EXECUTIVE SUMMARY

The ARIES study was undertaken to determine the economic, safety, and environmental potential of tokamak fusion reactors and to identify physics and technology areas with the highest leverage for achieving attractive fusion power plants [1, 2]. To this end, the ARIES team, a national effort with international participation, has performed detailed reactor-design work and has explored reactor optimization and trade-off sensitivities using a cost-based systems code. The design effort has been directed to maximize the environmental and safety attributes of fusion through careful design and selection of materials.

From the interplay of detailed design, environmental and safety analyses, and system studies, the ARIES visions of tokamak reactors emerge. The ARIES program is pursuing several designs, each with varying degrees of extrapolation from existing physics understanding and technological achievement. This report presents the findings and details of the ARIES-I study. The ARIES-I reactor is based on a "modest" extrapolation from our present data base and understanding of tokamak physics [3]. The design relies on technologies that have been, at a minimum, already demonstrated in the laboratory and can be brought to an engineering standard on a 20-year horizon. In such cases, trends are already in place, often in programs outside fusion. The ARIES-II design will explore the benefits of potential advances in tokamak physics such as achieving the second MHD stability regime [4]. The ARIES program will also explore the potential of advanced fuel cycles, particularly D-^{3}He, in the context of the ARIES-III design.

ARIES-I is a conceptual, DT-burning, 1000-MWe reactor. The design has a moderately high plasma aspect ratio ($A \equiv 1/\epsilon = 4.5$) and low plasma current ($I_p = 10$ MA) at a relatively high poloidal beta ($\epsilon\beta_p \approx 0.6$). This approach maximizes the self-induced bootstrap current, which in turn minimizes the auxiliary power required to maintain the full plasma current. The lower plasma current also reduces the forces induced by a plasma disruption. The choice to operate at lower plasma current in the first MHD stability regime leads to a lower toroidal beta [5] and to the need for a high magnetic field. The toroidal field at the plasma center is 11 T, and the maximum field at the coil is 21 T. It is found that the maximum stress in the structural material of these magnets is about 800 MPa and, therefore, industrially available structural alloys can be used. The reference magnet structural material is Incoloy 908, one of the materials considered for the ITER design [6]. The toroidal-field magnet is an example of a design approach that fits the criterion of an achievable technology on a 20-year time horizon with an appropriate R&D program. ARIES-I also incorporates the very low-activation silicon-carbide composite as the structural material for the blanket and shield. The use of silicon-carbide composite greatly enhances the overall environmental characteristics of ARIES-I-type reactors.

The major parameters of the ARIES-I reactor are given in Table I. The key features of the design are:

1. Passive safety and low environmental impact: The materials adopted for the structure, breeder, and neutron multiplier lead to a reactor that: (1) satisfies Federal Regulations (10CFR61) for shallow-land burial of waste (Class C) [7]; (2) achieves Level of Safety Assurance 2 (large-scale passive safety) [8, 9], in which the safety of the public is protected by completely passive means; and (3) meets the criterion that there would be no off-site prompt fatalities, even in the event of a worst-case accident with the release of all mechanistically vulnerable radioactive inventory. If the ARIES-I reference breeder material (lithium zirconate) is replaced by lithium orthosilicate or lithium oxide, the ARIES-I design may achieve a Level of Safety Assurance 1 (inherent safety). Lack of data and concerns about the irradiation effects on chemical stability and tritium retention for lithium oxide and lithium orthosilicate have precluded the choice of these low-activation, low-afterheat breeder materials at this time.

2. Acceptable cost of electricity: The cost of electricity (COE) for an ARIES-I-type tokamak is projected to be about 65 mill/kWh in constant 1988 dollars. This value is comparable to predictions for advanced fission reactors (47 to 78 mill/kWh) and coal-fired plants (50 mill/kWh) developed on the same basis [10, 11]. The estimated COE does not take credit for the elimination of the nuclear qualification (N-stamp) requirement for most of the ARIES-I components. If the N-stamp requirement is obviated by the enhanced safety features of the design, then the projected COE could be reduced by up to approximately 25% to 50 mill/kWh.

3. Plasma performance as close as possible to present-day experimental achievements: The plasma operates in the well-established first MHD stability regime [5] at moderately high aspect ratio ($A = 4.5$). Steady-state operation is achieved by maintaining the plasma current through a combination of bootstrap current (providing about 68% of the total) and fast-wave, radio-frequency current drive. The required plasma energy-confinement time is close to that achieved experimentally (*i.e.,* a factor of 2

to 3 above the L-mode scaling). Impurity control is achieved with a high-recycling, double-null divertor. Reasonable heat fluxes on the divertor plates (~ 5 MW/m^2) and low plasma temperatures (< 20 eV) at the plates are estimated. Overall, the ARIES-I physics modeling is unparalleled in the context of power reactor studies with regard to the degree of physics realism and the level of self-consistency among the MHD, transport, current-drive, and impurity-control calculations.

