ANNUAL REPORT

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FUSION RESEARCH CENTER
NUCLEAR & RADIOLOGICAL ENGINEERING PROGRAM
GEORGIA INSTITUTE OF TECHNOLOGY
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I. RESEARCH

A. COLLABORATION ON DATA INTERPRETATION AS PART OF THE DIII-D NATIONAL TOKAMAK TEAM

1. Calculation of neutral atom recycling and core fueling. (Z. W. Friis and W. M. Stacey, GIT; A. W. Leonard, GA; M. E. Rensink, LLNL)

A detailed analysis of neutral atom recycling and pedestal fueling in a DIII-D high-confinement mode discharge was performed, using the Georgia Tech GTNEUT code. Experimental data and 2D edge plasma fluid code calculations were employed to provide ion wall recycling and recombination neutral sources and background edge plasma parameters for a 2D edge neutral code calculation of detailed neutral density, ionization and charge-exchange distributions throughout the edge pedestal, scrape-off layer and surrounding halo region, divertor, and private flux regions.

The neutral particle recycling and pedestal fueling from wall reflection and volumetric recombination sources in a DIII-D H-mode discharge were considered. The investigation confirms previous studies that the edge pedestal in DIII-D is primarily fueled by recycling and recombination neutrals from the divertor region. The effectiveness of the different neutral sources for fueling the confined plasma was evaluated.

We found that the penetration of recycling neutrals into the pedestal region is highly non-uniform poloidally, both because the recycling and recombination sources are poloidally non-uniform and because neutral particles recycling from the upper baffle penetrate deeper into the pedestal (because the path length in mean free paths is shorter) than do neutrals recycling from the divertor region. Although the effects of poloidally asymmetric particle source and heat sinks will be ameliorated to some extent by rapid poloidal transport along the field lines, this result raises questions about the adequacy of one-dimensional plasma transport calculations that are sometime employed in the edge pedestal and suggests an area of further investigation.

1. Z. W. Friis, W. M. Stacey, A. W. Leonard and M. E. Rensink, "Analysis of neutral particle recycling and pedestal fueling in an H-mode DIII-D discharge", Phys. Plasmas 17, 022507 (2010).

2. Effect of rotation, Erad and neutrals on density profile in edge pedestal. (W. M. Stacey, GIT)

The edge density profile was calculated from the continuity and momentum balance equations, using experimental electric field and rotation velocities and a calculated recycling neutral source, to evaluate the relative importance of these quantities in determining the observed structure of the edge density profile in a DIII-D high-confinement mode discharge. A perturbation analysis, based on the difference in carbon and deutrerium toroidal velocities being small compared to the measured carbon toroidal velocity, was employed. The effect of the rotation velocities and the radial electric field dominated the effect of the recycling neutral ionization in the calculation of the edge density profile, which was in rather good agreement with the experimental density profile measured by Thomson scattering.

1. W. M. Stacey, "The effects of rotation, electric field, and recycling neutrals on determining the edge pedestal density profile", Phys. Plasmas 17, 052506 (2010).

3. Viscous Heating Correction to Interpretation of Experimental Thermal Diffusivities in the Edge Pedestal (W. M. Stacey GIT)

A formalism was developed for evaluating the viscous heating correction to the total ion radial energy flux in order to obtain the conductive heat flux, which should be used to interpret the thermal diffusivity from the measured density and temperature profiles. An evaluation of the viscous heating correction in the edge pedestal of a DIII H-mode discharge, using measured rotation velocities and plausible 1%-10% up-down rotation velocity asymmetries, indicates that this correction to the inferred experimental thermal diffusivities could be significant.

1. W. M. Stacey, " The effect of rotation and viscous heating on the interpretation of experimental heat diffusivities in the edge pedestal", Phys. Plasmas 17, 052504 (2010).

