

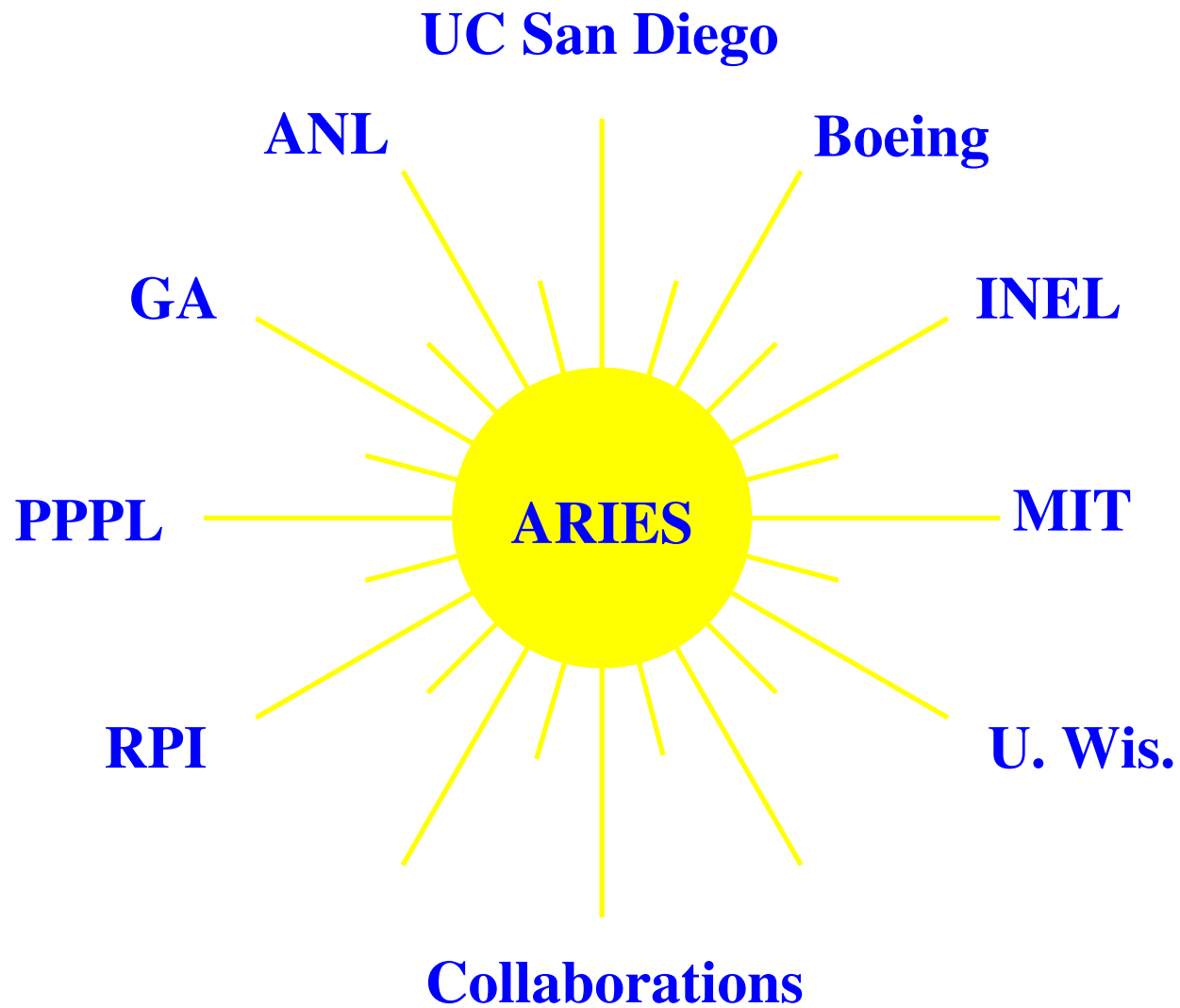
**CONCLUSIONS OF
THE ARIES AND PULSAR STUDIES:
DIRECTIONS FOR AN ATTRACTIVE
TOKAMAK POWER PLANT**

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ARIES Is a Community-Wide Study



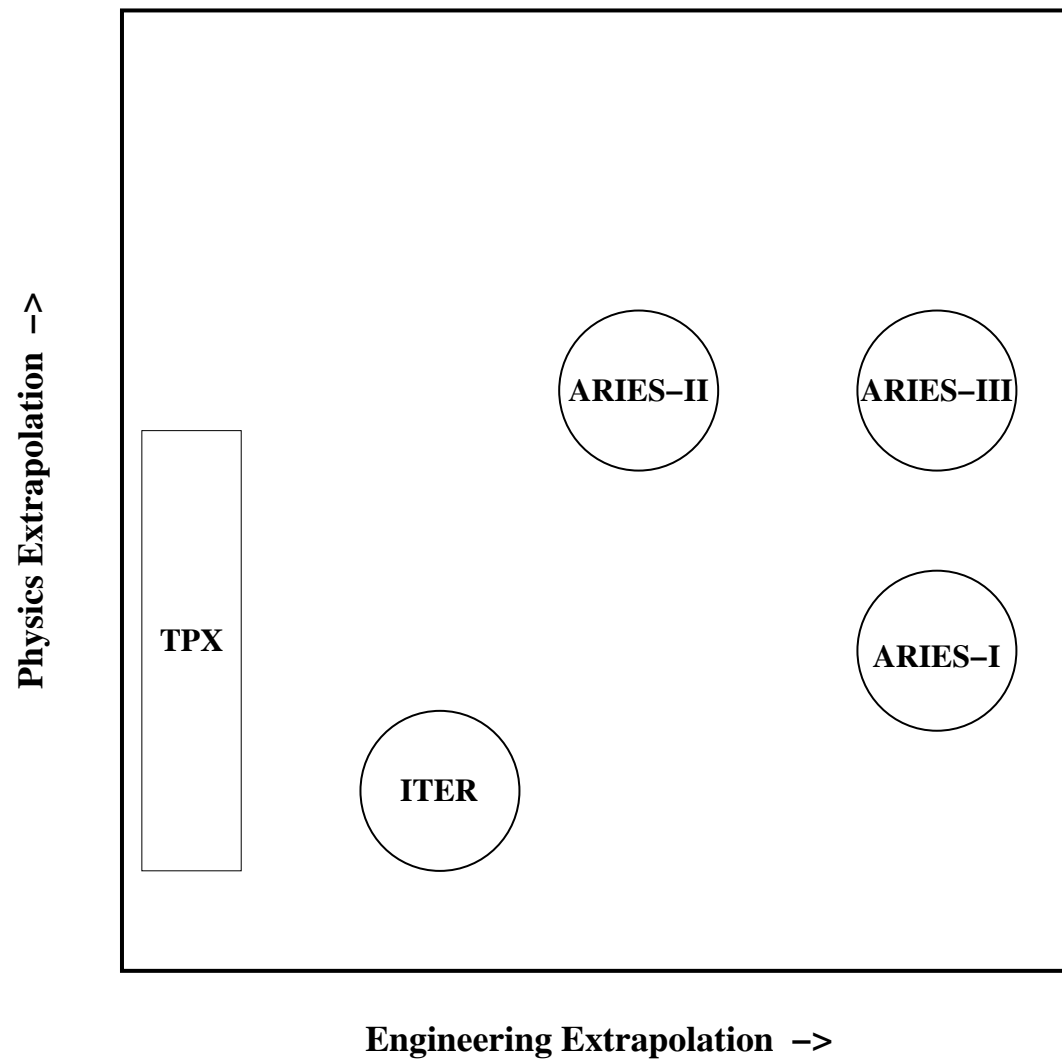
There Are Four ARIES Tokamak Plant Designs

