Advanced Design Program (ARIES)

Final Report

for the period

January 1, 2013 to December 31, 2015

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Synopsis

The original 3-year research plan proposed for ARIES included three main tasks:

1. Completion of ARIES research on PMI/PFC issues.
2. Detailed engineering design and analysis of divertors and first wall/blankets.
3. Mission & requirements of FNSF.

Major changes to the program occurred during the period of performance, impacting the pace and scope of the research. The ARIES budget was cut substantially (by more than half) during the first year. In January 2014 the program management officially transferred to PPPL, leaving UCSD with an additional budget cut (again in half), reduction in work scope and layoffs of both students and staff. Notwithstanding all of these major impediments, still the principal goals of the program were met. The ARIES-ACT study was completed and the results documented in a special issue of Fusion Science and Technology. These results include detailed engineering analysis of the blanket and divertor. Contributions were made to the newly formed FNSF program, now led by PPPL. These contributions include support for the originally planned development of the mission and requirements of the facility, but also substantial support in the development and definition of a design point.

Results are summarized briefly in the following sections, organized by year. Extensive documentation was produced in the form of peer-reviewed journal articles and project reports. These are listed at the end of this report. All of the ARIES results (including publications, project meeting presentations and minutes, conference calls, town meetings, US-Japan workshops, *etc.*) are publicly available from the on-line archive. That archive has been relocated to the URL http://aries.pppl.gov

2013: UCSD Contributions to the ARIES Study

In 2013 our primary accomplishments were: (1) the completion and documentation of the ARIES-ACT1 fusion power plant study and (2) design and analysis of the ARIES-ACT2 power plant. ACT1 is a high-beta (wall stabilized) tokamak with a high-temperature PbLi-SiC blanket. ACT2 is a lower beta tokamak with a dual-cooled (PbLi/SiC and He/steel) blanket having a more modest coolant outlet temperature. Table 1 summarizes the main system parameters for these two devices.

Table 1. ACT1 and ACT2 system parameters

	ACT1	ACT2	
R (m)	6.25	9.75	m
$\beta_{Nthermal}+\beta_{Nfast}$	5.64	2.6	
f_{BS}	0.91	0.77	
q_{95}	4.5	8	
I_p (MA)	10.93	13.98	MA
B_T on axis (T)	6	8.75	T
B_T on coil (T)	11.83	14.38	T
P_{recirc} (MW)	160	321	MW
Fusion gain	42.5	25	
$<P_n>$ @FW	2.45	1.47	MW/m^2
Peak q_{FW}	0.27	0.28	MW/m^2
Peak q_{div}	13.3	10	MW/m^2
h_{th}	0.58	0.45	
COE	64.32	86.2	mill/kWh

Extensive documentation was produced during 2013, as detailed in the publication list. All aspects of the ACT1 design study have been published in peer-reviewed journals, including physics, engineering, neutronics and safety.

UCSD provided project management and led various technical activities including power core engineering, vacuum vessel design and analysis, configuration and maintenance, and CAD drawings. We supported independent subcontractors, and hosted a long-term visitor from Karlsruhe Institute of Technology.

UCSD arranged three project meetings and several conference calls in 2013. We participated in several national and international meetings, most notably the 2013 US/Japan Workshop on Power Plant Studies and Advanced Technologies with participation from China and Korea (26-27 February 2013, Kyoto University, Uji Japan) and the 25th IEEE/NPSS Symposium on Fusion Engineering (June 10-14, 2013, San Francisco). Individuals contributed to several other meetings and workshops.

2014: UCSD Contributions to the FNSF Study

"Fusion Nuclear Science Facility" (FNSF) is a generic term referring to an experimental facility between ITER and a demonstration reactor, with the goal of fusion nuclear testing and validation. In 2014 the primary technical accomplishments at UCSD were: (1) FNSF device definition and R&D needs, (2) FNSF system code development, testing and implementation, and (3) final documentation of the ARIES-ACT1 power plant study. In addition, UCSD participated in project meetings and conference calls, and was involved in the organization of three international conferences and workshops.

