Report on Snowmass Outcomes

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NAS/NRC Burning Plasma Assessment Committee

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Background

- The 2002 Fusion Summer Study carried out a critical assessment of major next-steps in the fusion energy sciences program in both Magnetic Fusion Energy (MFE) and Inertial Fusion Energy (IFE).
- The conclusions of this study were based on analysis led by over 60 conveners working with hundreds of members of the fusion energy sciences community extending over 8 months.
- This effort culminated in two weeks of intense discussion by over 250 US and 30 foreign fusion physicists and engineers present at the 2002 Fusion Summer Study.

Objectives

- **Review the scientific issues in burning plasmas,**
  address the relation of burning plasma in tokamaks to innovative MFE confinement concepts, and
  address the relation of ignition in IFE to integrated research facilities.

- **Provide a forum for critical discussion and review of proposed MFE burning plasma experiments (IGNITOR, FIRE, and ITER) and assess the scientific and technological research opportunities and prospective benefits of these approaches to the study of burning plasmas.**

- **Provide a forum for the IFE community to present plans for prospective integrated research facilities, assess the present status of the technical base for each, and establish a timetable and technical progress necessary to proceed for each.**

opportunity for a broad community of MFE and IFE scientists to examine goals and proposed initiatives in

– burning plasma science (MFE), and

– integrated research experiments (IFE)

a forum for the critical uniform technical assessment of major next-steps in the fusion energy sciences program

– to provide crucial community input to the long range planning activities undertaken by the DOE and the Fusion Energy Sciences Advisory Committee

open to every member of the fusion energy science community

- MFE (tokamaks and other concepts) and IFE (280+ on-site participants)
- significant international participation (30+)

Snowmass and
Issues the NRC Panel will be addressing…

- ➔ What are the important scientific and technical problems to be addressed in the burning plasma experimental program?
- ➔ To what degree will the solutions further the development of fusion energy in magnetic confinement systems generally or in tokamaks specifically?
- What is the breadth of scientific interest in these problems?
- ➔ To what degree can each of the burning plasma experiments under development address the scientific and technical problems?
- → Does the plan for a burning plasma experimental program envision sufficient diagnostics, theory, and technology support to generate good understanding of the problems to be investigated?
- → What are the implications of a given experiment for the future development of the U.S. fusion program?
- How well will the burning plasma experimental program be integrated with the rest of the U.S. fusion program?
- Will it be well integrated with international efforts in fusion research?

Situation

- In the MFE program, the world is now at a major decision point: to go forward with exploration of a burning plasma, opening up the possibility of discoveries in a plasma dominated by self-heating from fusion reactions and filling this crucial and now missing element in the MFE program.
- In the IFE program, the decision to construct a burning plasma experiment has already been made.
  The National Nuclear Security Administration is currently building the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory.
  The NIF, and other facilities worldwide are expected to provide the needed data on inertial fusion burning plasmas.
  The IFE questions examined at the Fusion Summer Study revolve about the pace of development of the additional sciences and technologies needed for power production.

Context for the Snowmass study

FESAC Burning Plasma Panel 9/2001

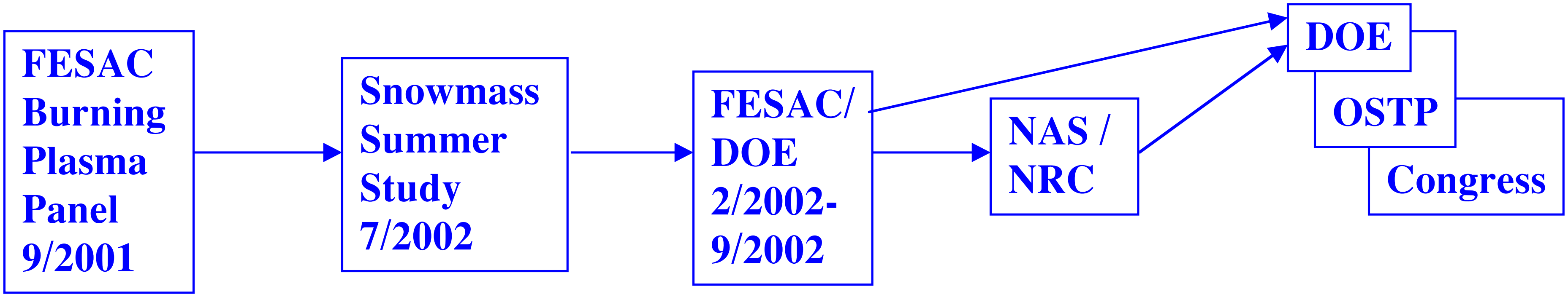
"Hold a "Snowmass" workshop in the summer 2002, for the critical scientific and technological examination of proposed burning plasma experimental designs and to provide crucial community input and endorsement to the planning activities undertaken by FESAC."