- ARIES-I is based on modest extrapolations in physics and on technology which has a 5 to 20 year development horizon (often by programs outside fusion).
- ARIES-III is an advanced fuel (D-³He) tokamak plant.
- ARIES-II/IV is based on greater extrapolations in physics (*e.g.*, 2nd stability).

Guidelines and Directions of the ARIES Research

- Optimization of tokamak power plant to achieve a combination of economic competitiveness, a high level of safety assurance, and attractive environmental features, thorough examination of a broad spectrum of tokamak and fusion-power-core configurations.
- Self-consistent integration of tokamak plasma, fusion power core, and balance of plant.
- Direct feedback and connection with present and proposed tokamak experiments and technology programs worldwide.
- Innovation and extrapolation from present data base only when they are needed and/or result in a dramatically improved product.

Expected Extrapolation for ARIES Power Plants



Fusion Plant Optimization Involves Interplay Among Four Major Cost Systems

- The four major cost items of a power plant are: (1) **current drive** and recirculating power, (2) **magnets**, (3) **blanket and shield**, and (4) **balance of plant**.
- Current-drive and recirculating power can be minimized by reducing the plasma current and maximizing bootstrap current, *i.e.*, the trade-off among MHD, bootstrap, and current drive determines the physics of optimum steady-state power plant.
- Magnet costs is reduced by increasing plasma β (trade-off against current-drive) for a given fusion power density. Alternatively, for the same β , higher magnetic field reduces the size of the tokamak and the cost of blanket and shield.
- High fusion power density (wall loading) reduces blanket and shield cost \implies First-wall neutron and heat flux concerns?
- Low activation material are needed to achieve the potential safety and environmental features of fusion. Advanced blanket designs increase the thermal efficiency of the power plant.

Major Parameters of ARIES Power Plants

	<u>ARIES-I</u>	<u>ARIES-II</u>	<u>ARIES-IV</u>
Aspect ratio	4.5	4.0	4.0
Plasma major radius (m)	6.75	5.6	6.0
Plasma minor radius (m)	1.5	1.4	1.5
Toroidal field on axis (T)	11.3	7.7	7.7
Toroidal field on the coil (T)	21	16	16
Plasma beta	1.9%	3.4%	3.4%
Plasma current (MA)	10	6.4	6.6
Bootstrap fraction	0.68	0.87	0.87
Current drive power (MW)	98	27	30
Neutron wall loading (MW/m ²)	2.5	3.5	3.2

Trade-off Among MHD, Bootstrap, and Current Drive Determines Optimum Tokamak Power Plant

- High β^* to increase fusion power density:

$$\star \beta < \beta_N \frac{I}{aB}$$

- Low current-drive power to minimize recirculating power fraction:

- ★ Low-current operation;

- ★ High $I_{BS}/I \rightarrow \epsilon\beta_p \sim 1$;

- ★ Good bootstrap current density alignment.

- The Troyon limit can be written as:

$$(\epsilon\beta_p) \left(\frac{\beta}{\epsilon}\right) < 0.5 (\beta_N/20)^2 (1 + \kappa^2)$$

- High I_{BS}/I condition leads to low values of β/ϵ .

Trade-off Among MHD, Bootstrap, and Current Drive Determines Optimum Tokamak Power Plant

- For 1st stability, it is not possible to exceed $I_{BS}/I_p \sim 0.7$ for conventional profiles.

