ARIES Systems Code Development, Visualization and Application

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***Abstract*— The ARIES research program has utilized its comprehensive ARIES systems code (ASC) and a new graphical user interface for visualizing the parameter space as important tools in its analysis of fusion power plant designs. Recently, the ASC has undergone modifications to accommodate different divertor designs, each having unique pumping powers, helium and liquid-metal pumps thermal heat recovery, and the latest material, fabrication, and costing algorithms. The modifications and changes made to the code have been documented and verified by members of the ARIES team to ensure accuracy of implementation and self-consistency of design. The code has also been modified to display a wider range of inputs/outputs, formulas, and algorithms for a greater degree of transparency and verification.**

After the changes to the code were completed and the version locked, the ASC has been employed to continue to scan the physics and technology operating space for relevant power plant designs. Four corners of aggressiveness and conservativeness in both physics and technology serve as the boundaries for the scans.

The Visual ARIES Systems Scanning Tool (VASST) has been used in parallel with the ASC scans to visualize the tremendous amounts of data resulting from these detailed systems scans. Displaying the data in a colorful and intuitive visual environment and giving the user explorative and visual interaction has helped extract meaningful relationships and trends from the data. Initially, broad scans from the ASC and VASST indicated areas of interest where further detail was needed. Further scans with a higher degree of detail helped enhance and further refine the database.

After the final scans, VASST facilitated in displaying and filtering the large database to choose two "strawmen" data points at two of the four corners of the aggressive/conservative operating space. These points then served as reference designs so more detailed design and calculations could be done. The results of the in-depth designs assist the ASC by feeding back information into the code that can then be generalized for a wider range of operating scenarios relevant to the scanning range. This substantiates the ASC and helps mesh simple formulae with detailed design.

Keywords - visualization tool; ARIES; VASST; systems code; fusion power plant; tokamak.

I. Introduction

The ARIES research team continues to develop integrated design studies of fusion power plant tokamaks for the commercial utility sector. An important tool in the developmental learning and optimization process has been the exploration of design parameters through the use of the ARIES systems code (ASC). The code has been developed by the ARIES team over the past several years and has increased in capability, functionality, and visualization during that time [1]. Much work has been done prior to this iteration of the code but this current version focuses on improving the user experience, visualizing the data, and a continuing effort to generalize and modularize the code.

In the past, the ASC was utilized by the team in the ARIES-RS [2], ST [3], and CS [4] studies to manipulate high-leverage parameters in order to minimize the cost of electricity (COE). The ASC helped define and optimize the reactor about this specific design point at minimal COE, which often produced the most favorable power plant for a specific set of constrained parameter choices. However, the optimal point was often difficult to justify or understand and the design was frequently very sensitive about that point to small changes of the parameters. For these reasons, the systems analysis approach was modified optimizing the lowest COE to scanning a wide operating space for a range of possible design solutions [1]. This change in philosophy offers the ability to more accurately understand the tradeoffs between the available system parameters and then to identify their impact and sensitivity to perturbations to create a better-motivated fusion device.

The scanning approach creates a need to display visually the dependence of the multi-dimensional parameters on one another, to be able to filter and extract meaningful data, and to provide direction to focus on more meaningful regions of the operating space. The Visual ARIES Systems Scanning Tool (VASST), which was introduced last year, has helped to visualize the tremendous amount of data contained within the scanned design space [5]. We have used VASST to filter the data and display it in an interactive and exploratory manner. It has helped to identify trends and provide insight into the tradeoffs of the parameter space and ultimately the COE. The power of VASST lies in its ability to filter and display the scanned data in real-time to show the user exactly how the parameters depend and interact with each other.

II. ASC DEVELOPMENT:

The ARIES systems code continues its development and improvements to reflect the most up-to-date work in its physics, engineering, and costing modules. The team strives to incorporate the latest conclusions from the fusion community and also to push the boundaries of what is possible while considering the future outlook of physics and engineering feats on the horizon.

