Advanced Design Program Performs Integrated Analysis

• Detailed and in-depth analysis is necessary to make scientific progress and impact the R&D program:
  * Interaction and trade-off among plasma parameters (MHD β limit, heating & current-drive, divertor, transport);
  * Interfaces between fusion plasma and other components (e.g., restriction on plasma elongation by location of stabilizer, and triangularity by inboard divertor slot)
  * Invoke physics and engineering constraints which are not in present-day experiments (e.g., simultaneous high power and high particle flux to divertor)

• In many areas models and tools necessary to analyze fusion systems are developed.
Advanced Design Program Identifies Key R&D Issues and Provides a Vision for the Program

⇒ ARIES studies have influenced research priorities in each of these areas and have been guided by new experimental trends and theoretical concepts.

Progress in Plasma Physics:
- Macroscopic stability;
- Wave-particle interaction;
- Microturbulence & transport
- Plasma-material Interaction

What is important
What is possible
Physics limits
Stimulus for new ideas
What has been achieved
What to demonstrate

ARIES Program
Theory Program
Experiments
# Advanced Design Program Has Had A Major Impact on Tokamak Research

## Major Physics Results

- Introduced the trade-off between plasma $\beta$ and bootstrap current.
- Showed that high-field magnets can be utilized to compensate for low $\beta$.
- Showed that true benefit of 2nd Stability regime was to reduce the current-drive power not increased $\beta$.
- Demonstrated that (1) in pulsed-tokamaks the plasma $\beta$ is limited by ohmic profile constraint, (2) physics of pulsed and steady-state tokamaks are essentially the same; (3) steady-state out performs pulsed operation because of technological constraints.
- Developed reversed-shear equilibria appropriate to power plants. It included a self-consistent divertor/plasma edge conditions with acceptable impact on ideal MHD, current drive, and power balance.

## Impact on the Program

- Initiation of Advanced Tokamak Research.
- KSTAR construction and TPX experiment design were influenced significantly.
- Major theoretical and experimental activities on advanced tokamaks
- ARIES-RS is the present focus of advanced tokamak research (DIII-D, C-Mod, FIRE).
- Recognition at Snowmass that any burning plasma experiments must have advanced tokamak capability.
Tokamak Research Has Been Influenced by the Advanced Design Program

“Conventional” high-β tokamaks (Pulsed operation)

2nd Stability high-β tokamaks (Too much bootstrap)

Advanced tokamak (Balanced bootstrap)

Current focus of tokamak research

PU: Pulsed Operation
SS: 2nd Stability
FS: 1st Stability, steady-state
RS: Reversed-shear
### Advanced Design Program Has Had A Major Impact on Alternative Concept Research

#### Major Scientific Results

- **Spherical Torus:** Developed the first self-consistent stability and current-drive calculations of high-\(\beta\), high bootstrap current ST equilibria. Showed that high plasma elongation (\(\kappa = 3\)) is necessary. Showed resistive ST center-posts can be designed to operate in power-plant conditions.

- **Stellarator:** Invented a new stellarator magnetic configuration to address the issue of large size.

- **Reversed-Field Pinch:** Identified the need to operate with a highly radiative core, poloidal divertors, and an efficient current drive system so that a compact RFP can be realized.

#### Impact on the Program

- \(\Rightarrow\) NSTX is influenced by ARIES-ST
- \(\Rightarrow\) The next step in ST program, DTST, uses ARIES-ST as the target.
- \(\Rightarrow\) Initiated a large interest in compact stellarator research in US.
- \(\Rightarrow\) Experiments on ZT-40 with a highly radiative core and helicity-injection current-drive. ZT-P device was built to study poloidal divertors for RFPS;
- \(\Rightarrow\) Design and experimental program on ZT-H were modified to address these issues.
The ARIES-ST Study Has Identified Key Directions for Spherical Tokamak Research

- Substantial progress is made towards optimization of ST equilibria with >95% bootstrap fraction:
  * toroidal $\beta = 54\%$, $\kappa = 3$;
- A feasible center-post design has been developed;
- Several methods for start-up have been identified;
- Current-drive options are limited;
- 1000-MWe ST power plants are comparable in size and cost to advanced tokamak power plants.
### Advanced Design Program Has Had A Major Impact on Fusion Technology Research