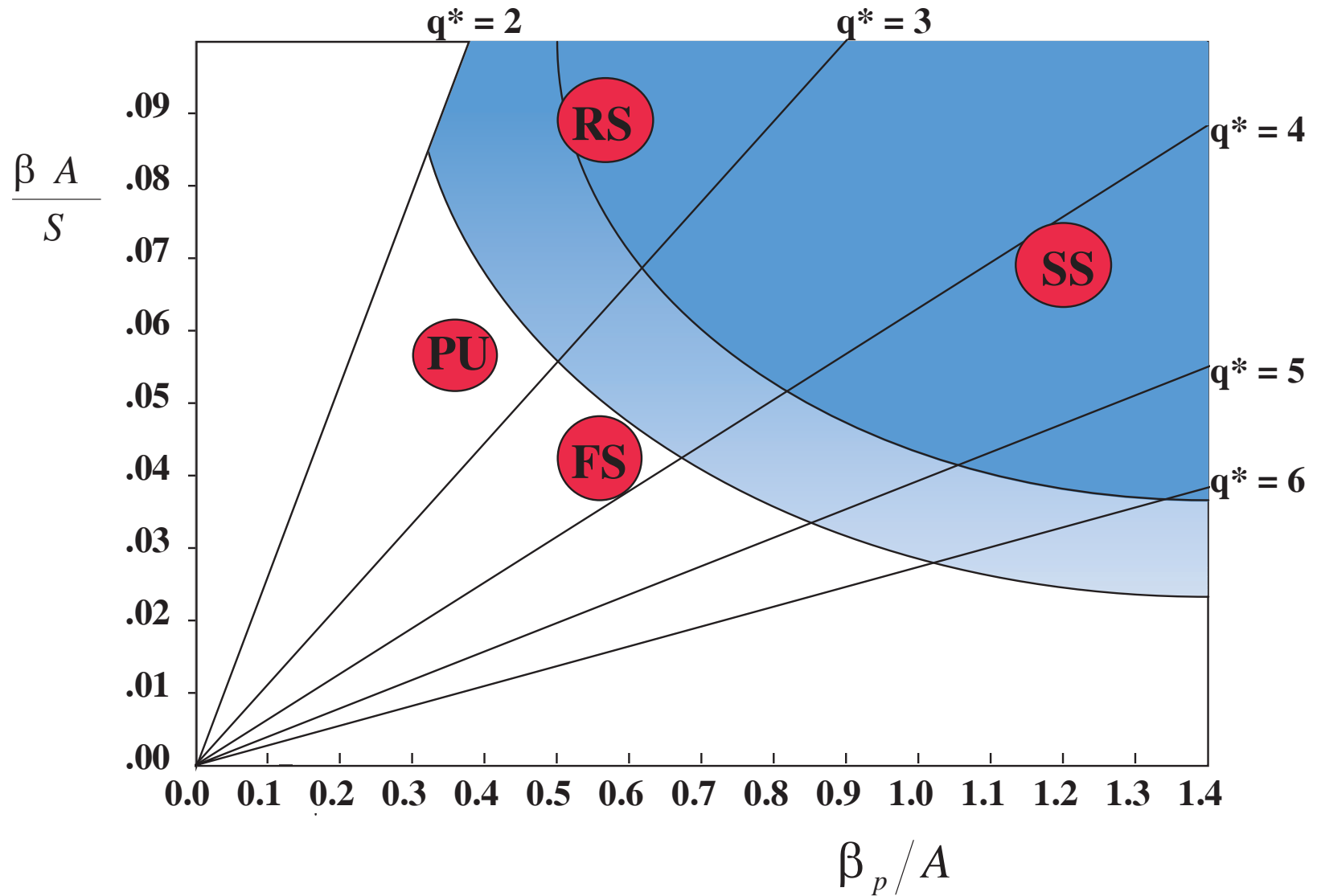
Operate at high aspect ratio (low current) and raise q_o . β is low, requiring high B to achieve reasonable fusion power density which scales as $(\beta B^2)^2$.

- Alternatively, use the current-drive system to produce favorable plasma current profiles which allow increasing β_N at $\epsilon\beta_p \sim 1$. (2nd Stability, reversed-shear mode).

Values of $I_{BS}/I_p \gtrsim 0.9$ are possible for several configurations:

- ★ Centrally peaked current with $q_0 \sim 2$ and $\beta_N \sim 5$;
- ★ Off-axis peaked current with $q' < 0$ and $\beta_N \sim 5$;
- ★ No second stability found for kink $n = 1$ mode with no conducting wall.

Tokamak Physics Regimes



The Operating Space of Tokamak Power Plants

	1st Stability Regime	2nd Stability Regime
Steady State	Modest β Modest β_p <u>ARIES-I</u>	Modest to high β High β_p <u>ARIES-II to -IV</u>
Pulsed	High β , low β_p or Modest β , Modest β_p <u>PULSAR</u>	Not Possible

Principal Conclusions of ARIES Study – Plasma Engineering

- Optimum tokamak power plants all have a low plasma current and a large bootstrap current fraction.
 - ★ 1-st stability tokamaks optimize at high aspect ratio with a low plasma β .
 - ★ 2-nd stability tokamaks optimize at a modest β regime in which $\epsilon\beta_p \propto 1$.
 - ★ The PULSAR study indicates that the pulsed tokamaks also optimize in this regime.
- Plasma parameters are inter-dependent. An attractive power plant requires optimization of a self-consistent plasma as opposed to optimization of a single plasma parameter (*i.e.*, a plasma with highest β does not necessarily result in an optimum tokamak plant).

Engineering Features of ARIES-I

- Advanced superconductor (Nb_3Sn) toroidal-field magnets.
- ARIES-I blanket is a He-cooled design with SiC composite structural material, and Li_2ZrO_3 solid tritium breeders.
- Be is used as the neutron Multiplier.
- W is used as the coating of the divertor plates.
- To reduce activation, both Zr and W are proposed to be isotopically tailored.
- An advanced Rankine power conversion cycle as proposed for future coal-burning plants (49% gross efficiency).

Engineering Features of ARIES-IV

- ARIES-IV blanket has used the ARIES-I design experience.
- ARIES-IV blanket is a He-cooled design with SiC/SiC composite structural material, Li_2O solid tritium breeder, and Be neutron multiplier.
- SiC bulk material and B_4C are used as the shield material.
- An advanced Rankine power conversion cycle as proposed for future coal-burning plants (49% gross efficiency).
- By eliminating the Li_2ZrO_3 breeder and W coating of the divertor plate, and minimizing Be inventory, a high level of safety assurance is projected for ARIES-IV.