The main emphasis on the code improvements has been to add greater flexibility and modularity to the code structure. “Hard-wired” numbers that were hidden deep within the code have been extracted and placed in easily modifiable input files. These include numbers such as costing factors, inflation factors depending on year, magnet build data such as maximum stress, current density and magnetic field, materials costs, densities and cost basis, power flow data such as current drive, pumping efficiencies, radiated and conducted power fractions, maximum fluxes and a range of plasma parameters. These input files can now be amended as needed by external users rather than code developers and this does not require re-compiling the code. Granted, the calling of input files takes more time than directly accessing numbers within the code, but the flexibility of this approach is an important point for the team. Additionally, more of the internal algorithms and equations are now being displayed as output files to ensure transparency with all aspects of the code and to catch any obvious errors in the calculations.

The systems code has also adopted three possible divertor designs that the team has developed and is considering - the flat plate, the combined plate and finger, and the tapered T-tube design with linear taper, all helium-cooled and all December 2010 designs. Each design was modeled over varying surface heat fluxes to determine the pumping power required over the thermal power removed. These correlations (Figure 1. have been implemented in the code to better account of the pumping power required for the divertor design under scrutiny. There has also been parallel experimental work by Georgia Tech to draw comparisons from the UCSD modeling to an experimental plate-design divertor they have been operating. Work is still ongoing to find the correct correlations so that accurate comparisons can be made between the experimental and theoretical results.

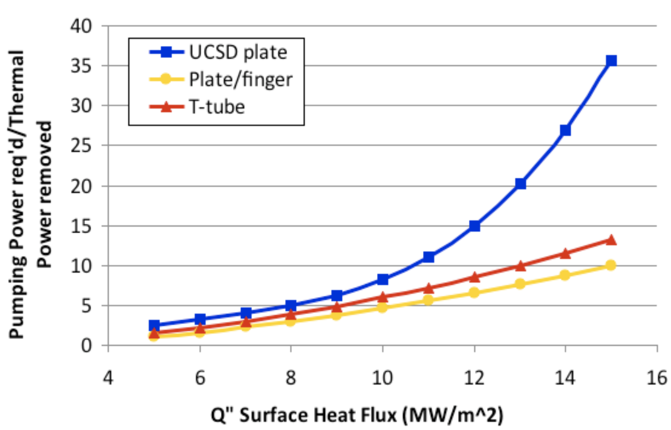

Figure 1. Pumping power correlations for the three helium-cooled December 2010 divertor designs.

Additionally, pumping power correlations have been adopted into the code for the two different blanket designs under analysis by the ARIES team, the SiC (silicon carbide) and DCLL (dual-coolant liquid metal) blankets. The DCLL blanket design is composed of both liquid metal and helium cooling and both coolant types are included together in this correlation. The helium flows through the first wall, grid plates and heat exchanger while only the liquid metal that flows through the inboard side of the first wall/blanket is taken into account. On the outboard side the MHD effects will be substantially smaller due to the lower field strength and larger space available. The pumping power correlation was determined over an average neutron wall loading range of 2-4 MW/m^2. The resulting correlation gives the pumping power required over thermal power removed by the blanket. The blanket thermal power includes the neutron power, neutron energy multiplication factor, and first wall surface heating. The SiC blanket coolant is strictly liquid metal and again, only the inboard side of the first wall/blanket is considered because the majority of the MHD effects occur here. The SiC pumping power correlation was determined in the same manner as the DCLL and over the same range, and takes slightly more pumping power compared to its rival.

The team also considered the thermal power that can be recovered from the liquid metal coolant after being pumped through the reactor. The pumping efficiency of a liquid metal MHD pump might only be ~40% of the pumping power but it is estimated that ~80% could be recaptured. The liquid metal would be heated by the MHD pump that moves it as well as the pressure drop through the system. This resulting thermal heat could then be recaptured and converted to electrical power using the Brayton power cycle, assuming a thermal conversion efficiency of ~50%. The power recovered can be quite substantial for a 1000 MW plant, on the order of ~40%. Whether a liquid metal MHD pump can attain the pressures we require (1-2 MPa) is an additional point to consider.

The team has also considered the recirculating power estimates from ITER and has extrapolated their detailed assessment to an ARIES-AT-type tokamak. The total recirculating power that is now incorporated in the ASC is assumed to be 65 MW and is composed of 30 MW miscellaneous and 35 MW cryogenic loads. The miscellaneous loads include, but are not limited to, buildings, tritium plant, vacuum pumps, remote handling, hot cells, power systems, diagnostic equipment and liquid/gas distribution. The cryogenic loads include liquid nitrogen and liquid helium pumps, cryogenic piping, gravity supports and thermal shields. Future editions of the code will reflect more detailed information and

Since the DCLL blanket is composed of different components than the SiC blanket and built in a different way, it is difficult to track and maintain two separate blanket modules in parallel. Both blankets share much of the same coding within the ASC, yet there are many differences as well. So there is an ongoing effort to fully incorporate the two blanket modules into one general systems code. The continuing goal is to generalize and modularize the code so that the two current blankets can be easily interchanged with a simple switch and so that possible future blanket models can be easily incorporated.