4. Particle Pinch Effects in the L-H Transition (W. M. Stacey, GIT; and R. J. Groebner, GA)

The various terms in the radial force balance in the edge plasma were evaluated using experimental data from the low (L) and high (H) confinement phase of a DIII-D discharge in order to investigate the differences in the radial force balance between the several electromagnetic and pressure gradient forces in L-mode and H-mode. The roles of cross-field toroidal momentum transport and of a radial pinch velocity in determining different radial particle fluxes in L-mode and H-mode were elucidated. Evaluation of the radial force balance in the edge plasma using measured data reveals that there is a major difference in the particle pinch between L-mode and H-mode, in the shot analyzed, that could account for why the H-mode density profile is dramatically different than the L-mode profile. This difference in the pinch is related to differences between L-mode and H-mode in Erad and the poloidal rotation velocity in the edge plasma. There is a rather large, inward net electromagnetic force (inward pinch velocity) in the H-mode phase of the discharge. There is a smaller, outward net electromagnetic force (outward pinch velocity) in the L-mode phase of the discharge. Thus, the outward pressure gradient forces must be larger in the H-mode phase than in the L-mode phase in order to satisfy momentum and particle balance constraints. This insight suggests the possibility that a better understanding of the origin of the edge Erad and poloidal rotation could lead to ways to control the pinch and in turn the edge density profile.

1. W. M. Stacey and R. J. Groebner, "Force balance and ion particle transport differences in high and low confinement tokamak edge pedestals", Phys. Plasmas (submitted 2010).

5. Particle Pinch Effects in ELM Suppression by Magnetic Resonance Perturbations (W. M. Stacey, GIT; and T. E. Evans, GA)

The force balance in the plasma edge in a matched pair of DIII-D tokamak discharges with and without resonance magnetic perturbations (RMPs) was evaluated in order to investigate the effects on particle transport of RMP applied for the purpose of suppressing edge-localized modes (ELMs). Experimental data were used to evaluate the radial and toroidal force balances, which may be written as a pinch-diffusion relation for the radial ion flux to facilitate investigation of transport effects. The major effect of the RMP in this study was to reduce the density below the ELM threshold by reducing the stronger inward particle pinch that would otherwise be present in an H-mode discharge, and by increasing the particle diffusion coefficient in the RMP discharge. In this RMP discharge, the reduction in inward pinch was due primarily to the change in direction of the electric field over a significant part of the edge pedestal, but changes in poloidal rotation due to the RMP were also important.

It appears that the radial electric field and the poloidal velocity are knobs for density control. Further investigations are obviously in order to understand how the RMP affects the radial electric field and poloidal rotation. An even more intriguing area for future exploration is the search for other possible means to control the radial electric field and the poloidal rotation in the plasma edge, thereby to achieve density control and ELM suppression by reducing the large inward velocity pinch in the edge of an H-mode plasma.

1. W. M. Stacey and T. E. Evans, "Mechanisms of ELM suppression by resonance magnetic perturbation", Phys. Plasmas (submitted 2010).

6. Evolution of the Radial Force Balance Between ELMs (W. M. Stacey, GIT; and R. J. Groebner, GA)

The evolution of edge pedestal parameters between edge-localized modes (ELMs) was analyzed for an H-mode DIII-D discharge. Experimental data were averaged over the same sub-intervals between successive ELMs to develop data that characterize the evolution of density, temperature, rotation velocities, etc. over the interval between ELMs. These data were interpreted within the context of the constraints imposed by particle, momentum and energy balance, in particular in terms of the pinch-diffusion relation for radial particle flux that is required by momentum balance. It was found that in the edge pedestal there is an increase of both inward (pinch) electromagnetic and outward (diffusive) pressure gradient forces over the inter-ELM interval.