1. FNSF device definition and R&D needs. During the early stages of the FNSF study, it is crucially important to establish the role, mission and requirements of the device. This requires a deep understanding of the current status of R&D in both plasma confinement and fusion technology, and the expected roles and requirements of other facilities and programs on the pathway to fusion energy (such as ITER, Demo, confinement experiments and nuclear technology R&D programs). UCSD contributed to the development of scenarios, and also led the production of "white papers" describing the R&D status and needs in four areas:

(a) challenges using water in a fusion power core,
(b) the technology readiness of helium as a fusion power core coolant,
(c) a strategy for FNSF divertor development, and
(d) R&D needs related to the materials-design interface for fusion power core components.

2. FNSF system code. Systems analysis of FNSF helps to explore tradeoffs and identify potentially attractive regions of parameter space. The engineering module of the ARIES systems code was substantially updated and rewritten for higher performance and more seamless integration with the other elements of the system code. The engineering algorithms for pumping power were improved, including more sophisticated treatment of the DCLL blanket and the helium-cooled divertor. Support was provided to PPPL in other areas of code development and parameter space exploration for FNSF.

3. ARIES-ACT closeout. Extensive documentation was produced during 2014, as detailed in the publication list. Three papers on ARIES-ACT with UCSD primary authors were submitted, reviewed, revised and accepted for publication in the journal *Fusion Science and Technology*.

4. Other activities. UCSD staff attended (in person) both of the project review meetings held during 2014, at PPPL (January) and Idaho Falls (June). In March, Dr. Tillack hosted the 2014

US/Japan Workshop on Power Plant Studies and Advanced Technologies. He served on the program committee, as well as attended and presented an invited talk, at the 21st ANS Topical Meeting on Fusion Energy. Dr. Tillack also serves as the Technical Program **chair** of the 2015 IEEE/NPSS Symposium on Fusion Engineering; his responsibilities began to ramp up in 2014, and continued through June 2015.

2014 Conferences and Meetings

M. S. Tillack and J. P. Blanchard, “First wall, divertor and blanket/shield issues,” Fusion Nuclear Science Facility Study Kick-off Meeting, January 2014, Princeton Plasma Physics Laboratory.

M. S. Tillack, “Overview of the ARIES ACT2 power core,” US-Japan Workshop on Fusion Power Plant Studies and Advanced Technologies, March 2014, UC San Diego.

M. S. Tillack, P. W. Humrickhouse and S. Malang, “Assessment of water and helium as fusion power core coolants,” FNSF Face-to-Face Meeting, June 2014, Idaho National Laboratory.

M. S. Tillack, “Key challenges for developing an attractive tokamak power plant” (invited), 21st Topical Meeting on the Technology of Fusion Energy (TOFE), November 2014.

C. E. Kessel, et al., “The Fusion Nuclear Science Facility (FNSF), the Critical Step in the Pathway to Fusion Energy,” (invited), 21st Topical Meeting on the Technology of Fusion Energy (TOFE), November 2014.

2015: Design Options, Systems Analysis, and Transient Heating Prescriptions for FNSF

1. Evaluation of design options for FNSF

Starting in 2014, design options for FNSF were evaluated. Most notably, at UC San Diego we published a journal article on the use of water in the fusion power core and a technical report on the use of helium as a power core coolant. In 2015 we continued this activity by reviewing divertor design options and DCLL blanket design options.

The most attractive and credible divertor option for high-temperature operation in a high-fluence neutron environment is the He-cooled W-alloy concept. That concept has remaining uncertainties, but the database is growing with worldwide R&D efforts, especially at KIT. If we restrict water from the power core, then the only alternative under scrutiny is liquid metal cooling. That option has much greater uncertainty, especially the free surface option with its strong interactivity with the plasma. We contributed to the 2015 DOE PMI workshop, with results published in two white papers and in the final report, "Fusion Energy Sciences Workshop on Plasma Material Interactions: Report on Science Challenges and Research Opportunities in Plasma Materials Interactions," May 4-7, 2015. We also presented a review of divertor design options at an FNSF project meeting.