"Specifically, the workshop should determine which of the specific burning plasma options are technically viable but should not select among them."

"Request the Director of the Office of Energy Sciences to charge FESAC with the mission of forming an "action" panel in Spring 2002, to select among the technically viable burning plasma experimental options."

"Initiate a review by a National Research Council panel in Spring 2002, with the goal of determining the desirability as well as the scientific and technological credibility of the burning plasma experiment design by Fall 2003."

MFE Context for the Snowmass study



Identifying MFE issues and assessing burning plasma experiments

	FIRE IGNITOR ITER	BP contributions to ICCs
Physics	Argue for scientific and technological benefits of approaches	Assess benefits of a tokamak BPX to ICC path
Technology	Identify key scientific, technological, and path issues Determine assessment criteria Perform uniform assessments of approaches	
Experimental Approach and Objectives		

Major MFE Conclusions

- Why a burning plasma

2. Burning plasma options

3. Assessment of contributions of the options

4. Assessment of the feasibility of the options

5. Assessment of fusion development paths

6. Relation to the national program

Preamble to the MFE section of the Executive Summary

Fusion energy shows great promise to contribute to securing the energy future of humanity.

The science that underlies this quest is at the frontier of the physics of complex systems and provides the basis for understanding the behavior of high temperature plasmas.

Grounded in recent excellent progress in the study of magnetically confined plasmas, the world is now at a major decision point:
to go forward with exploration of a burning plasma, opening up the possibility of discoveries in a plasma dominated by self-heating from fusion reactions.

Preamble to the MFE section of the Executive Summary - continued

This exciting next step to explore burning plasmas is an essential element in the Fusion Energy Science Program whose mission is to “Advance plasma science, fusion science and fusion technology—the knowledge base needed for an economically and environmentally attractive fusion energy source.”

The study of burning plasmas will be carried out as part of a program that includes advancing fundamental understanding of the underlying physics and technology, theory and computational simulation, and optimization of magnetic confinement configurations.

Conclusion #1 - Why a burning plasma

- The study of burning plasmas, in which self-heating from fusion reactions dominates plasma behavior, is at the frontier of magnetic fusion energy science.

- The next major step in magnetic fusion research should be a burning plasma program, which is essential to the science focus and energy goal of fusion research.

Conclusion #1 - Supporting Material

- **a crucial and missing element in the fusion energy sciences program**
  - a large step forward in demonstrating magnetic fusion as a source of practical fusion energy

- **The tokamak is now at the stage of scientific maturity that we are ready to undertake the essential step of burning plasma research.**

- **Burning plasmas afford unique opportunities to explore, for the first time in the laboratory, high-temperature-plasma behavior in the regime of strong self-heating.**
  - effects of energetic, fusion-produced alpha particles on plasma stability and turbulence; the strong, nonlinear coupling that will occur between fusion alpha particles, the pressure driven current, turbulent transport, MHD stability, and boundary-plasma behavior.

- **Recent physics advances in tokamak research, aimed at steady-state and high performance, demonstrate the potential to significantly increase the economic attractiveness of the tokamak.**
  - Therefore, Advanced Tokamak (AT) research capability is highly desirable in any burning plasma experiment option.

- **Physics and technology learned in a tokamak-based burning plasma would be transferable to other configurations.**

Conclusion #2 - Burning plasma options

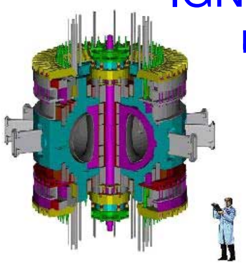
- The three experiments proposed to achieve burning plasma operation range from compact, high field, copper magnet devices to a reactor-scale superconducting-magnet device.

- These approaches address a spectrum of both physics and fusion technology, and vary widely in overall mission, schedule and cost.

Conclusion #2 - Missions (Proposers)

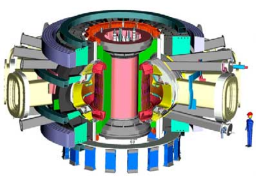
- **The following mission statements were provided by the proposing teams:**

  – IGNITOR is a facility whose mission is to achieve fusion ignition conditions in deuterium-ım plasmas for a duration that exceeds the intrinsic plasma physics time scales.



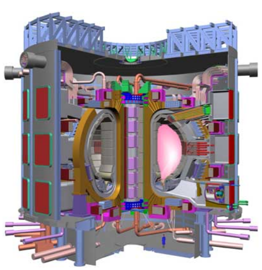
  It utilizes high-field copper magnets to achieve a self-heated plasma for pulse lengths comparable to the current redistribution time. IGNITOR will study the physics of the ignition process and alpha particle confinement as well as the heating and control of a plasma subject to thermonuclear instability.

  – FIRE is a facility whose mission is to attain, explore, understand and optimize magnetically confined fusion-dominated plasmas.