Evaluation of the pinch-diffusion relation for the radial particle flux imposed by momentum constraints indicates that the net radial particle flux in the edge pedestal is determined by a near balance between a large inward electromagnetic force (the pinch--produced primarily by rotation and the radial electric field) and a large outward diffusive force (produced by the pressure gradient). Both of these forces increase with time between ELMs in the sharp-gradient edge pedestal region, although the data were not sufficiently resolved in time to determine unambiguously what took place immediately following an ELM crash. The increase in time of the pinch velocity between ELMs was due primarily to the increasing deuterium poloidal rotation velocity and radial $V_\theta \times B_\phi$ force.

1. W. M. Stacey and R. J. Groebner, "Evolution of the H-mode edge pedestal between ELMs", Phys. Plasmas (submitted 2010). W. M. Stacey and R. J. Groebner

7. **Rotation in Tokamaks** (C. Bae and W. M. Stacey, GIT)

Rotation of tokamak plasmas is not only of intrinsic interest for understanding transport but also is important for the stabilization of tokamak plasmas and other reasons. The neoclassical viscosity depends on the poloidal dependence of various quantities, which in turn depend on the poloidal dependence of the magnetic geometry, among other things. The objective of this research is to derive the neoclassical toroidal and poloidal rotation theory for tokamaks using the more accurate representation of the equilibrium flux surface geometry given by the "Miller equilibrium flux surface model". The Miller model improves earlier flux surface models by taking into account the shifted centers $R_o(r)$ of the flux surfaces (Shafranov shift), the elongation κ, and triangularity δ, thus more accurately describing the actual flux surfaces in tokamak plasmas. The momentum balance equations governing toroidal and poloidal rotation have been derived in Miller flux surface geometry.

1. C. Bae and W. M. Stacey, "Neoclassical rotation theory for toroidal and poloidal rotation velocities using Miller equilibrium analytical flux surface geometry", DPP-APS Mtg,, Chicago, 2010.

8. Numerical Investigations of Generalized Diffusion Theory in the Edge Pedestal (J-P Floyd and W. M. Stacey, GIT)

It has been found that satisfaction of the momentum and particle balance equations requires the radial particle flux in the edge pedestal of a tokamak satisfies a pinch-diffusion relation. When this pinch-diffusion equation is substituted into the continuity equation, a generalized diffusion equation with a derivative of a convective term, as well as the usual second derivatives of the diffusive terms, arises. Most of the major codes used for edge plasma analysis (UEDGE, SOLPS, etc.) are based on a purely diffusive radial particle flux, so the question arises as to whether these codes can be modified readily to include the pinch term. One aspect of this question is the difference in numerical properties of the diffusion and the pinch-diffusion equations. We have investigated this question by comparing the numerical solutions of the coupled pinch-diffusion and continuity equations, on one hand, with the numerical solutions of the generalized diffusion equations that result when the pinch-diffusion relation for the particle flux is substituted into the continuity equation. We find that the generalized diffusion equations have difficulty reproducing the "exact" solution of the coupled continuity and pinch-diffusion particle flux equations in the steep-gradient region where the pinch term is varying rapidly in space.

1. J.-P. Floyd and W. M. Stacey, "Numerical Investigation of the Generalized Diffusion Equations Resulting from the Use of the Pinch-Diffusion Particle Flux",DPP-APS Mtg,, Chicago, 2010.

9. H-Mode Edge Pedestal Benchmarking Activity (J. D. Callen, U. Wisconsin, R. J. Groebner and T. H. Osborne, GA; J. M. Canik and L. W. Owen, ORNL; A. Y. Pankin and T. Rafiq, Lehigh Univ., T. D. Rognlien, LLNL)

An H-mode edge pedestal benchmarking activity is ongoing to compare the experimental interpretation and prediction of transport in the edge pedestal made by a variety of 2D (UEDGE, SOLPS) and 1.5D (ONETWO, GTEDGE, ASTRA) transport codes (GTEDGE is the Georgia Tech 1.5D edge transport code). Initial studies have concentrated on DIII-D ELMing H-mode shot 98889. The interpreted experimental thermal diffusivities in the edge pedestal agree rather well among the various interpretive codes, and the predictive (ASTRA) code can match experimental temperature profiles with a suitable combination of theoretical thermal diffusivities. Evidence suggesting an inward particle pinch has been found in the form of extremely small diffusion coefficients need to fit a purely diffusive model to the measured density profiles.