The DCLL blanket was chosen as the top candidate base blanket for FNSF due to its attractive features, compatibility with FNSF design parameters, and long history of R&D in the US and worldwide. The DCLL blanket can operate in different temperature regimes, which is one of its attractive features. We provided input to the evaluation of operating parameters, and also helped to coordinate analysis tasks performed at other institutions, most notably UCLA.

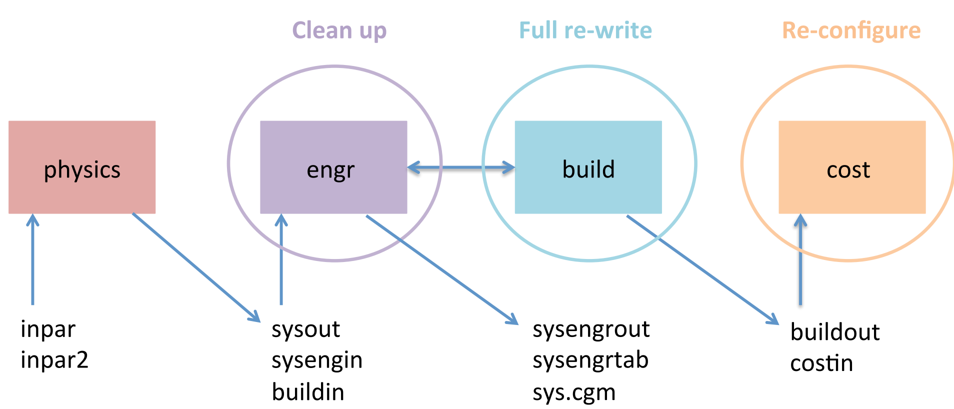

Figure 1. Schematic of the system code flow from physics analysis, to engineering analysis to build and costing.

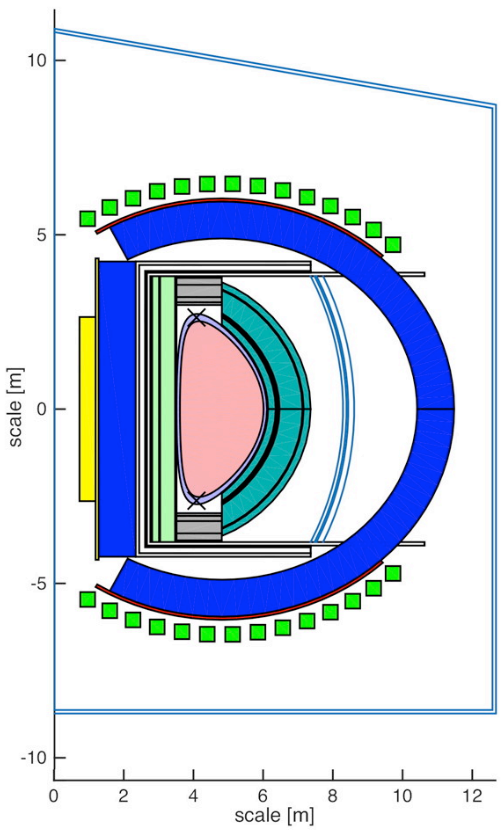

Figure 2. Cross section of latest FNSF reference design as defined by the new build algorithm

2. System code efforts

In 2015, the system code, shown in Figure 1, which is used to impose self-consistency and explore design variations, was extensively rewritten. The engineering, tokamak build and costing routines were recreated "from scratch". In 2015, we continued debugging activities, performed benchmarking against results obtained using the previous code, and implemented several improvements. Most notable among these improvements were: (1) changes to costing for concepts that do not generate and sell electricity, and (2) fixes to the build, espcially in the placement of the outboard TF coils. (Figure 2 shows a current cross section of the tokamak as produced by the build section of the code).