“If” statements have been incorporated to toggle between the two different blankets and the three different divertors, as well as between “COE” and “systems” modes. COE mode is a production mode used for scanning all the parameters from the input files whereas system mode is used for a comprehensive analysis on a single point with detailed geometry printouts. The radial build, shown in Figure 3. below, is an example of the detailed geometry printout that displays the radial build of the machine constructed around the plasma geometry.

The ASC code previously used elliptical approximations to describe the plasma contour shape. It also included the divertor’s surface area when computing the plasma surface area, which then fed into the neutron wall loading calculation. Now the code has incorporated more accurate discretized geometry formulas to describe the shape, which take into account the plasma’s elongation, triangularity and squareness (1). The plasma surface area now uses the surface area of the plasma with the addition of the scrape-off layer, currently 10 cm. The surface area calculation is iterated around the plasma contour line in the code to a high degree of resolution (2). This has yielded more accurate estimates for wall loading for further neutronics calculations.

$$\begin{aligned} R(\theta) &= R_o + a \cdot \cos(\theta + \sin^{-1}(\delta) \cdot \sin(\theta)) \\ Z(\theta) &= a \cdot \kappa \cdot \sin(\theta + \varsigma_o \cdot \sin(2\theta)) \; for\ \theta < \pi/2 \\ Z(\theta) &= a \cdot \kappa \cdot \sin(\theta + \varsigma_i \cdot \sin(2\theta)) \; for\ \theta \geq \pi/2 \end{aligned} \quad (1)$$

$$S.A. = 2 \times \sum \left[(R_i - R_{i-1})^2 + (Z_i - Z_{i-1})^2 \right]^{1/2} \cdot 2\pi \left[R_o + \frac{(R_i - R_{i-1})}{2} \right] \quad (2)$$

R_o is the plasma major radius, a is the plasma minor radius, κ is the plasma elongation, δ is the plasma triangularity, ς_o, ς_i is the plasma squareness on the outboard side and inboard side, respectively, θ is the poloidal angle. The surface area multiplication factor of 2 is used for up/down symmetry.

Over the past months, many interim points have been scanned by the ASC and shared with the ARIES team for their consideration and comments. All input parameters and output files have been formatted and displayed so that all aspects of the code could be analyzed for completeness and accuracy, which is paramount for producing truthful and comprehensive results. Granted, some assumptions and correlations are known to be approximate, but knowing and documenting the basis for the assumptions and their limitations help to achieve a credible design. Numerous amendments have been made to the costing algorithms as new data and insight have become available and as major material costs have decreased. Compositions, thicknesses, surface areas and volumes of all the components of the power plant have been checked and verified through internal communication between the team members and many minor errors and discrepancies have been caught and corrected as a result of these exchanges.

All the modifications and error corrections implemented in the systems code have been documented and backed up to ensure traceability and transparency. This chronicle of changes is maintained so that future users or maintainers of the code know its history and what has taken place within it over time. The software called Subversion by Apache.org is maintained remotely on a server and contains a listing of all changes between submissions. Additionally, an ongoing spreadsheet has been maintained that chronicles the parameters defining the databases in use. The chronicle maintains what version of the ASC and VASST were used, what input parameters were given, what blanket was employed, what assumptions were relied on, what costing algorithms were used, and what filters were implemented. With this documentation plan we can assess our progress, refer to prior databases, enable transparency and avoid confusion when quoting results.

III. VISUALIZATION USING VASST:

The objective of the VASST GUI is to provide a user with a tool to better visualize and grasp the extent of the database containing the feasible tokamak operating space from the ASC. The graphical user interface strives to be an intuitive and easy to use interactive tool such that trends and relationships between parameters in aggressive and conservative tokamak regimes can be found or emphasized.