1. J. D. Callen, R. J. Groebner, T. H. Osborne, J. M. Canik, L. W. Owen, A. Y. Pankin, T. Rafiq, T. D. Rognlien and W. M. Stacey, "Analysis of pedestal transport", Nucl. Fusion 50, 064004 (2010).

B. DEVELOPMENT OF THE SUB-CRITICAL BURNER REACTOR (SABR)

1. **Dynamic Safety Analysis** (T. S. Sumner, W. M. Stacey, S. M. Ghiaasiaan—GIT)

The transient response of the SABR subcritical, sodium-cooled, TRU-fueled, fast transmutation reactor design concept ensuing from several accident initiation events has been simulated. The results establish such things as the number of primary loop pumps that could fail or the magnitude of flow reduction in the intermediate loop heat removal capability due to either pump failure or intermediate heat exchanger failure that could be tolerated without core damage, the consequences of loss of electrical power, and the consequences of control rod ejection or neutron source excursions.

Loss-of-power (LOPA), loss-of-heat-sink (LOHSA), loss-of-flow (LOFA), control rod ejection, and neutron source excursion accidents were simulated using the RELAP5-3D code to model the reactor and heat removal systems dynamics, together with a plasma power and particle balance model for the neutron source dynamics. It was found that: i) the core power can be reduced to decay heat levels in a couple of seconds by turning off the neutron source heating power when any accident condition is detected; ii) a LOPA thus reduces the core to the decay heat level in a couple of seconds and natural circulation prevents core damage; iii) undetected LOFAs in which 50% of the primary coolant pumps fail can be survived without core damage, and only when 75% of the pumps fail does fuel melting occur (at 8.4 s); iv) an undetected LOHSA with 50% loss of sodium flow in the intermediate loop can be survived without core damage, and only with 75% loss of sodium flow in the intermediate loop does fuel melting occur (at 150 s); and v) neutron source excursions due to inadvertent increases in plasma heating or fueling could be limited by operation near inherent density and beta limits.

SABR can withstand without coolant boiling up to a quarter of the coolant pumps in either the primary or intermediate coolant loops failing. If any additional coolant pumps fail the coolant will either exceed or come very close to its boiling temperature. However, a failure of three-quarters of the coolant pumps in either the primary or intermediate coolant loops will result in fuel melting. With only about ten seconds before fuel melting begins, there is not enough time to for operators intervention to terminate the transient, and this indicates the need for an automatic control system.

Because SABR cannot sustain multiple pump failures without experiencing coolant boiling and possibly fuel melting, coolant pumps in both the primary and intermediate coolant loops should be kept on entirely separate electrical systems than any other pump to ensure that a failure of one pump is not likely to be followed by a second pump failure. After a single pump failure is detected, the neutron source should be quickly shut off. Even if all of SABR's pumps fail, if the neutron source is shut down at the same time, natural circulation will provide enough coolant mass flow to remove the decay heat being generated in the fission core.

The above results are based on calculations which did not model the effect of the large negative fuel expansion reactivity coefficient expected in SABR, so they are pessimistic with respect to core damage.

The other category of transients is those affecting SABR's neutron population in the fission core. To prevent accidents related to inadvertent control rod removals from possibly causing coolant boiling in the fission core, two design changes are possible. The best option is to decrease the total control rod worth. Because control rods are only used for small changes in the fission power level and they are not essential to shut down the reactor, a decrease in control worth would not be a reduction in the SABR's level of safety.

Rather large increases in fusion neutron source strength can be tolerated before coolant boiling or fuel melting occurs. Throughout the fuel cycle, it would take an increase of at least 50% of the neutron source strength before SABR's heat removal system would be incapable of regulating core temperatures. In the case of EOC operation, the neutron source would have to exceed its maximum design strength before core failure occurs.