Many of the costing algorithms used in the old ARIES systems code were based on net electric power. For FNSF, electricity to operate the plant may be purchased rather than generated. Even using net electric power as a "placeholder" would be inappropriate, because these devices tend to use large amounts of recirculating power for sustainment. For example, Figure 3 shows a scan of design points comparing the gross electric power vs. net electric power (assuming electricity is generated using high grade heat from the power core). Net electric can be much less than gross electric, or even negative in some cases. Costing algorithms were changed to use thermal power, electricity consumption, or other parameters that more accurately represent system size and cost in this regime.

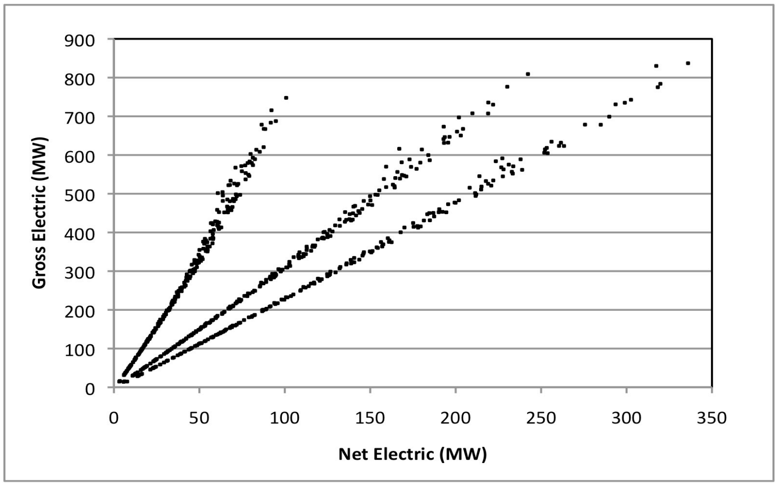

Figure 3. Comparison of gross electric and net electric power for a range of FNSF design points

Several scans of parameter space were generated as part of the debugging and testing of the code. These were also used in the selection of a reference design point for more detailed analysis. For example, Figure 4 shows a scan of the facility total capital cost as a function of the fusion power for three different major radii (4, 5 and 6 m). The chosen reference design point has a major radius of 4.8 m and fusion power of 517 MW.

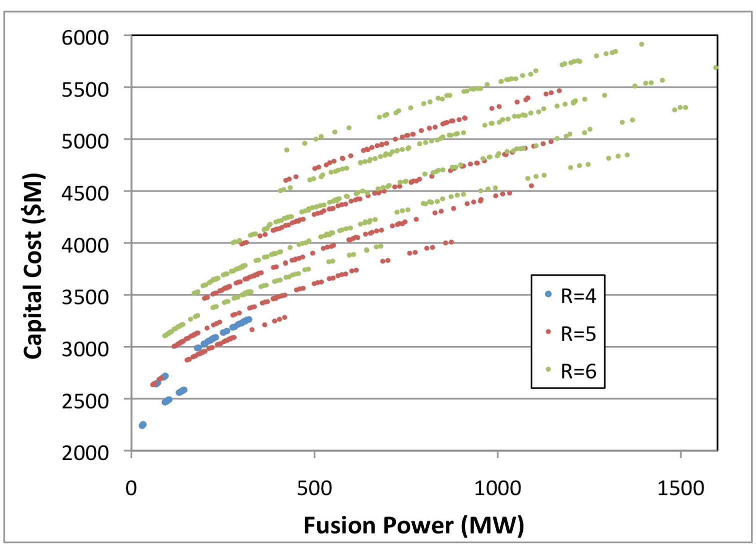

Figure 4. Capital cost of the facility vs. fusion power

3. Transient specifications

In order to perform analysis of the transient behavior of in-vessel components, transient loading conditions must be defined. In ARIES-ACT, a methodology was established to approximate the thermal and electromagnetic loading on in-vessel components using scaling laws calibrated against real experimental data. Using that methodology, we estimated FNSF loading conditions from ELMs and disruptions using baseline FNSF design parameters (see Table 2).