The VASST software, written in Matlab, has undergone improvements, namely the capability of filtering and displaying relevant data in real time for the user. This new functionality allows the user to select multiple constraints and quickly adjust them by moving slider bars back and forth to immediately see the results. The points will appear or disappear as the slider is dragged with the mouse. This is especially helpful to see the sensitivity of points to certain individual filters as well as a combination of filter criteria. One can see if the selected filter is on the cusp of removing all the data points on the screen and at what point the cusp or cutoff occurs. This can be used to visualize the groupings of conservative and aggressive points and see the distinction between the two [5]. The user can also visually gauge if the relationship scales linearly, quadratically, etc. This can be done on a multitude of user-selected plots and scales. Another helpful feature is the ability to turn on a bounding box to show the area enclosing all the data points (Figure 2.). Then, as filters are applied, the bounding box can be referenced to see where the extent of the unfiltered data lies and where the remaining concentration of data points lie in relation to the bounding box. This can also help show where data might be missing or sparse to influence future scanning ranges and resolutions. Points that reside at extreme “corners,” or any point for that matter, can be clicked on with the mouse and all of its parameters displayed. The ability to quickly understand why a data point resides where is does on the plot and why it has “survived” the multiple filters is helpful in assessing the point’s viability and credibility at that extreme physical or technological regime. An experienced user can swiftly assess the data and draw conclusions about that area.

One method in use of multimedia collaboration between physicists and engineers on the team is the utilization of screen sharing for VASST so that everyone can view, comment and contribute to the manipulation of parameters and filters. This allows multiple users at different locations to collaborate in real time on one design. While this is helpful for coming to a consensus on a particular design, it is also very useful for one to explore the parameter space on his or her own and try out a number of plotting and filtering techniques. While examining the plots, often more ideas and questions arise that spur further exploration.

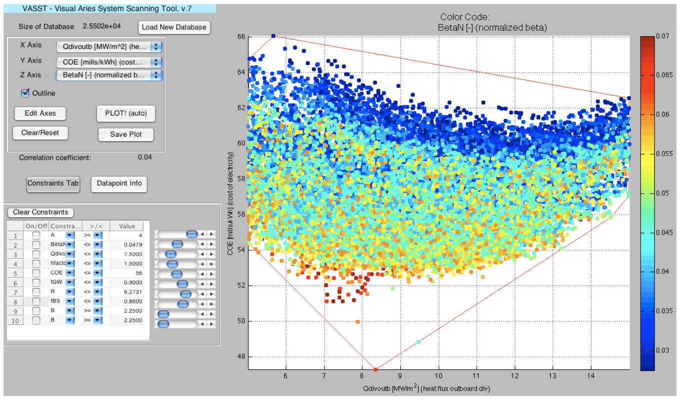

Figure 2. VASST graphical user interface showing the data points bounded by the bounding box (center), the plotting and editing menus (top left), the filtering criteria and slider bars (bottom left), and the color scale for the third plotting dimension (right).

IV. Application of the ASC in Collaboration with VASST:

We have utilized VASST most recently in the ARIES Physics and Technology Assessment to help narrow down "strawmen" points at two of the four corners of our defined tokamak parameter space. This "box" encompasses the entire tokamak parameter space considering the extremes of aggressive and conservative physics and technology. The aggressive technology corners utilize the SiC blanket while the conservative technology employs the DCLL blanket; the strawmen points for this blanket are still forthcoming. The strawmen designs provide the ARIES team a basis for which further detailed analysis can be done. Wisdom gained from this analysis is integrated into the code for further enhancement of current and future designs and serves as a guide for the range of future scanning criteria.

To initiate the scan, the revisions to the ASC were finalized as described in section I and the version of the code was locked at SVN #30 and documented. From this point on, any future modifications to the code would be assigned a new revision number. The assumptions, equations, engineering and costing algorithms used in SVN #30 will only be valid there since together they composed that design. The ASC begins its scan by submitting the code and input files in "COE" mode to the PPPL cluster computer composed of many nodes [5]. The scanning range and resolution of major parameters is shown below in Table 1. A tradeoff must be reached between the desired resolution and the computation time of ~2000 points/hr/node. Fine scans are sometimes required afterwards to "zoom in" on areas of interest where possible attractive designs can be reached. Again, iterations and feedback between systems code runs and more detailed analysis lead to a more comprehensive and realistic power plant design.