  FIRE would study burning plasma physics in conventional regimes with Q of about 10 and high-beta advanced tokamak regimes with Q of about 5 under quasi-stationary conditions. FIRE employs a plasma configuration with strong plasma shaping, double-null poloidal divertors, reactor level plasma exhaust power densities and pulsed cryogenically cooled copper coils as a reduced cost approach to achieve this mission.

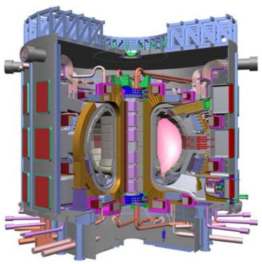
  – The overall objective of ITER is to demonstrate the scientific and technological feasibility of fusion energy.



  ITER would accomplish this objective by demonstrating controlled ignition and extended burn of deuterium-tritium plasmas, with steady-state as an ultimate goal, by demonstrating technologies essential to a reactor in an integrated system, and by performing integrated testing of the high heat flux and nuclear components required to utilize fusion energy for practical purposes.

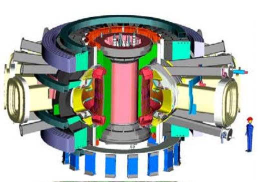
Conclusion #2 - Cost

- **Cost information was obtained from the ITER and FIRE teams and was assessed within the limited resources available for the Snowmass work. All costs were converted to 2002-US dollars. ITER assumes an international cost-sharing approach while FIRE costs are estimated as a US project.**

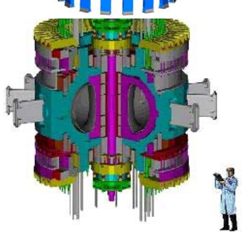


The purpose of the ITER cost information is to provide accurate estimates of the relative “value” of all the tasks necessary for construction to facilitate international negotiations on task sharing. The cost information is based on a large engineering effort (about 1000 PPY) and a large R&D effort (about $900M) with prototypes of all key components. Also, the ITER cost information (about 85 procurement packages) is based on input from the industries in all the parties. The estimate of the ITER total “value”, when converted to 2002 US dollars, is about $5 billion. The actual cost estimate is to be developed by each party using its own procedures, including the use of contingency. Thus, the ITER cost information does not included explicit contingency.

The US will need to carefully estimate the cost of any potential contributions to ITER. These estimates should include adequate contingency and any additional required R&D to mitigate against potential cost increases.



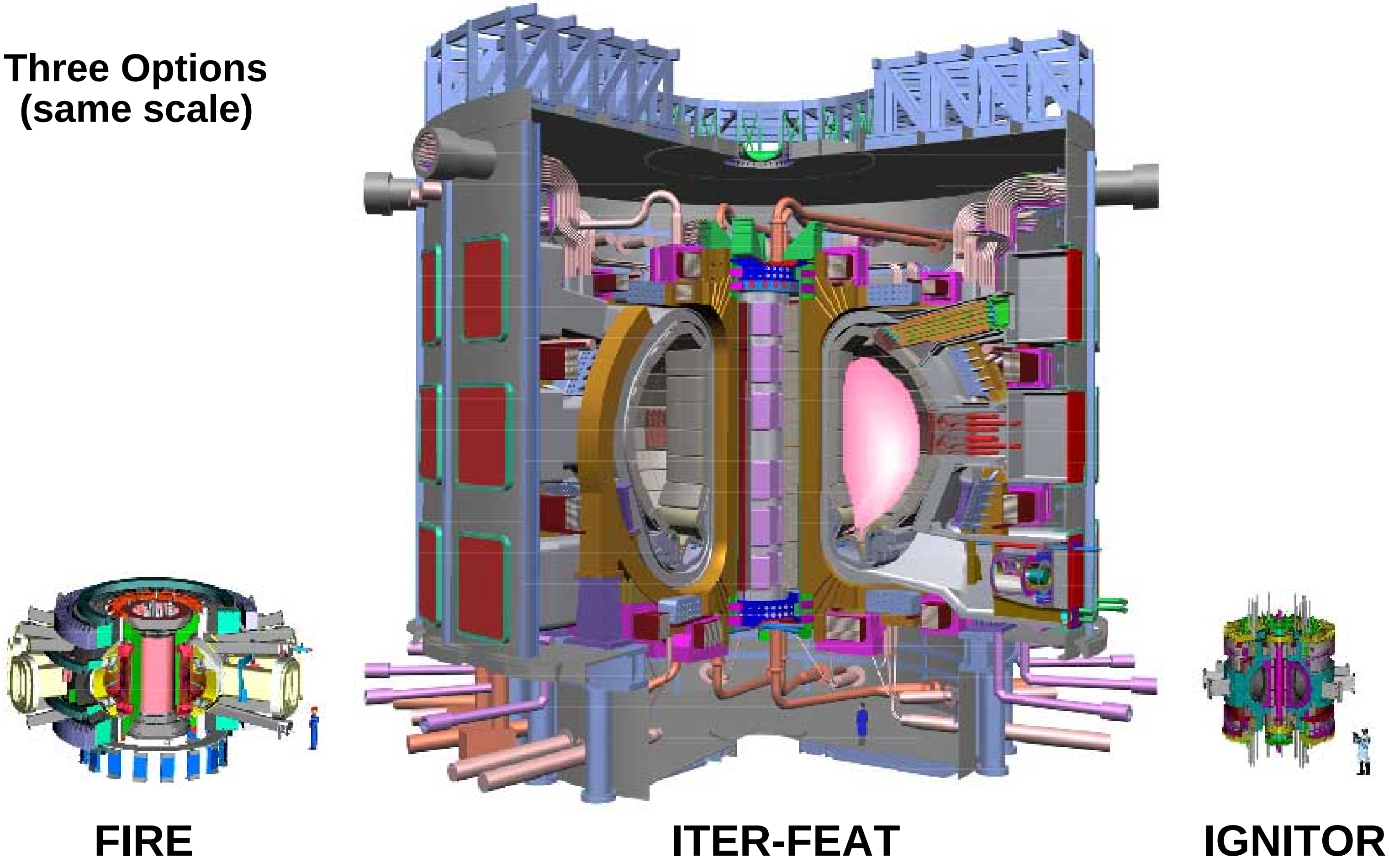
The estimate for FIRE is about $1.2 B including about a 25% contingency. It is based on an advanced pre-conceptual design using in-house and some vendor estimates. However, substantial further engineering is needed as well as some supporting R&D.