The general methodology is to determine the total energy released, E, (sometimes as a fraction of the total available energy), the time over which the energy is released, t, and the deposition area, A. A temporal profile of heat flux, q, can be obtained from q=E/(At). In most cases, a triangular waveform is assumed, such as that shown in Figure 5, with the possibility of different rise and fall times. Results for ELM's and disruptions are presented in Tables 3 and 4.

Table 2. Baseline parameters for transient analysis

Parameter	**Value**	**Explanation**
P_f, MW	517	fusion power
R, m	4.8	major radius
P_{SOL}, MW	173	particle transport power through the scrape off layer
$f_{rad,divertor}$	0.9	Fraction of SOL power radiated in the divertor
λ_q, mm	5.05	$\lambda_q\,(m) = 7.25\text{x}10^{-2}\, q_{95}^{0.75}\, n_L^{0.15} / (P_{SOL}^{0.4} B_T)$
$q_{div,OB}^{peak}$, MW/m^2	10.8	peak outboard divertor heat flux averaged over the conduction footprint
$q_{div,IB}^{peak}$, MW/m^2	3.9	peak inboard divertor heat flux averaged over the conduction footprint
$A_{FW,OB}$, m^2	183	total outboard first wall area
$A_{FW,IB}$, m^2	97	total outboard first wall area
$A_{div,cond}$, OB, m^2	1.33	steady state (inter-ELM) conduction footprint on the outboard divertor
$A_{div,cond}$, IB, m^2	1.14	steady state (inter-ELM) conduction footprint on the inboard divertor
$A_{div,rad}$, OB, m^2	31.7	steady state (inter-ELM) radiation footprint on the outboard divertor
$A_{div,rad}$, IB, m^2	13.6	steady state (inter-ELM) radiation footprint on the inboard divertor

Table 3. ELM loading conditions

Parameter	Value	Explanation
V_{plasma}, m^3	263	
W_{ped}, MJ	39	
T_{ped}, keV	3.0	
n_{ped}, $10^{20}/m^3$	1.25	
DW_{ELM}/DW_{ped}	0.2	
DW_{ELM}^{large}, MJ	7.8	total ELM energy
$DW_{ELM}^{large,divertor}$, MJ	3.9	half goes to the divertor, half to FW
area expansion factor in divertor	4	observed experimentally
$A_{ELM,div}^{OB}$, m^2	5.32	footprint area in **each** divertor top/bottom
$A_{ELM,FW}^{OB}$, m^2	45.75	1/4 of the OB FW area (IB FW not exposed)
$A_{disrupt,FW}^{OB}$, m^2	91.5	1/2 of the OB FW area for disruptions
$t_{\|\|}$, ms	0.38	$\tau_{\|\|} = 2\pi R\ q_{95}/c_{s,ped}$
$Dt_{ELM,rise}$, ms	0.76	2 * $t_{\|\|}$
$Dt_{ELM,fall}$, ms	1.52	4 * $t_{\|\|}$
f_{ELM}, Hz	6.65	$f_{ELM}*W_{ELM}$ = 20-40% of P_{SOL}
f_{ELM} x DW_{ELM}^{large}, MW	52	transport power into ELM's
$q_{div,OB}^{peak}$ (ELM), MW/m^2	418	peak heat flux in divertor from ELM (actual)
inter-ELM transport power, MW	121	
inter-ELM fraction	0.70	
$q_{div,OB}^{peak}$ (inter-ELM), MW/m^2	7.56	
$q_{div,IB}^{peak}$ (inter-ELM), MW/m^2	2.73	
$q_{FW,OB}^{peak}$ (ELM), MW/m^2	74.8	actual peak