While some of the accidents simulated can cause damage in SABR if uncontrolled, core damage can be prevented for all transients by shutting off the neutron source. The fission core power level will quickly decrease to decay heat levels leaving at most 7.1% power and enough coolant mass flow from natural circulation to cool the reactor until whatever caused the accident can be corrected. Whether a pump or a heat exchanger fails or a reactor operator utilizes the control rods improperly, simply eliminating the source neutrons will allow for a safe progression of the ensuing accident.

1. T. S. Sumner, W. M. Stacey and S. M. Ghiaasiaan, "Dynamic Safety Analysis of the SABR Subcritical Transmutation Reactor Concept", Nucl. Techmol. 171, 123 (2010).

2. **Fuel Cycle Analysis** (C. S. Sommer, W. M. Stacey, B. Petrovic—GIT)

A fuel cycle analysis has been performed for the SABR transmutation reactor concept, using the ERANOS fast reactor physics code. SABR is a sodium-cooled, TRU-Zr fueled, subcritical fast reactor driven by a tokamak fusion neutron source. Three different four-batch reprocessing fuel cycles, in which all the transuranics from the spent nuclear fuel discharged from LWRs are fissioned to greater than 90% (by recycling 4 times), was examined.

A four batch reprocessing fuel cycle for the SABR transmutation reactor concept, in which all the TRU from SNF is fissioned to greater than 90%, was examined using the ERANOS fast reactor physics code. The total fuel residence time in the reactor was limited in the first three cycles by a set radiation damage limit (100, 200, and 300 dpa) to the cladding material. In the fourth cycle the fuel residence time was determined by trying to achieve 90% burn up in a once through cycle. The reference cycle for this study was chosen to be the 200 dpa fuel cycle due to expected future radiation damage limits of the clad.

SABR contains 32 MT of "fresh" TRU at BOL, corresponding to a k_{eff} of 0.972. Utilizing an out-to-in shuffling scheme where at the end of a 700 day burn cycle (in the reference cycle) the fuel in the innermost fuel ring (next to the plasma) is removed from the core and sent to reprocessing, the fuel in the other rings is shifted inward by one ring, and new fuel is loaded into the outermost ring. The fuel removed from the reactor is separated pyrometallurgically into fission products and transuranics. The fission products are sent to a geological repository and the transuranics are mixed with "fresh" TRU from SNF, fabricated into fuel, and recycled into the outermost ring of SABR. After several burn cycles, an equilibrium is established for the compositions at the beginning and end of cycle. The reference fuel cycle contains 29.0 MT of TRU at BOC corresponding to a k_{eff} of 0.894 and 27.1 MT of TRU at EOC corresponds to a k_{eff} of 0.868. The neutron source strength required to maintain 3000 MW of fission power is 75 MW at BOL, 240 MW at BOC, and 370 MW at EOC. For the fuel cycles with residence times limited by radiation damage limits of 100 and 300 dpa to the structural materials, the EOC fusion powers are 220 and 460 MW respectively. Thus, it seems appropriate to design the fusion neutron source to produce up to 500 MW of power. If the radiation damage limits could be overcome, TRU burnup of greater than 90% could be achieved in a once through cycle by leaving the fuel in the reactor until k_{eff} is less than 0.6. This would require a fusion neutron source strength greater than 500 MW to maintain the fission power of 3000 MW.

The TRU fission rate in SABR is 1.05 MT per full power year (FPY) of operation. Allowing for 60 days downtime for refueling and shuffling after each burn cycle and 10% unavailability during the burn cycle, SABR could achieve 84% overall availability, which allows SABR to fission all the transuranics in the SNF discharged annually from 3.5 1000 MWe LWRs. For a given batch of fuel that resides in the reactor for the four burn cycles between reprocessing steps, 23.8% of the TRU is fissioned.