**Major Fusion Technology Results**

- Introduced SiC composites as a high-performance fusion material.
- Explored gas injection and impurity radiation to reduce heat load in the divertors.
- Innovative superconducting magnet designs using plates and a structural cap (later used in ITER);
- Demonstrated benefits of RF systems (especially fast waves) for current drive and the respective launchers (e.g., folded wave-guides);
- Introduction of advanced manufacturing techniques which reduce the unit costs of components drastically.
- Emphasis on safety & environmental aspects of fusion;

**Impact on the Program**

- Large world-wide research activity on SiC composites material.
- Experiments in linear plasma machine and later in large tokamaks.
- Current goals of magnet R&D program.
- Spurred interest in RF current drive experiments (e.g., fast-wave current drive in DIII-D in mid 90s).
- Application in next-generation experiments.
- Direct impact on research on fusion materials and chamber technologies.
Impact of Latest Developments in Other Scientific Disciplines Are Continuously Considered.

Examples include:

- SiC Composites (Aerospace)
- High-temperature superconductor;
- Advanced manufacturing techniques (Aerospace)
- Advanced engineered material for high heat-flux components.
Engineered Microstructure of Porous Media Enables High Heat Flux Removal

- Enhanced heat transfer surface area
- Increased turbulence and boundary layer modification near heat transfer surface
- Reduced radiation opacity

ESLI High Porosity Fibrous material

Ultramet Foam
National Advanced Design Program Allows Fusion Scientists to Investigate Fusion Systems Together

- The team comprises key members from major fusion centers (universities, national laboratories, and industry). A typical team member spends 25% of his time on this activity. About 2/3 of resources is allocated to universities this year. Seven students were supported last year.

- Decisions are made by consensus in order to obtain the best technical solution without institutional bias.

- Team is flexible and expert groups and advocates are brought in as needed to ensure the flow of the latest information from R&D program. As such, high-leverage issues are readily transferred back to the R&D program.

- Workshop and “Town meeting” are held for direct discussion and dissemination of the results

- Because we draw from expertise of the national program, we are unique in the world in the ability to provide a fully integrated analysis of power plant options including plasma physics, fusion technology, economics, safety,
IFE Chambers Requirements and Options

- About 100 MJ of X-rays and debris Ions are released by the target over about 10 ns. For a practical chamber size, the energy load on an “un-protected” chamber wall is about 2GW/m²

Options:

- **Gas Protection:** Low-density high-Z gas in the chamber absorbs X-rays and debris and radiate in 0.1 to 100 ms.

- **Wetted Walls:** Thin liquid layer absorbs the incident energy. The evaporated material recondenses on the chamber wall.

- **Thick Liquid Wall:** Energy yield is absorbed by regenerating liquid walls.

- For each option, the chamber environment should return to its “normal” condition in about 100 to 200 ms.
Integrated Analysis of IFE Chambers Requires State of the Arts Analysis in Several Areas

• **Material response to intense target yield:** Response of the solid and liquid material (chamber wall and final optics) and gases to intense target emissions (plasma, X-rays, neutrons).

• **Chamber clearing:** Understanding the limits on chamber clearing rates set by radiation cooling from optically thick and/or thin plasma-gas regimes, followed by molecular recombination, and then condensation on surfaces or droplets.

• **Beam Transport:** Investigation of beam transport (lasers/heavy ions) through final optics and chamber in plasma-gas environment.

• **Target Injection and Heating:** Understanding the effects of target heating on cryogenic fuel layers due to thermal radiation, conduction, and convection in the chamber. Investigation of the impact of chamber environment on target trajectory.
National Advanced Design Program Is a High-Leverage Research Effort

- **High Quality of Science:** Detailed and in-depth analysis is necessary to make scientific progress.

- **High-Leverage Research:** Integrated design & analysis beyond current experiments identifies key R&D Issues.

- **Community input and consensus:** An environment is created for fusion scientists to investigate fusion systems together. Team members bring in the latest information from R&D program. State-of-art analysis, innovation, and high-leverage issues are readily transferred back to the R&D program.

- **Interaction with other disciplines:** Impact of latest development in other scientific fields on fusion systems are evaluated.

- **Impact on Education:** Approximately 2/3 of the research is performed by universities (UCSD, U. Wisc., RPI, MIT). Seven students were supported by this activity last year.

- **A high-leverage niche on the international fusion program.** It is recognized internationally as a credible driving force towards an attractive end product and influences world-wide fusion research.