4. High-field magnets: The desire to minimize the plasma current and disruption forces while maximizing poloidal beta and bootstrap-current fraction leads to reactors with high aspect ratio and high magnetic field. The toroidal-field magnets use Nb_3Sn superconductor in combination with an advanced CuNb stabilizer that is partially load bearing. The maximum field at the coil is 21 T, which is below the limit of the Nb_3Sn superconductor. The coil structure is Incoloy 908 operating at a stress level of about 800 MPa, which is consistent with its allowable stress. The allowable stress is lower for a structure subjected to cyclic loads, as would be the case if the reactor plasma were pulsed.

5. Low-activation, composite structural blanket: The blanket and shield use silicon-carbide composite as the structural material; they are manufactured as large integrated pieces utilizing techniques already in use or under development in the aerospace industry. The silicon-carbide composite structure was chosen because it is capable of high-temperature, high-stress operation while minimizing the level of induced radioactivity and afterheat. The coolant is helium at 10 MPa pressure. The breeder material is sphere-pac solid lithium zirconate with isotopically tailored zirconium to reduce neutron-induced activation. The low-activation neutron multiplier is beryllium.

6. Advanced Rankine power cycle: An advanced Rankine steam power cycle is adopted because the coolant exit temperature is sufficiently high (650 °C). This cycle is similar to that planned for future coal-fired power plants [12]. The predicted gross thermal efficiency is 49%.

The attractive features of fusion as embodied in a reactor of the ARIES-I type will not be achieved automatically. The necessary physics and technology demonstrations must be achieved through appropriate R&D programs. The key research and development items are:

A. Tokamak Physics

1. Establish the scaling of plasma energy transport at high aspect ratio (4.5 and higher).
2. Demonstrate fully the fast-wave, radio-frequency (RF) current-drive technique and high bootstrap current.
3. Determine burning-plasma dynamics in systems dominated by alpha-particle heating.
4. Determine alpha-particle transport and removal characteristics in a burning plasma.
5. Demonstrate impurity control in poloidal divertors at the loadings and plasma conditions predicted for a high-recycling divertor.
6. Reduce the probability of major disruptions.

B. Reactor Technology

1. Develop manufacturing technology for high-performance, large-scale silicon-carbide (SiC) composite components.
2. Determine the effects of irradiation on the properties of SiC composites.
3. Verify the toroidal-field magnet design, including the use of partial load-bearing stabilizing materials and Nb_3Sn superconductors operating up to 21 T.
4. Determine the high-temperature properties of alternative solid breeders under irradiation. Lithium oxide and lithium orthosilicate would be excellent low-activation, low-afterheat alternative solid tritium breeders. Specifically, determine the irradiated chemistry of lithium orthosilicate, including the possible formation of metasilicate and its impact on the properties of the material.
5. Specialize a technology such as atomic-vapor laser-isotope separation (AVLIS) to the isotopic tailoring of zirconium (to be used in a lithium-zirconate tritium breeder) and of tungsten (to be used in the divertor target coating).
6. Verify the passive safety features of the ARIES-I design through testing and demonstration.
7. Develop the requisite remote maintenance technology and procedures to ensure acceptable levels of reactor reliability and availability.
8. Develop a steady-state, high-speed ($\sim$ 5 to 20 km/s) pellet-injection system.

The ARIES-I conceptual design study demonstrates that a tokamak fusion reactor with a physics design base that is close to existing achievements can fulfill the promise of fusion as an attractive energy source. The three ARIES designs will form a spectrum of possible tokamak reactors based on different advancements in physics and technology. This ensemble of ARIES designs will highlight and quantify the areas with the highest leverage for achieving the best tokamak reactor and will provide a sensible basis for evaluating the full potential of the tokamak as a commercial reactor.

Table I.
Operating Parameters of the ARIES-I Tokamak Reactor

Aspect ratio	4.5
Major radius (m)	6.75
Minor plasma radius (m)	1.50
Plasma vertical elongation	1.8
Plasma current (MA)	10.2
Toroidal field on axis (T)	11.3
Toroidal beta	1.9%
Average neutron wall load (MW/m^2)	2.5
Primary coolant	Helium at 10 MPa
Structural material	Silicon-carbide composite
Breeder material	Sphere-pac Li_2ZrO_3
Neutron multiplier	Sphere-pac beryllium
Coolant inlet temperature (°C)	350
Coolant exit temperature (°C)	650
Fusion power (MW)	1,925
Total thermal power (MW)	2,544
Net electric power (MW)	1,000
Gross efficiency	49%
Net plant efficiency	39%
Recirculating power fraction	20%
Mass power density (kWe/tonne)	99
Cost of electricity (mill/kWh)	65

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