Engineering Features of ARIES-II

- ARIES-II blanket is made of vanadium alloy (V-5Cr-5Ti) structural material with liquid lithium as the coolant and tritium breeder.
- ARIES-II blanket utilizes an insulating layer (TiN) which will reduce the MHD pressure drop by a factor of 20 (< 1 MPa).
- Because of the low pressure drop, the blanket design has been optimized toward heat transfer and simplicity.
- Because of high coolant outlet temperature, a gross thermal efficiency of $\sim 45\%$ is estimated.

Principal Conclusions of ARIES Study – Blanket Engineering

- ARIES designs demonstrate that potential safety and environmental features of fusion can be realized (at least at the level of conceptual designs).
- The advanced physics of ARIES-II/-IV did not lead to a major reduction in extrapolation from present technology data base.
- A large gap exists between present data base and needs of a fusion power plant. The technology program is in an early scientific stage and requires considerable effort even to enter an engineering phase.
- An extensive fusion technology and materials R&D effort must begin NOW in order for these technologies to be tested at nearly full scale in ITER and be ready for the fusion DEMO. Intense neutron source is not sufficient to provide this data base.
- The material development program should emphasize materials that also have other applications (*e.g.*, aerospace and automotive industries). This will ensure that these materials are developed at reasonable costs.

Principal Conclusions of ARIES Study – Blanket Engineering

- SiC composite is an attractive structural material for fusion application, but many developmental issues are to be resolved.
- The safety characteristics of fusion power plants can be compromised by small components (*i.e.*, coating of the divertors)
- Even with Li_2O as the breeding material, tritium self-sufficiency cannot be assured without Be in the blanket.
- The tritium inventory in high temperature Li_2O as well as the maximum operating temperature of Li_2O are uncertain.

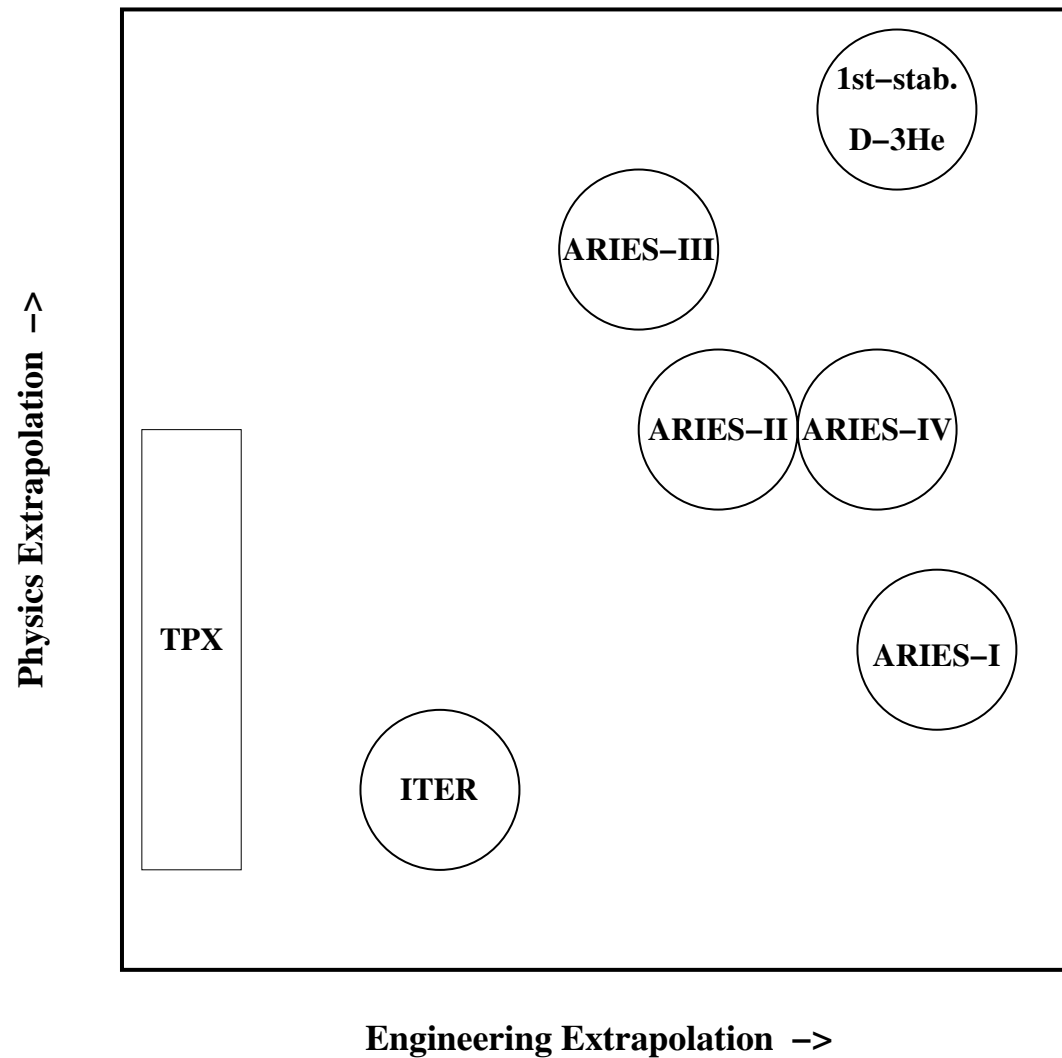
Principal Conclusions of ARIES Study – Blanket Engineering

- An insulating coating is required for self-cooled liquid lithium designs. The development and demonstration of the reliability of such an insulating coating in fusion environment remains.
- The recovery of bred tritium from lithium to a concentration of ~ 1 ppm is a critical issue.
- The demonstration of safe operation of a large liquid metal system in fusion environment is necessary.

Principal Conclusions of ARIES-III Study

- Realization of D–³He tokamak power plants requires major advances in physics.
- Use of D–³He fuel results in simplification of the fusion power core (no breeding blanket).
- The engineering of the first wall and divertor is difficult:
 - ★ High surface heat flux,
 - ★ High reflectivity for μm waves (1-30 THz synchrotron radiation),
 - ★ High thermal load of a disruption.
- The radiation-damage lifetime of the first wall and shield is longer than the plant lifetime.
- A parallel path to achieving the attractive safety and environmental features of fusion is the development of very-low-activation material for D–T power plants.