As an Italian project, IGNITOR has been designed in detail with supporting R&D. It has a detailed cost estimate that is confidential for business purposes and was not made available to the assessment team.

Conclusion #3 - Assessment of contributions of the options

- IGNITOR, FIRE, and ITER would enable studies of the physics of burning plasma, advance fusion technology, and contribute to the development of fusion energy. The contributions of the three approaches would differ considerably.



Conclusion #3

- **IGNITOR, FIRE, and ITER would enable studies of the physics of burning plasma, advance fusion technology, and contribute to the development of fusion energy. The contributions of the three approaches would differ considerably.**
  - IGNITOR offers an opportunity for the early study of burning plasmas aiming at ignition for about one current redistribution period.
  - FIRE offers an opportunity for the study of burning plasma physics in conventional and advanced tokamak configurations under quasi-stationary conditions (several current redistribution time periods) and would contribute to plasma technology.
  - ITER offers an opportunity for the study of burning plasma physics in conventional and advanced tokamak configurations for long durations (many current redistribution time periods) with steady state as the ultimate goal, and would contribute to the development and integration of plasma and fusion technology.

Conclusion #3 - Common Benefits

- **The three candidate burning plasma devices would contribute a number of key benefits, i.e., capabilities for studies of the physics and technology of burning plasmas (under the assumption that each facility will achieve its proposed performance).**

- **Common benefits from all three candidate burning plasma devices include the following:**
  - PHYSICS
    - 1. Strongly-coupled physics issues of equilibrium, stability, transport, wave-particle interactions, fast ion physics, and boundary physics in the regime of dominant self-heating.
  - TECHNOLOGY
    - 2. Plasma support technologies (heating, fuel delivery, exhaust, plasma-facing components, and magnets) will benefit most because parameters and plasma conditions will be close to those required for power production.
    - 3. Nuclear technologies (remote handling, vacuum vessel, blankets, safety and materials) will advance as a result of the experience of operating in a nuclear environment. The level of benefit will depend on tritium inventory, pulse length, duty factor, and lifetime fluence.

Conclusion #3 - IGNITOR

- **Key benefits from IGNITOR are the following:**

  – PHYSICS
    - 1. Capability to address the science of self-heated plasmas in a reactor-relevant regime of small ρ^* (many Larmor orbits) for globally MHD-stable plasmas at low βN (normalized plasma pressure).
    - 2. Capability to study sawtooth stability at low beta with isotropic alpha particles and self-consistent pressure profile determined by dominant alpha heating.

  – TECHNOLOGY
    - 3. Development of high-field copper magnets with advanced structural features, including bucking and wedging and magnetic press.
    - 4. Development of high-frequency RF antennas for wave heating in a burning plasma environment.

Conclusion #3 - FIRE

- **Key benefits from FIRE are the following:**

  – PHYSICS
    - 1. Capability to address the science of self-heated plasmas in reactor-relevant regimes of small ρ* (many Larmor orbits) and high βN (normalized plasma pressure) with a large fraction of non-inductive current sustained for up to a few current relaxation times.
    - 2. Exploration of high self-driven current regimes with strong shaping and active MHD stability control.
    - 3. Study of removal of helium ash and impurities with exhaust pumping.