TABLE I. ASC Scanning Range Across the Aggressive-Conservative Physics Space Using SiC Blanket Design

	Range	**Resolution**
R (m)	4.0 - 8.0	0.5
B_T (T)	4.0 - 9.0	0.5
β_N	0.0275 - 0.06	0.0025
Qcyl (q95)	3.5 - 5.4	0.2
Q gain	15 - 40	5
n/n_{GW}	0.5 - 1.1	0.05
Impurity fraction	0.001 - 0.003	0.001
Plasma elongation κ	2.0 - 2.2	0.2
Aspect ratio	4.0, 3.0, 2.5, 2.0	-
Current drive efficiency	0.27	-
τ_p/τ_e	5	-
Plasma trangularity δ	0.7	-
Plasma squareness ς	IB, OB = 0, 0	-

The sequence of the filtering criteria used in VASST for the aggressive strawmen selection (ACT-I) is as follows: Set A = 4, β_N < 0.045, Qdivoutb < 7.5 MW/m^2, hfactor < 1.5, COE < 56 mills/kWh, n/n_{GW} < 0.95, and R < 5.5 m. Filtering of the peak divertor heat flux on the outboard side was also done at intervals of 15, 10 and 7.5 MW/m^2 to see the effect on the resulting points. The cap of 7.5 MW/m^2 was chosen to give the divertor design some headroom to accommodate high-flux transients, ELMs, and other off-normal/non-steady state events. This choice will be substantiated further down the road when more detailed analysis is done on the divertor design. Additionally, points with lower normalized beta than ARIES-AT were considered more favorably since the achievements on current machines and systems analysis indicate the benefits of pushing for higher values are diminishing. The H98 values coincide with the best achieved in advanced tokamak (AT) discharges on present experiments to date. These AT plasma are typically produced at elevated edge safety factors (q95), although it is not clear if this is a fundamental constraint. Therefore it is being pursued in the solution of possible operating points

After these filters and additional considerations were applied, a resulting group of ~10-20 points emerged from the database of 6.2 million data points. The database is large because net electric power is unrestricted. Careful consideration and comparison of the points yielded the two 1000 MWe advanced tokamak power plants utilizing the SiC blanket, one for aggressive physics called ACT-I and one for conservative physics called ACT-II. A summary of the major parameters compared to the ARIES-AT design point is given below in Table II and the radial builds are drawn in Figure 3. The major differences between the three designs are highlighted in yellow.

TABLE II. SUMMARY OF THE TWO APRIL 2011 STRAWMEN POINTS ACT-I, II COMPARED TO ARIES-AT DESIGN POINT

	ARIES - AT	ACT-I *Aggr. Physics*[a]	ACT-II *Cons. Physics*[b]
Blanket design	SiC	SiC	SiC
Major radius [m]	5.2	5.5	6.75
Plasma aspect ratio [-]	4	4	4
Plasma elongation [-]	2.2	2.2	2
Plasma tiangularity [-]	0.84	0.7	0.7
Normalized beta [-]	5.4	4.5	2.75
Toroidal magenetic field [T]	5.86	5.5	7.25
Greenwald density fraction [-]	1.0037	0.95	0.85
H98 [-]	1.349	1.441	1.169
q95 [-] or qcyl	3.55	4.4	4.8
Plasma current [MA]	12.8	10.58	13.28
Bootstrap fraction [-]	0.91	0.90	0.61
Max div heat flux OB [MW/m2]	14.7	6.7	7.3
FW surface area [m2]	425.6	504.9	692.6
Max FW heat flux [MW/m2]	0.282	0.274	0.257
Plasma surface area [m2]	(427)	470.3	662
Plasma surface area w/ SOL [m2]	-	502.3	698
Ave. neutron wall load [MW/m2]	3.29	3.07	2.37
Ave. n. wall load w/ SOL [MW/m2]	-	2.89	2.24
CD power to plasma [MW]	35	26.9	121.3
Recirculated power faction [MW][c]	14.5%	14.7%	24.7%
Thermal power [MW]	1982	2065	2332
Fusion power [MW]	1755	1806.5	1958.5
COE [mills/kWh]	47.5[d]	55.02	63.95
Costing base year	1992	2009	2009

a,b. A full listing of parameters is available at: http://aries.ucsd.edu/ARIES/WDOCS/system.shtml

c. Recirculated power is sum CD, aux, plasma heating, cryogenic, divertor and blanket pumping power