Required Extrapolation for ARIES Power Plants



Cost Comparison of Fusion with Other Sources (for 1,200 MWe Power Plants, in mills/kWh)

FOSSIL

- Advanced Coal* 61
- Future Gas Turbines* 68 - 86

FISSION

- PWR-Best Experience/Ave. Exp. 57/90-95
- Advanced LWR (APWR) * 45
- Improved LWR (IPWR) * 47

FUSION (Tokamak)**

- ARIES-I 75 - 96
- ARIES-II/IV 60 - 80

*DOE - 1992 U.S.\$ Estimates

**Based on ORNL nuclear data base methodology.

Present-Day Cost of Electricity

- At present, mostly gas turbines are installed as the new power plants at a cost ranging from 80 to 100 mills/kWh depending on location of the plant and cost of natural gas. Obviously, the market believes coal and fission are considerably more expensive than 80 to 100 mills/kWh.

Advanced-Fission Cost Estimate Assumes that All of the Problems with Fission Are Solved

- Public acceptance of fission so that funds for building a new power plant can be obtained at a reasonable interest rate.
 - Relaxation of regulatory environment so that the licensing costs, which are not included in the cost projections, would be small.
 - Improved safety (LSA=3 in fusion terms) would allow elimination of certain redundant components resulting in a 25% cost saving. For comparison, in fusion cost analysis, we assume a 25% cost saving for LSA=1 plants (5% cost saving for LSA=3 plants).
 - Solution to waste disposal problem with minimal cost.
 - Unlimited fuel at present-day costs without problems regarding proliferation of nuclear material.
 - Assume substantial improvement in the availability (to 90%).
- ⇒ The cost of fission reactors would be considerably larger than any alternate sources if any of these assumptions are not realized.
- ⇒ We should develop a fusion-specific cost algorithm/model so that potential advantages of fusion are accounted for.

Principal Conclusions of ARIES Study

- Safety and environmental features of fusion power plant should be significantly better (*i.e.*, viewed as totally different) than fission reactors for fusion to be economically competitive. On the other hand, even ARIES-I would be acceptable if its safety and environmental features can be realized.
- Improved physics performance beyond ARIES-II/IV only marginally improves the economics of a power plant for a fixed and reasonable neutron wall loading. These improvements are much smaller than cost saving due to enhanced safety and environmental features of fusion.

Principal Conclusions of ARIES Study

- It is not clear whether increased wall loading beyond that of ARIES-II/IV would lead to improved economics because the following important items are not included in systems analysis:
 - ★ Impact of wall loading on safety and environmental features of the power plant. (Increased wall loading leads to increased inventory and afterheat.)
 - ★ Impact of wall loading on reliability, maintainability, and availability of the power plant. (Increase wall loading leads to lower reliability and/or higher unit cost and lower availability because of shorter radiation lifetime.)
- ⇒ Both safety and licensing and RAMI issues have major impact on the cost of the power plant and should be investigated.

Objectives of the PULSAR Study

- Study the feasibility and potential features of a tokamak with a pulsed mode of operation as a fusion power plant.
- Identify trade-offs which lead to the optimal regime of operation for a pulsed tokamak power plant.
- Identify critical and high-leverage issues unique to a pulsed tokamak power plant.
- Compare steady-state and pulsed tokamak power plants.

Approach: Build upon the ARIES designs and focus on issues unique to pulsed tokamak power plants:

PULSAR-I: SiC/He blanket;

PULSAR-I: V/Li blanket.

Pulsed vs Steady-State Operation

- Steady-state tokamaks (*i.e.*, ARIES-I) reduce the current-drive power by maximizing the bootstrap current fraction. The plasma should have a high β_p :
 - ★ β would be low;
 - ★ Substantial (~ 100 MW) of recirculating power is still needed.
- Pulsed tokamaks use “efficient” inductive current drive:
 - ★ Constraint on β_p is removed and β could be higher;
 - ★ Recirculating power for current drive is eliminated.
- Also, pulsed tokamak operation is “perceived” to be closer to the present plasma physics data base and understanding.

Pulsed vs Steady-State Operation

- Pulsed mode of operation, however, requires many critical issues to be resolved such as:
 - ★ Large and expensive power supplies for PF system;
 - ★ Thermal energy storage;
 - ★ Magnet design (cyclic fatigue, larger PF coils, rapid PF ramp rates);
 - ★ Fatigue in the first wall, blanket, shield, and divertor;
 - ★ Reliability of complex components under cyclic operation.

Power Flow in a Pulsed Tokamak

- Utilities require a minimum electric output for the plant to stay on the grid;
- Grid requires a slow rate of change in introducing electric power into the grid.
- Large thermal power equipment such as pumps and heat exchangers cannot operate in a pulsed mode. In particular, the rate of change of temperature in the steam generator is $\sim 2^{\circ}\text{C}/\text{min}$ in order to avoid boiling instability and induced stress.

\Rightarrow Therefore, steady electric output is required and energy storage system is needed.

Principal Conclusions of the PULSAR Study

- Both steady-state and pulsed power plants tend to optimize at larger aspect ratio and low current.
- Even though the plasma β is larger in a pulsed tokamak, the fusion power density (wall loading, etc) would be lower because for the same magnet, the achievable maximum field at coil would be lower (due to lower allowable stresses in the coils).
- The pulsed tokamak requires smaller extrapolation from present tokamak data base because there is no current drive system.
- It is “perceived” that pulsed operation would be more susceptible to plasma disruptions which would have major impact on the plant availability.