  – TECHNOLOGY
    - 4. Development of electrical insulation for high-field pulsed copper magnets in a high neutron fluence environment.
    - 5. Development of high heat flux plasma-facing components with steady-state heat removal capability (tungsten/beryllium).

Conclusion #3 - ITER

- **Key benefits from ITER are the following:**

  - PHYSICS
    - 1. Capability to address the science of self-heated plasmas in reactor-relevant regimes of small ρ^* (many Larmor orbits) and high βN (plasma pressure), and with the capability of full non-inductive current drive sustained in near steady state conditions.
    - 2. Exploration of high self-driven current regimes with a flexible array of heating, current drive, and rotational drive systems.
    - 3. Exploration of alpha particle-driven instabilities in a reactor-relevant range of temperatures.
    - 4. Investigation of temperature control and removal of helium ash and impurities with strong exhaust pumping.

  - TECHNOLOGY
    - 5. Integration of steady-state reactor-relevant fusion technology: large-scale high-field superconducting magnets; long-pulse high-heat-load plasma-facing components; control systems; heating systems.
    - 6. Testing of blanket modules for breeding tritium.

Conclusion #4 - Assessment of the feasibility of the options

- There are no outstanding engineering-feasibility issues to prevent the successful design and fabrication of any of the three options.
  However, the three approaches are at different levels of design and R&D.

- There is confidence that ITER and FIRE will achieve burning plasma performance in H–mode based on an extensive experimental database.

  IGNITOR would achieve similar performance if it either obtains H–mode confinement or an enhancement over the standard tokamak L–mode. However, the likelihood of achieving these enhancements remains an unresolved issue between the assessors and the IGNITOR team.

Conclusion #4 - Stages of development

- **The three options are at very different stages of engineering development.**
  - ITER and IGNITOR have well-developed engineering designs.
  - ITER has been supported by a comprehensive R&D program. Also, ITER has demonstrated full-scale prototypes for essentially all major components of the fusion core and their maintenance.
  - FIRE is at the advanced pre-conceptual design level. It has benefited from previous R&D for CIT/BPX/IGNITOR and, most recently, from ITER R&D.
  - IGNITOR has carried out R&D and built full-size prototypes for essentially all major components.

Conclusion #4 - Projections

- **Projections for the three options are based on present understanding of tokamak physics.**
  - Based on 0D and 1.5D modeling, all three devices have baseline scenarios which appear capable of reaching Q = 5 – 15 with the advocates' assumptions. ITER and FIRE scenarios are based on standard ELMing H–mode and are reasonable extrapolations from the existing database.
  - IGNITOR's baseline scenarios, based on cold edged L–mode, depend on a combination of enhanced energy confinement and/or density -peaking. An unresolved issue arose as to whether an adequate database exists (proposers) or does not exist (assessors) for assessing confinement projections in the proposed IGNITOR operational modes: L–mode limiter or H–mode with x-point(s) near the wall. Further research and demonstration discharges are recommended.
  - More accurate prediction of fusion performance of the three devices is not currently possible due to known uncertainties in the transport models. An ongoing effort within the base fusion science program is underway to improve the projections through increased understanding of transport.
  - Each device presents a reasonable set of advanced scenarios based on present understanding. ITER and FIRE have moderate- and strong-shaping respectively and the control tool set needed to address the issues of high beta and steady-state related to Advanced Tokamak regimes. FIRE has the capability to sustain these regimes for one to three current redistribution times, while ITER has the capability to sustain these regimes for up to 3000 s allowing near steady-state operation. IGNITOR presents credible advanced performance scenarios using current ramps and intense heating to produce internal transport barriers on a transient basis.

Conclusion #4 - Issues

- **A number of issues have been identified and are documented in the body of the report.**
  - For example, on ITER and FIRE,
    - the predicted ELM-power loads are at the upper boundary of acceptable energy deposition; ELM-control and amelioration is needed.
  - On FIRE,
    - control of the neoclassical tearing mode by lower hybrid current drive is not sufficiently validated. Also, FIRE has a concern about radiation damage of magnet insulators.
  - On ITER,
    - tritium retention is a concern with carbon-based divertor materials.
- **These issues are the subjects of continuing R&D.**

Conclusion #5 - Assessment of fusion development paths

- **The development path to realize fusion power as a practical energy source includes four major scientific elements:**
  - Fundamental understanding of the underlying science and technology, and optimization of magnetic configurations
  - Plasma physics research in a burning plasma experiment
  - High performance, steady-state operation
  - Development of low-activation materials and fusion technologies

Conclusion #5 - Portfolio

- A diversified and integrated portfolio consisting of advanced tokamak, ICCs, and theory/simulation is needed to achieve the necessary predictive capability.

- A burning plasma experiment should be flexible and well-diagnosed in order to provide fundamental understanding.