d. ARIES-AT COE in 2009$ x 1.4323 = 68.03 mills/kWh

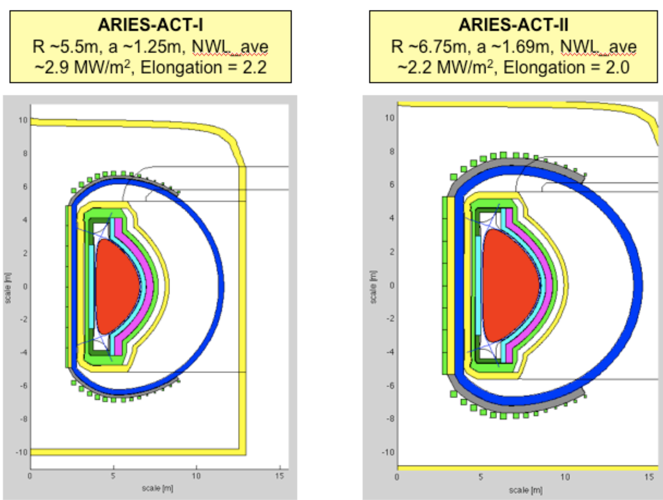

Figure 3. Radial build drawings from the systems code of the aggressive physics ACT-I and the conservative physics ACT-II. The drawings are scaled to the same dimesions for comparison.

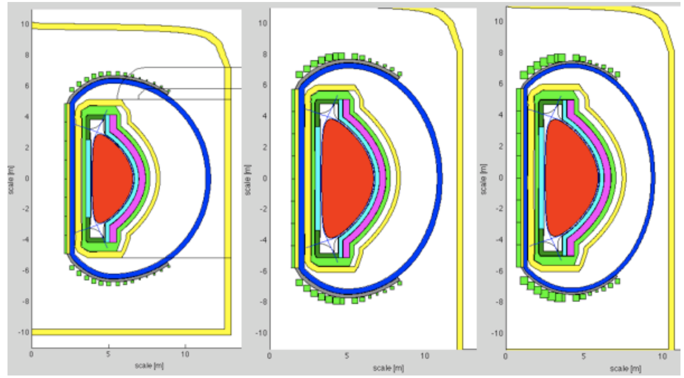

Figure 4. Radial build drawings from the scanning of the aspect ratio. A = 4.0 (left), A = 3.0 (center), A = 2.5 (right). As aspect ratio is reduced from left to right, note decreasing major radius, elongation of TF coil (blue) and increased size of PF coils on top and bottom (green).

An additional exercise that utilized the ASC and VASST was a scan of aspect ratios from A = 4.0, 3.0, 2.5, 2.0. We are looking at various systems as the aspect ratio is decreased to ensure the designs are consistent. Although space is limited to show all the screen shot comparisons from VASST, the following trends were observed. As the aspect ratio decreases a) the major radius decreases, b) the toroidal field at the plasma decreases, c) the plasma current increases, and d) the maximum TF coil field increases. The comparison of the radial builds for A = 4.0, 3.0 and 2.5 is shown in Figure 4.

V. CONCLUSIONS

The ARIES systems code and visualization GUI VASST have both undergone revisions to improve their capabilities and to better develop their complementary interaction with one another. The ASC has been modified in numerous areas to improve its ease of use, flexibility and transparency. The addition of real blanket and divertor designs, thermal heat recovery accountability, as well as more accurate plasma surface area and neutron wall loading calculations all help to improve the code's credibility and completeness. VASST has been modified to allow for on-the-fly filtering of the database points so that trends, correlations and filtering cutoffs between parameters can more easily be visualized and compared.

ASC and VASST have been utilized in the current ARIES Physics and Technology Assessment in selecting two aggressive technology strawmen points from the two corners of the parameters space, which will be used as the basis of further analysis. Subsequent revisions and improvements to the code will benefit from this work and further substantiate the code.

Future work includes higher-resolution scanning at areas of interest within the parameter space as well as completing the revisions to the DCLL blanket module so that the conservative technology points can be included and evaluated. The ongoing goal of VASST is to continually improve the user interface with a visually interactive and explorative tool that might help extract meaningful relationships from the tokamak databases.

ACKNOWLEDGMENT

This work at UCSD was supported under U.S. Department of Energy grant number DE-FG02-04ER54757.

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