Principal Conclusions of the PULSAR Study

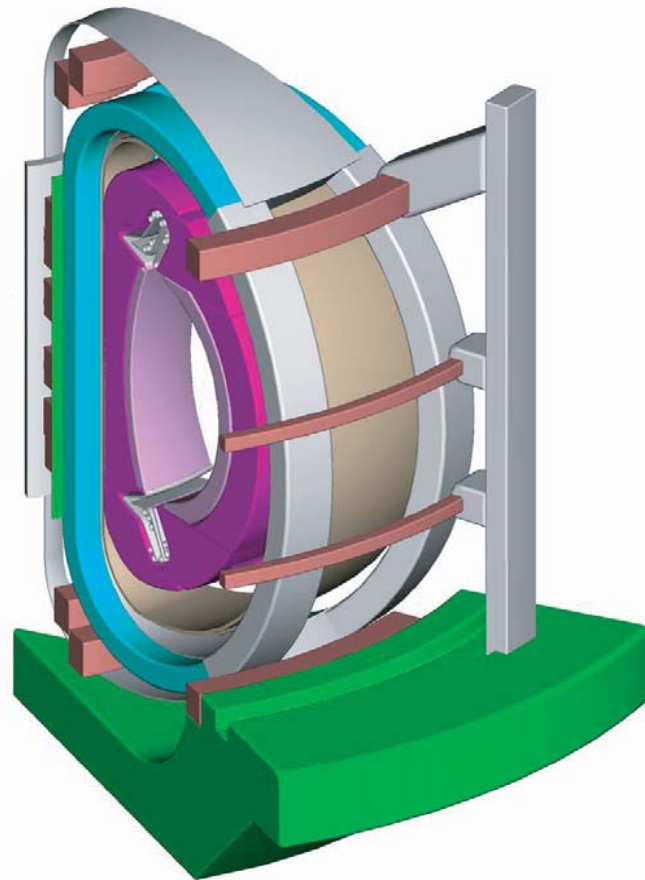
- A major innovation of the PULSAR study is a low-cost thermal storage system.
- Much more engineering data base is needed in order to make a sound assessment of impact of the fatigue on the design of the blanket and shield of a pulsed power plant.
- The magnet system and the fusion power core are much more complex in a pulsed tokamak. Ensuring that these systems would achieve the same reliability as a steady-state device would be a challenge and would definitely increase the cost of these component significantly.
- Assuming the same availability and unit cost for components, PULSAR is $\sim 20\%$ more expensive than a comparable ARIES-I-class steady-state power plant.

Major Parameters of PULSAR Power Plant

	<u>PULSAR</u>	<u>ARIES-I</u>	
Aspect ratio	4.0	4.5	
Plasma major radius (m)	8.5	6.75	7.9
Plasma minor radius (m)	2.1	1.5	1.75
Toroidal field on axis (T)	6.7	11.3	9
Toroidal field on the coil (T)	12	21	<u>16</u>
Plasma beta	2.8%	1.9%	1.9%
Plasma current (MA)	13	10	10
Bootstrap fraction	0.38	0.68	0.68
H factor (ITER89P)	2.5	2.5	1.9
Neutron wall loading (MW/m ²)	1.3	2.5	2.0
Cost of electricity (Mills/kwh)	92*		83

*Assuming the same plant availability and unit cost for components.

The PULSAR-I Fusion Power Core



The Operating Space of Tokamak Power Plants

	1st Stability Regime	2nd Stability Regime
Steady State	Modest β Modest β_p <u>ARIES-I</u>	Modest to high β High β_p <u>ARIES-II to -IV</u>
Pulsed	High β , low β_p or Modest β , Modest β_p <u>PULSAR</u>	Not Possible

PULSAR Plasma Regime of Operation

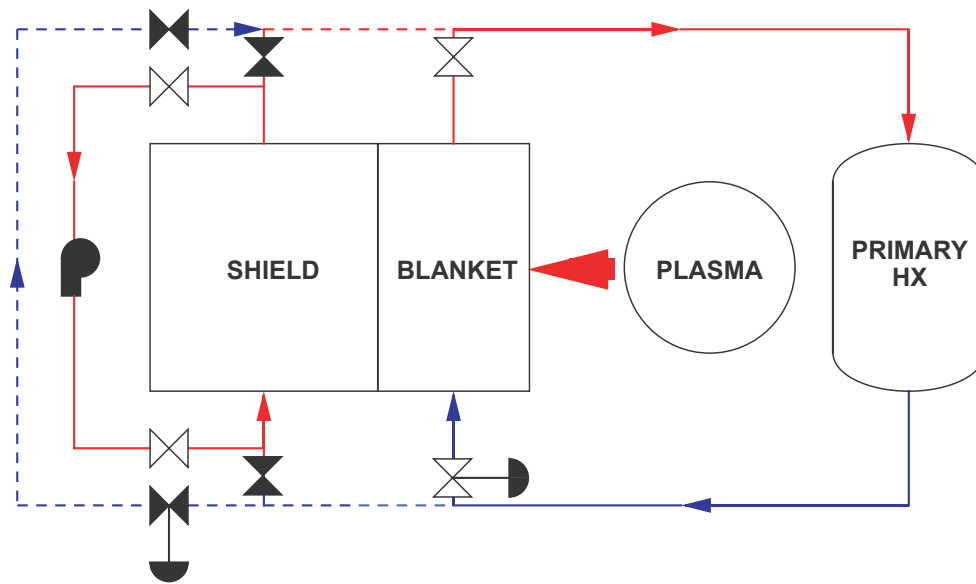
- The loop voltage induced by the “inductive” current-drive system is constant across the plasma:
 - ★ Current-density profiles (induced and bootstrap) are determined by n and T profiles;
 - ★ Pressure profile is $n \times T$
- Current-density profile cannot be tailored to achieve the highest possible β :
 - ★ β_N is limited to ~ 3.0 ;
 - ★ Bootstrap fraction is not large ($\sim 30\%$ to 40%);
 - ★ Second-stability operation is not possible.
- A large scan of possible ohmic equilibria was made and a fit to the data base was used in the system analysis.