Conclusion #5 - Fusion power technologies

- **Fusion power technologies are a pace-setting element of fusion development.**

- **Development of fusion power technologies requires:**

  – A strong base program including testing of components in a non-nuclear environment as well as fission reactors.

  – A materials program including an intense neutron source to develop and qualify low-activation materials.

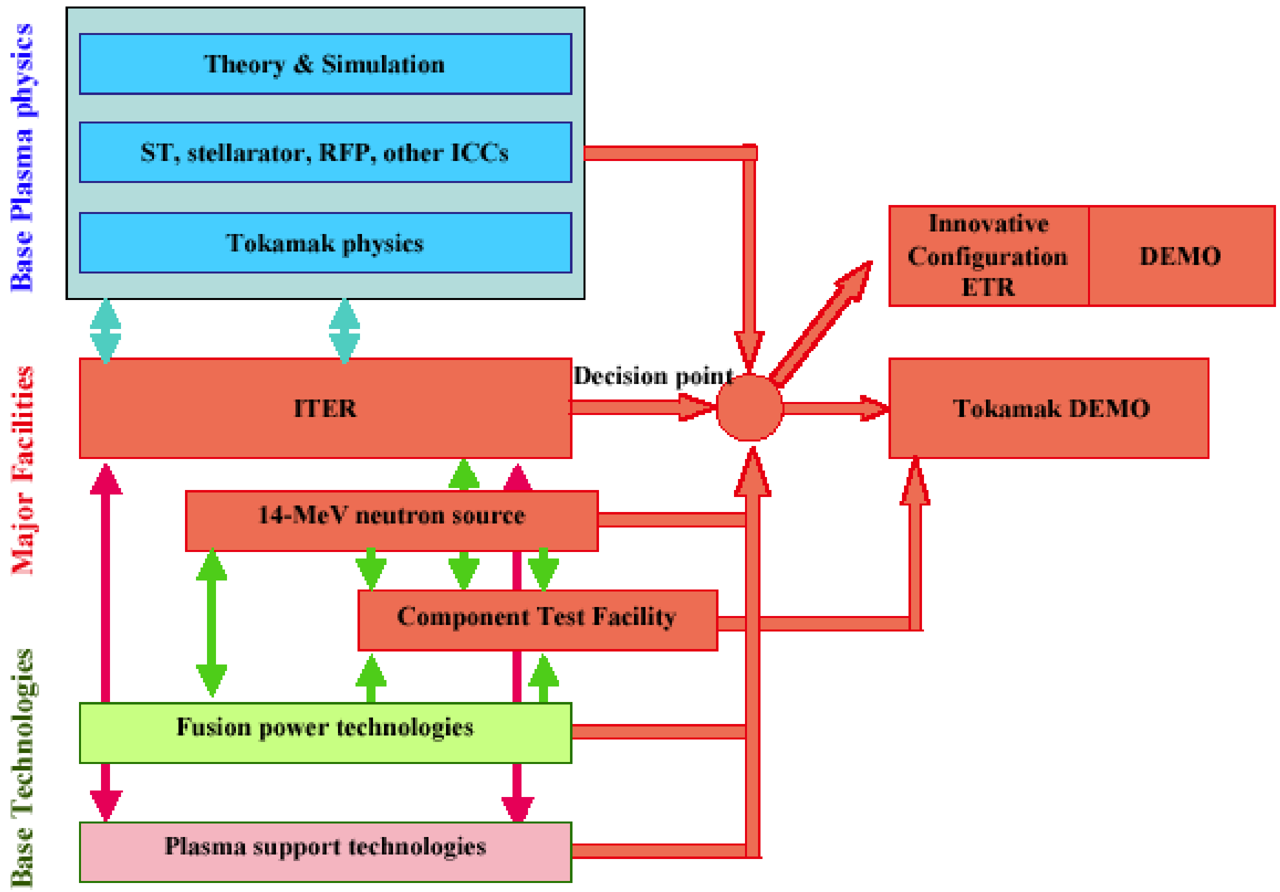
  – A Component Test Facility for integration and test of power technologies in fusion environment.

Conclusion #5 - ITER Development Path

An international tokamak research program centered around ITER and including these national performance-extension devices has the highest chance of success in exploring burning plasma physics in steady-state.

- ITER will provide valuable data on integration of power-plant relevant plasma support technologies.

