supply.

Potential advantages:

- Reduced waste volume.
- Plant-lifetime components

Opportunities:

- Promising physics embodiments need to be demonstrated.

Several Non-Electric Applications Have Been Proposed

- **Neutron sources for fusion-fission applications**
  (Breeding of ^{233}U, Burning of Pu and other actinides, Burning of depleted Uranium)
  - Fusion embodiment: Low Q (~1-5), CW or high duty factor, approaching power-plant technology (tokamak & ST)
  - Metrics: 1) Cost of neutrons, 2) Neutron spectrum effectiveness, 3) k_{eff}
- **Use of process heat for co-generation (e.g., hydrogen production)**
  - Fusion embodiment: Large output power plants
- **Deep-space propulsion applications**
  - Fusion embodiment: Large power output (1-8 GW), advanced fuel (D-^3He), ST, FRC, and other emerging concepts.
  - Metrics: 1) Specific impulse (exhaust velocity), 2) Specific power (kW/kg)

Summary of Assessment, Issues, & Opportunities

Item	**Neutron Source**	**Space Propulsion**
Market Penetration & Customer	〈 Nuclear power industry 〈 DOE/Waste Disposal	〈 NASA
Competition	〈 Fission 〈 Accelerators 〈 Burial	〈 One of the few options for deep-space missions.
Environment, Safety, & Licensing	〈 Applications look more like fission than fusion	〈 Safety implications not yet assessed.

Summary of Assessment, Issues, & Opportunities

Item	**Neutron Source**	**Space Propulsion**
Impact on Time-scale	〈 Could provide an intermediate mission prior to pure fusion systems	〈 NASA interest provides outside advocate for fusion development
Key Issues	〈 Must establish a market niche 〈 Impact on fusion image 〈 Impact on pure fusion development plan 〈 Technology, reliability, & availability implications	〈 Technical basis must be established
Opportunities	〈 System studies 〈 NSO program	〈 NASA/DOE cooperation

Subgroup A: "Long-term Visions for Fusion Power"

- What is the projected market for electrical energy production in the next century?

  Demand for non-polluting technologies will be enormous.

- What is Fusion's Potential for penetrating the energy market in the next century?

  It depends on pace of technical progress and demonstrating its environmental potential.

- Is there a potential role for advanced fusion fuels?

  Physics embodiments need to be demonstrated.

- What is Fusion's potential for applications other than conventional power plants?

  Several applications have been identified

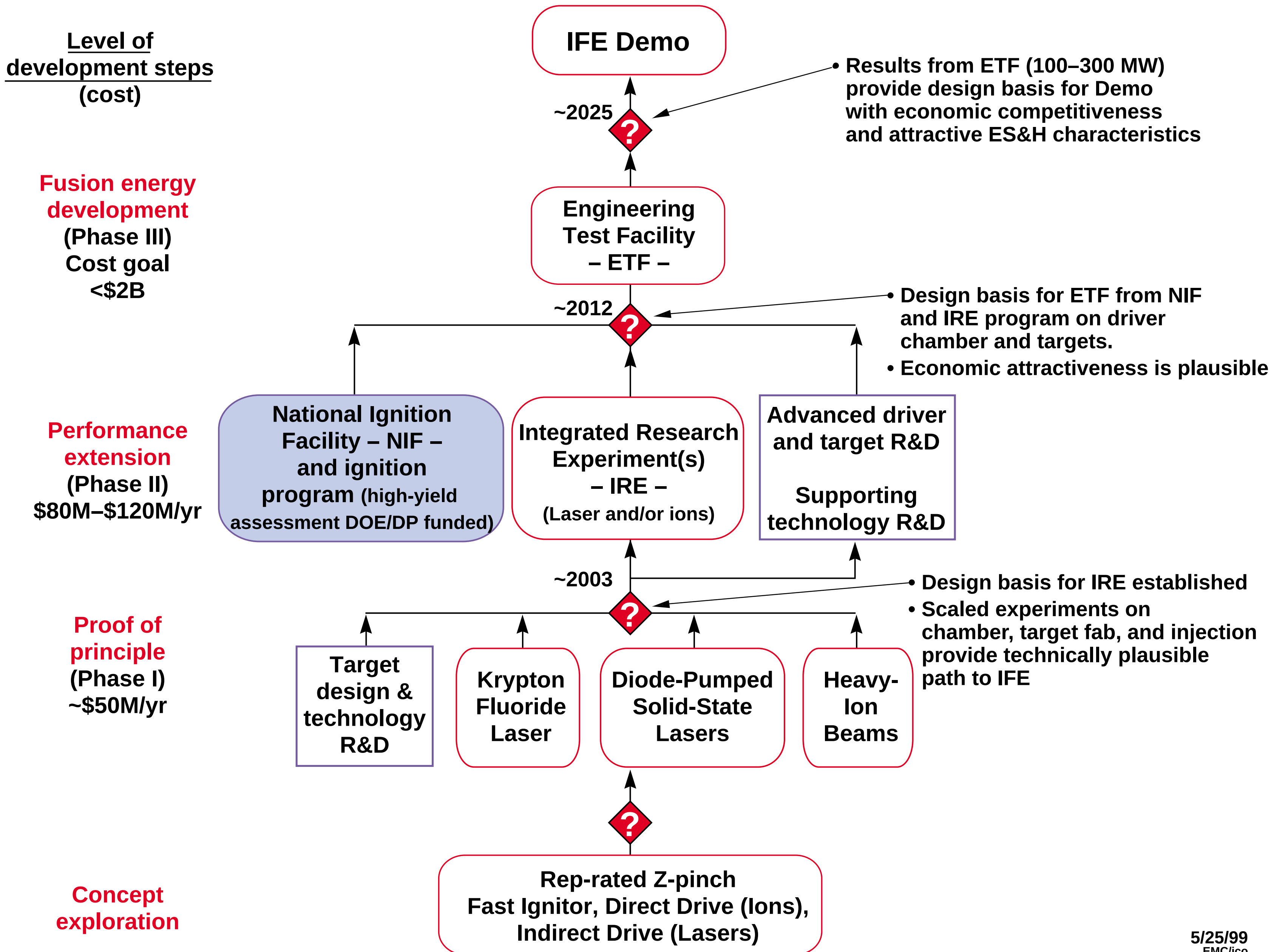
1999 Fusion Summer Study
Energy Issues Working Group Subgroup B
Development Path Issues

Summary
Friday, July 23, 1997

by
Ron Stambaugh

Convenors: W. Meier, J. Navratil, N. Sauthoff, R. Stambaugh

The Inertial Fusion Development Strategy is integrated with the Fusion Energy Road Map



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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.

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 above be answered for each different driver and target type in IFE? How generic are the results from NIF?

Concensus Answer: 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, chamber, and target 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.

An Issue Left Unresolved

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

• 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.

WHY AN MFE BURNING PLASMA?

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.

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

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

Scientific Transferability

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

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

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

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.

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

NEXT STEP OPTIONS FOR FUSION ENERGY DEVELOPMENT

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

    ITER-RC, FIRE, IGNITOR, DTST, JET-Upgrade

  - **Devices For Long Pulse Æ Steady-State Research**

    LHD, KSTAR, JT-60SU, ITER-RC, ST-VNS, FIRE

  - **Devices For Nuclear Technology Development**

    ITER-RC, ST-FDF

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.