PULSAR Energy Storage System

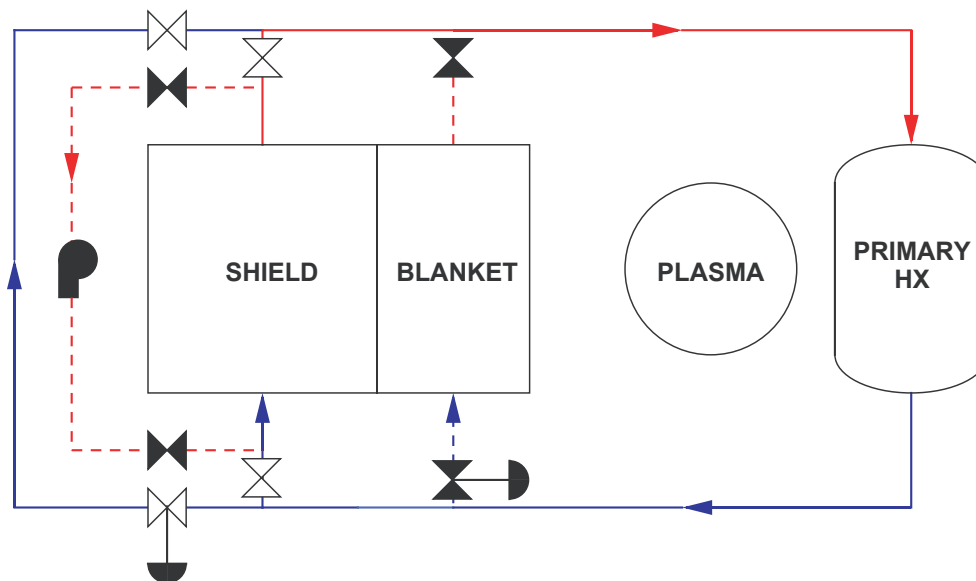
- An external energy storage system which uses the thermal inertia is inherently very large:
 - ★ During the burn, $T_{coolant} > T_{storage}$
 - ★ During the dwell, $T_{coolant} < T_{storage}$
 - ★ But coolant temperature should not vary much. Therefore, thermal storage system should be very large.
- PULSAR uses the outboard shield as the energy storage system and uses direct nuclear heating during the burn to store energy in the shield;
 - ★ This leads to a low cost energy storage system but the dwell time would be limited to a few 100's of seconds.

The PULSAR Thermal Energy Storage System

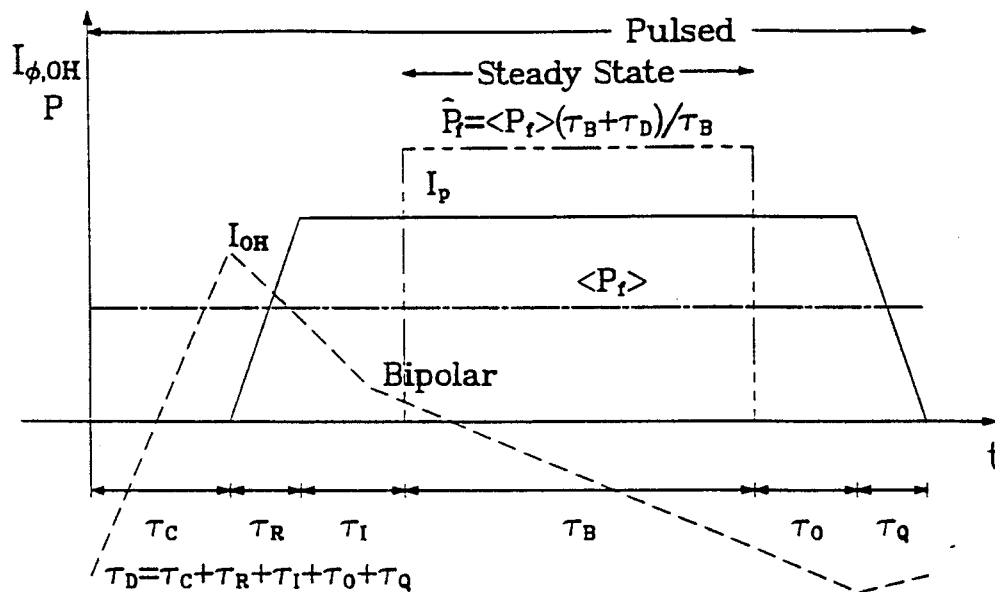
Energy Accumulated in Outer Shield During Burn Phase



Thermal Power Is Regulated by Mass Flow Control During Dwell Phase



The PULSAR Operation Cycle



Period	Event	Cost Impact
τ_C	Charge OH coils	Power Supplies ac losses Thermal storage
τ_R	Discharge OH coils Charge EF coils	Dump resistor Power Supplies ac losses rf capacity Thermal storage
τ_I	Ignite plasma	rf capacity Thermal storage
τ_B	Generate power	Volt-seconds
τ_I	De-ignite plasma	Thermal storage
τ_Q	Shutdown plasma	Thermal storage

Major Parameters of PULSAR Power Plant

PF charge-up time, τ_c 56 s

Current ramp time, τ_r 26 s

Plasma ignition time, τ_i 54 s

Plasma de-ignition time, τ_o 38 s

Plasma shutdown time, τ_q 26 s

Total: Dwell time, τ_d 200 s

Burn time, τ_b 7,200 s

Number of cycles 3,200 /year

The PULSAR Operation Cycle

- Plasma physics sets a “lower” limit for the dwell time.
- Because of the large step change in the cost of thermal storage system, the dwell time is basically set by the thermal storage system.
- The burn time is determined through trade-offs in the magnet system:
 - ★ Shorter burn time increase the number of cycles and lowers the allowable stresses;
 - ★ Longer burn time requires larger PF coils (higher volt-seconds) and larger out-of-plane loads on the TF coils.
- The cost of electricity is insensitive to burn time between 1 to 4 hours.