Table 4. Disruption loading conditions

Parameter	Value	Explanation
W_{th}, MJ	169	plasma stored energy
mitigation factor	0.1	10% W_{th} to divertor in mid-plane disruption
$W_{th,div}$, MJ	16.9	
$W_{th,FW}$, MJ	152.1	90% W_{th} to first wall
$W_{th,FW,OB}$, MJ	121.7	80/20 split OB/IB
$W_{th,FW,IB}$, MJ	30.4	
$A_{dis,div}^{OB}$, m^2	13.3	per divertor, 10x expansion *vs*. SS
$A_{dis,div}^{IB}$, m^2	11.4	"
$A_{dis,FW}^{OB}$, m^2	91.5	half of the OB FW
$A_{dis,FW}^{IB}$, m^2	48.5	half of the IB FW
Dt_{TQ}, ms	1.9	(average of 1.2-2.5 ms)
thermal quench rise time, ms	1.9	
thermal quench fall time, ms	5.7	2-4 times the rise time (we use 3)
$q_{th,div}$, MW/m^2	217	peak, 10% to 2 OB divertors, 65% imbalance
$q_{th,FW,OB}$, MW/m^2	350	peak, 90% to FW, 80%OB
$q_{th,FW,IB}$, MW/m^2	165	peak, 90% to FW, 20%IB
W_{mag}, MJ	124.6	$W_{mag,int} + 0.2W_{mag,ext}$
$W_{mag,int}$, MJ	70	plasma internal energy
$W_{mag,ext}$, MJ	273	external inductance with structures
Dt_{CQ}, ms	18	(correlation from ITER database)
$f_{rad,FW}$	0.8	fraction of W_{mag} radiated to FW
$f_{rad,FW,OB}$	0.8	fraction of FW radiation to OB
$f_{rad,FW,IB}$	0.2	fraction of FW radiation to IB
$q_{mag,FW,OB}$ MW/m^2	48.4	
$q_{mag,FW,IB}$ MW/m^2	22.8	

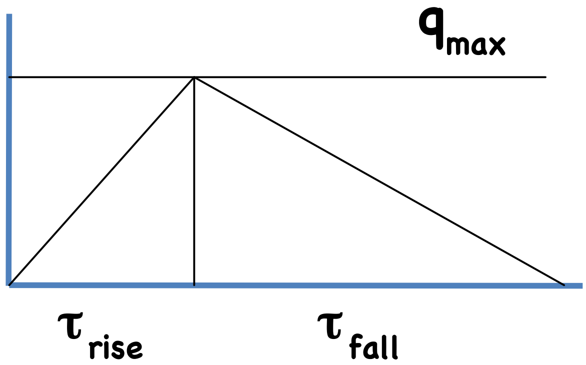

Figure 5. Generic description of heat flux vs. time due to transients.

Publication List

ARIES-ACT Final Report (Special Issue of *Fusion Science and Technology*)

"The ARIES Advanced and Conservative Tokamak Power Plant Study,"
C. E. Kessel, M. S. Tillack, F. Najmabadi, F. M. Poli, K. Ghantous, N. Gorelenkov, X. R. Wang, D. Navaei, H. H. Toudeshki, C. Koehly, L. EL-Guebaly, J. P. Blanchard, C. J. Martin, L. Mynsburge, P. Humrickhouse, M. E. Rensink, T. D. Rognlien, M. Yoda, S. I. Abdel-Khalik, M. D. Hageman, B. H. Mills, J. D. Rader, D. L. Sadowski, P. B. Snyder, H. St. John, A. D. Turnbull, L. M. Waganer, S. Malang, A. F. Rowcliffe,
Fusion Science and Technology **67** (1), 2015, Pages 1-21.

"ARIES-ACT1 System Configuration, Assembly, and Maintenance,"
X. R. Wang, M. S. Tillack, C. Koehly, S. Malang, H. H. Toudeshki, F. Najmabadi, ARIES Team
Fusion Science and Technology **67** (1), 2015, Pages 22-48.