1. C. M. Sommer, W. M. Stacey and B. Petrovic, "Fuel Cycle Analysis of the SABR Subcritical Transmutation Reactor Concept", *Nucl. Technol.*, accepted (2009).

2. W. M. Stacey, C. M. Sommer, T. S. Sumner, B. Petrovic, S. M. Ghiaasiaan, C. L. Stewart, "SABR Fusion-Fission Hybrid Fast Burner Reactor Based on ITER", 11th OECD/NEA Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, San Francisco, 1-5 November (2010).

3. Nuclear Power Implementation Scenario Studies (V. Romanello, W. Maschek, F. Gabrielli, A. Schwenk-Ferrero, A. Rineiski, B. Vezzoni—Karlsruhe Institute of Technology; M. Salvatores—CEA; C. Sommer, , W. Stacey, B. Petrovic--GIT

Different types of fast spectrum dedicated burners have been proposed for the management of radioactive wastes in the framework of various advanced fuel cycle scenarios. Accelerator Driven Systems (ADS) and critical, low conversion ratio fast reactors have been studied, e.g. within the European context.

A potential alternative system is a fusion-fission hybrid. In the present study, the SABR *(Sub-critical Advanced Burner Reactor)* system has been considered, a sodium cooled fast reactor driven by a D-T fusion neutron source. The fusion neutron source based on ITER physics has a maximum source strength of 500 MWth. Operating SABR sub-critically allows to load it with a 100% transuranic (TRU) fuel, thus increasing the amount of TRUs that can be burned in the reactor, and consequently maximizing the number of LWRs supported by a single burner reactor. The fuel residence time in SABR is limited by the radiation damage of the cladding - not criticality - resulting in a greater single pass burning performance. The increased residence time increases fuel burn up and facilitates reprocessing.

In order to intercompare the different systems, a systematic study is underway within a collaboration between the GIT (USA) and KIT (Germany). The performances of the three types of systems (FFH, ADS, low CR critical fast reactors) will be compared when burning MA or TRU (i.e. Pu+MA). The present paper reports results of the first phase of such study, i.e. the comparison of SABR and of an ADS when used as MA burners.

In practice, the performance of the SABR system is investigated in a double strata European scenario by means of COSI6 code simulations. Two groups of nations are taken into consideration: the first one with a stagnant or phasing-out nuclear policy, the second with an ongoing nuclear development, both deploying in common a regional set of transmutation facilities; regional strategies can provide in fact a framework for the implementation of innovative fuel cycle strategies with an appropriate share of efforts and facilities among different countries. The chosen scenario has already been investigated using an ADS to burn MA. In the paper the fuel cycle scenario is analyzed in terms of the required number of SABR systems, fuel fabrication and reprocessing facilities and of the impact on the geologic repository issues. On the basis of a European scenario the performance of the SABR system is compared to that of the ADS.

1. V. Romanell[1], C. Sommer, M. Salvatores, W. Stacey, W. Maschek, B. Petrovic, F. Gabrielli, A. Schwenk-Ferrero, A. Rineiski, B. Vezzoni, “Advanced Fuel Cycle Scenario Study in the European Context by Using Different Burner Reactor Concepts”, 11th OECD?NEA Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, San Francisco, 1-5 November (2010).

II. PEOPLE INVOLVED IN GEORGIA TECH FUSION RESEARCH CENTER

A. GEORGIA TECH FACULTY AND STUDENTS

1. **Faculty** W. M. Stacey (NRE), B. Petrovic (NRE), S. M. Ghiaasiaan (ME)
2. **NRE Students** C. Bae, A. Bopp, J.-P. Floyd, C. M. Sommer, T. S. Sumner, C. L. Stewart, Z. W. Friis (all NRE)

B. COLLABORATORS

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6. **Oak Ridge National Laboratory** J. M. Canik, L. W. Owen.
7. **University of Wisconsin** J. D. Callen