Toroidal-Field Magnets

- The TF magnet system for ARIES designs consists of TF coils bucked against a bucking cylinder. The overturning forces are reacted against each other through structural caps on the top and bottom of TF coils. The OH solenoid is inside the bucking cylinder.
- The ARIES TF magnet design cannot be applied to PULSAR.
- Because the plasma start-up time is short, large eddy currents would be induced in toroidally-continuous components such as the bucking cylinder and the structural caps. These eddy currents result in:
 - ★ Large joule losses in cryogenic structure;
 - ★ Reduced coupling of the PF coils to the plasma;
 - ★ Impact on plasma equilibrium and position.

Toroidal-Field Magnets

- The PULSAR TF magnet system is similar to the ITER design:
- OH solenoid is located between the TF coil and the bucking cylinder;
- Shear panels are used between the TF coils;
- Inner legs of the TF coils are keyed together to support the shear loads.
- Because of the elaborate key system, the supportable stress in the inner leg of the TF coils is reduced to an equivalent of ~ 50 MPa for a uniformly distributed forces.

Fatigue in First Wall and Blanket

V alloys:

- Fatigue (at 40,000 cycles) reduce the design stress by $\sim 20\%$.
- No thermal fatigue data is available.
- No irradiated fatigue data is available.

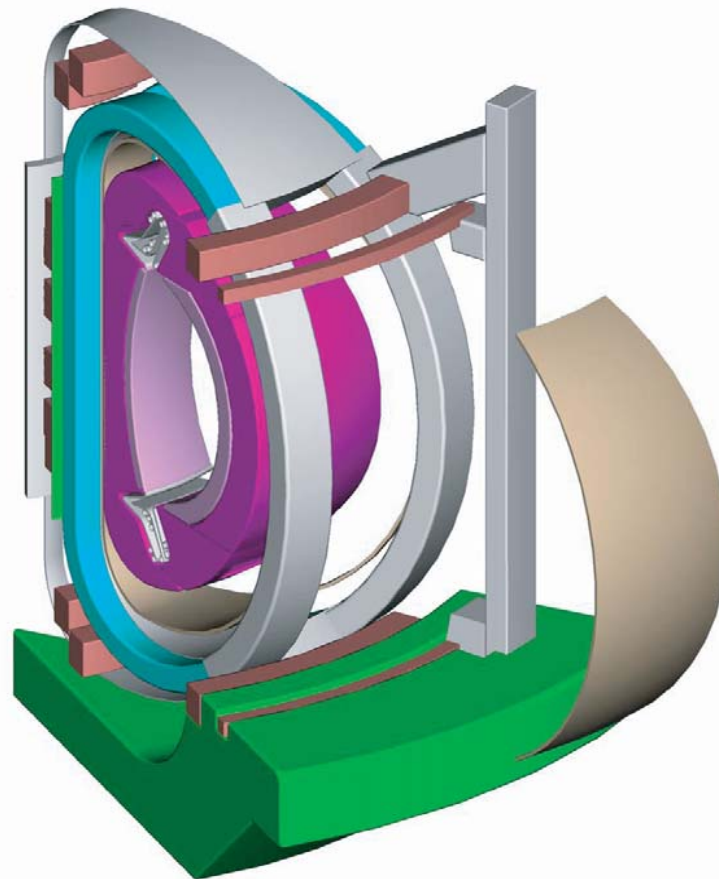
SiC Composites:

- No fatigue data.
- Data for SiC fiber/ Si_3N_4 matrix indicate that fatigue reduced the allowable stress in the material by 65%.

Fatigue in First Wall and Blanket

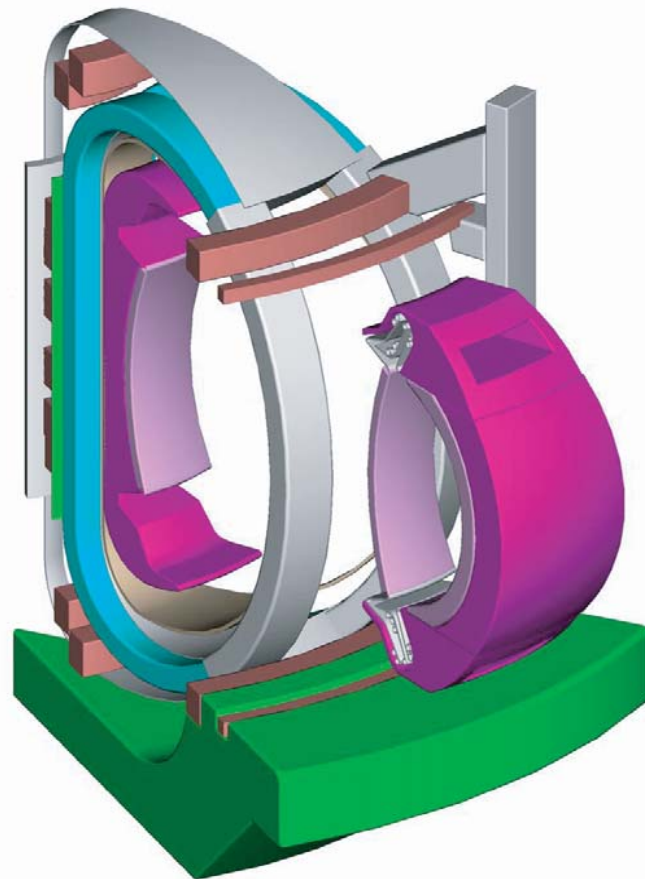
- The limited fatigue data for V-alloy structural material indicate that ARIES-II type designs can be utilized PULSAR-II divertor, first wall, blanket, and shield.
- Assuming that SiC fiber/Si₃N₄ matrix data applies to SiC composite, ARIES-IV type designs can be utilized PULSAR-I first wall, blanket, and shield. The ARIES-IV type divertor design may not be feasible for PULSAR-I.
- Much more engineering data is needed in order to make a sound assessment of the impact of fatigue on the design of the pulsed tokamak power plants.

Maintenace of The PULSAR-I Fusion Power Core Remove Vaccum Vessel Access Port



Maintenace of The PULSAR-I Fusion Power Core

Remove Fusion Core Sector



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