"Design and Analysis of the ARIES-ACT1 Fusion Power Core,"
M. S. Tillack, X. R. Wang, D. Navaei, H. H. Toudeshki, A. F. Rowcliffe, F. Najmabadi, ARIES Team
Fusion Science and Technology **67** (1), 2015, Pages 49-74.

"Physics Basis for An Advanced Physics and Advanced Technology Tokamak Power Plant Configuration: ARIES-ACT1,"
C. E. Kessel, F. M. Poli, K. Ghantous, N. N. Gorelenkov, M. E. Rensink, T. D. Rognlien, P. B. Snyder, H. St. John, A. D. Turnbull
Fusion Science and Technology **67** (1), 2015, Pages 75-106.

"Neutronics Characteristics and Shielding System for ARIES-ACT1 Power Plant,"
L. El-Guebaly, L. Mynsberge, ARIES-ACT Team
Fusion Science and Technology **67** (1), 2015, Pages 107-124.

"Plasma Heat-Flux Dispersal for ACT1 Divertor Configurations,"
M. E. Rensink, T. D. Rognlien
Fusion Science and Technology **67** (1), 2015, Pages 125-141.

"Experimental Evaluation of the Thermal Hydraulics of Helium-Cooled Divertors,"
M. Yoda, S. I. Abdel-Khalik, D. L. Sadowski, B. H. Mills, J. D. Rader
Fusion Science and Technology **67** (1), 2015, Pages 142-157.

"Thermomechanical Analysis for An All-Tungsten ARIES Divertor,"
James P. Blanchard, Carl Martin
Fusion Science and Technology **67** (1), 2015, Pages 158-166.

"ARIES-ACT1 Safety Design and Analysis,"
Paul W. Humrickhouse, Brad J. Merrill
Fusion Science and Technology **67** (1), 2015, Pages 167-178.

"Activation and Environmental Aspects of ARIES-ACT1 Power Plant,"
L. El-Guebaly, L. Mynsberge, C. Martin, D. Henderson, ARIES-ACT Team
Fusion Science and Technology **67** (1), 2015, Pages 179-192.

"ARIES-ACT2 DCLL Power Core Design and Engineering,"
X. R. Wang, M. S. Tillack, C. Koehly, S. Malang, H. H. Toudeshki, F. Najmabadi, ARIES Team
Fusion Science and Technology **67** (1), 2015, Pages 193-219.

"Physics Basis for a Conservative Physics and Conservative Technology Tokamak Power Plant: ARIES-ACT2,"
C. E. Kessel, F. M. Poli
Fusion Science and Technology **67** (1), 2015, Pages 220-239.

Proceedings of the 20th ANS Topical Meeting on the Technology of Fusion Energy

M. S. Tillack, X. R. Wang, S. Malang, F. Najmabadi and the ARIES Team
"ARIES-ACT1 Power Core Engineering"
Fusion Science and Technology **64**(3) 427-434 (2013).

J. P. Blanchard and C. J. Martin
"Fracture in All-Tungsten Divertors for ARIES"
Fusion Science and Technology **64**(3) 435-439 (2013).

"The Evaluation of the Heat Loading from Steady, Transient, and Off-Normal Conditions in ARIES Power Plants"
C. E. Kessel, M. S. Tillack and J. P. Blanchard
Fusion Science and Technology **64**(3) 440-448 (2013).

"Design Challenges and Activation Concerns for ARIES Vacuum Vessel"
L. El-Guebaly, T. Huhn, A. Rowcliffe, S. Malang, and the ARIES-ACT Team
Fusion Science and Technology **64**(3) 449-454 (2013).

"Overall Power Core Configuration and System Integration for the ARIES-ACT Fusion Power Plant"
X. R. Wang, M. S. Tillack, S. Malang, F. Najmabadi and the ARIES Team
Fusion Science and Technology **64**(3) 455-459 (2013).