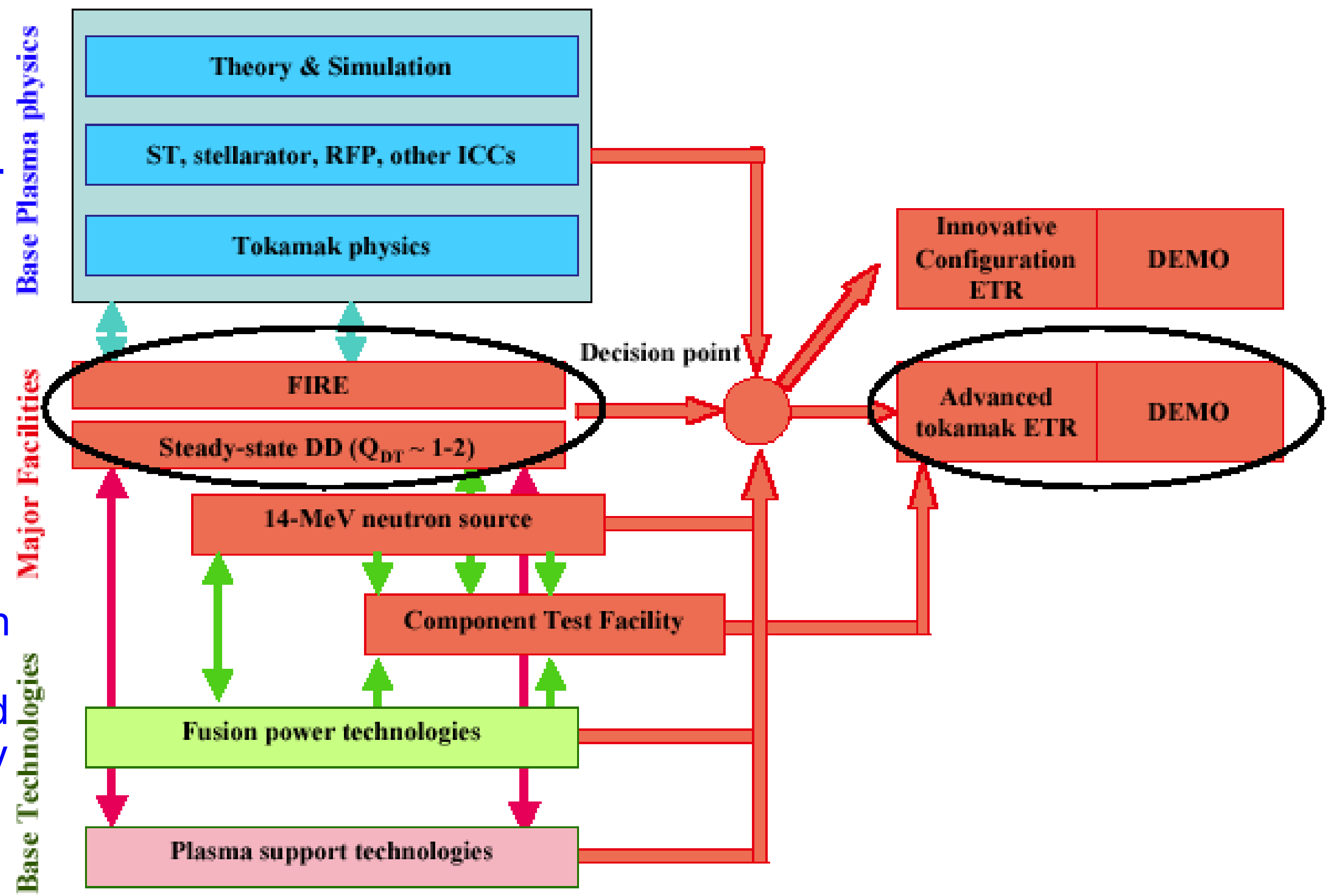
- Assuming successful outcome (demonstration of high-performance AT burning plasma), an ITER-based development path would lead to the shortest development time to a demonstration power plant.



Conclusion #5 - FIRE Development Path

A FIRE-based development plan reduces initial facility investment costs and allows optimization of experiments for separable missions.

- It is a lower risk option as it requires "smaller" extrapolation in physics and technology basis.
- Assuming a successful outcome, a FIRE-based development path provides further optimization before integration steps, allowing a more advanced and/or less costly integration step to follow.



Conclusion #5 - IGNITOR in the Fusion Development Path

- **IGNITOR allows early demonstration of an important fusion milestone, burning plasmas with a low initial facility investment cost.**
  - Because of its short pulse length, IGNITOR cannot thoroughly investigate burn control and/or advanced tokamak modes.
  - IGNITOR could be an element of a portfolio of experiments supporting ITER-based or FIRE-based development scenarios.

Principal Advantages of Different Development Scenarios

ITER:

- Early exploration and optimization of integrated burning plasma, steady state (AT) operation, and plasma support technologies.
- Minimizes number of steps (and time) to tokamak-based fusion power.

FIRE:

- Reduces initial facility investment costs and allows optimization of experiments for separable missions.
- Provides further optimization before integration steps.

IGNITOR:

- Early demonstration of an important fusion milestone, burning plasmas.
- Low initial facility investment cost.

Fusion Power technologies are the pace setting element of fusion development. Their development requires:

- Strong base program including testing of components in non-nuclear environment as well as fission reactors.
- Material program including an intense neutron source to develop and qualify low-activation material.
- A Component Test Facility for integration and test of power technologies in fusion environment.