"MELCOR accident analysis for ARIES-ACT"
Paul Humrickhouse, *et al*
Fusion Science and Technology **64**(2) 340-344 (2013).

"State-of-the-Art 3-D Assessment of Elements Degrading TBR of ARIES ACT-SiC Blanket"
L. El-Guebaly, A. Jaber, L. Mynsberge, and the ARIES-ACT Team
Fusion Science and Technology **64**(3) 582-586 (2013).

"Vacuum Vessel Analysis and Design for the ARIES-ACT Fusion Power Plant"
H. H. Toudeshki, F. Najmabadi, X. R. Wang and the ARIES Team
Fusion Science and Technology **64**(3) 675-679 (2013).

"An Experimental Study of the Effects of Thermal Conductivity Ratio in Helium-Cooled Divertor Modules"
B. Mills, J. Rader, D. L. Sadowski, M. Yoda, and S. I. Abdel-Khalik
Fusion Science and Technology **64**(3) 670-674 (2013).

"Verification of Thermal Performance Predictions of Prototypical Multi-Jet Impingement Helium-Cooled Divertor Module"
J. Rader, B. Mills, D. L. Sadowski, M. Yoda, and S. I. Abdel-Khalik
Fusion Science and Technology **64**(2) 282-287 (2013).

"Optimization of Pin-Fin Arrays for Helium-Cooled Finger-Type Divertors"
J. Rader, B. Mills, D. L. Sadowski, M. Yoda, and S. I. Abdel-Khalik
Fusion Science and Technology **64**(2) 315-319 (2013).

Other Documentation

C. E. Kessel, J. P. Blanchard, A. Davis, L. El-Guebaly, N. Ghoniem, P. W. Humrickhouse, S. Malang, B. J. Merrill, N. B. Morley, G. H. Neilson, M. E. Rensink, T. D. Rognlien, A. F. Rowcliffe, S. Smolentsev, L. L. Snead, M. S. Tillack, P. Titus, L. M. Waganer, A. Ying, K. Young, Y. Zhai, "The Fusion Nuclear Science Facility, the Critical Step in the Pathway to Fusion Energy," *Fusion Science and Technology* **68** (2) 2015, 225-236.

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C. Koehly, X. R. Wang, M. S. Tillack and F. Najmabadi, “Alternative Design Options for a Dual-Cooled Liquid Metal Blanket for ARIES-ACT2,” UCSD-CER-13-02, August 2013.

D. Navaei, X. R. Wang, M. S. Tillack, S. Malang, and the ARIES Team, “Elastic-plastic analysis of the steel-to-tungsten transition joint for a high performance divertor,” *Fusion Engineering and Design* **88** (2013) 361-367.

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M. S. Tillack, A. D. Turnbull, C. E. Kessel, N. Asakura, A. M. Garofalo, C. Holland, F. Koch, Ch. Linsmeier, S. Lisgo, R. Maingi, R. Majeski, J. Menard, F. Najmabadi, R. Nygren, T. D. Rognlien, D. D. Ryutov, R. D. Stambaugh, P. C. Stangeby, D. P. Stotler, “Summary of the ARIES Town Meeting: Edge Plasma Physics and Plasma Material Interactions in the Fusion Power Plant Regime,” *Nuclear Fusion* **53** (2013) 027003.

M. S. Tillack, P. W. Humrickhouse, S. Malang and A. F. Rowcliffe, “The use of water in a fusion power core,” UCSD-CER-14-01, October 2014.

M. S. Tillack, N. M. Ghoniem, J. P. Blanchard and R. E. Nygren, “The materials-design interface for fusion power core components,” UCSD-CER-14-02, October 2014.

M. S. Tillack, P. W. Humrickhouse, S. Malang and R. E. Nygren, “Technology readiness of helium as a fusion power core coolant,” UCSD-CER-14-03, December 2014.

L. M. Waganer, “ARIES Cost Account Documentation,” UCSD Report UCSD-CER-13-01, June 2013.