Conclusion #6 - Relation to the national program

- A strong base science and technology program is needed to advance essential fusion science and technology and to participate effectively in, and to benefit from, the burning plasma effort.

- In particular, the development path for innovative confinement configurations would benefit from research on a tokamak-based burning plasma experiment.

Conclusion #6 - Base Program foundation

- **It has been a much-affirmed premise of the current fusion energy program that a strong base program forms a foundation for the field.**
  - The base program is also essential to the successful and full exploitation of a burning plasma effort. U.S. participation in a burning plasma experiment clearly requires a cadre of fusion physicists and engineers.
  - In addition tokamak experiments are needed to contribute to the database that helps guide and influence a burning plasma experiment.
  - For the U.S. to benefit fully from a burning plasma experiment requires not only experimentalists and engineers, but also theorists and computational scientists who can interpret the results, and generalize them for application to future tokamak experiments and non-tokamak configurations.

Conclusion #6 - Benefits to ICCs

- **The development of innovative confinement configurations would benefit from a burning plasma experiment based on the tokamak configuration.**
  - Research in innovative configurations is essential for the broad development of fusion science and for the evolution of an optimal approach to fusion energy.
  - The results from a tokamak burning plasma experiment will be sufficiently generic to accelerate the development of other toroidal fusion configurations.
    - The tokamak shares many physics features with the spectrum of toroidal configurations, including nonaxisymmetric tori (the stellarator family), axisymmetric tori with safety factor $q > 1$ (including advanced tokamaks and spherical tokamaks), and axisymmetric tori with $q < 1$ (including the reversed field pinch, spheromak, and field reversed configurations).
    - The behavior of alpha particles in these configurations is expected to have features in common, so that tokamak results can influence research in other configurations.

Conclusion #6 - Physics/Technology Transfer

- **There are many geometric differences between a tokamak and these neighboring configurations;**
  however, if the results from a tokamak burning plasma experiment are understood at the level of fundamental physics, then these results can be transferred through theory and computation.
  - This transferability is expected to apply to the classical confinement of alpha particles, alpha-generated instabilities, the effect of alpha particles on existing instabilities, the effect of turbulence and MHD instabilities on alpha confinement, and aspects of burn control.
  - Clearly, the transferability is largest for configurations that are geometrically closest to the tokamak.
    However, nearly all physics results obtained in the tokamak configuration have had influence on the large family of toroidal configurations, and it seems clear that this influence will extend to results from tokamak burning plasma experiments.

- **The technological information learned from a tokamak burning plasma experiment will strongly apply to other configurations.**
  - Areas of technology transfer include superconducting magnets, plasma facing components, fueling, heating sources, blankets and remote handling.

Key issues and transferability (from ICC presentation)

- **α - generated instabilities:**
  - physics of spectra, excitation, damping extend to other configurations; geometric details differ
- **α - effects on existing instabilities:**
  - drift-precession effects transferable
- **Fluctuation-driven α transport:**
  - effect on electrostatic fluctuations, sawteeth transferable
- **RF wave interactions with α particles:**
  - interaction physics transferable
- **Burn control, nonlinear coupling:**
  - some control aspects transferable
- **The unknown:**
  - ??

Physics Transferability
(from ICC presentation)

- Transferability requires understanding at a fundamental level, through experiment, theory, computation
- Nearly all past tokamak results have influenced other configurations

General Observations

- **Strong sense of excitement and unity in the community for moving forward with a burning plasma step [quite unprecedented!]**

- **Overwhelming consensus that**
  - Burning plasmas are opportunities for good science --- exploration and discovery
  - Tokamaks are ready to proceed -- the sci-tech basis is sufficient
  - Other toroidal configurations (ICCs) would benefit from a burning tokamak plasma
  - The base program and the ICC elements play a critical role in the overall fusion energy science program which includes a burning plasma

- **Progress made since the Madison Forum on Major Next Step Options [April 1998] has been enormous. At that time we had:**
  - Strong divisions in the community on ITER versus “smaller modular” as best path
  - Serious technical concerns raised about the projected performance of ITER-FDR
  - Serious concerns about the cost of the ITER-FDR device
  - ICCs community felt BP step was premature and felt threatened: advocated delay!
  - Key (and unique) science goals of the BP step were not well defined
  - IFE not integrated into program and challenged MFE “development path” planning

General Observations

- **IGNITOR, FIRE and ITER would all produce scientific and technological benefits**
  - their missions are distinct, and were clarified

- **All 3 approaches have science and technology issues, but NO SHOW STOPPERS: the issues are being addressed by continuing R&D**

- **The Snowmass Study performed the technical assessment,**
  IT DID NOT SELECT THE PREFERRED APPROACH(es)

- **Snowmass Participants Strongly Confirmed: "NOW is the time for action!"**