ReNeW
Research Needs Workshop

Overview of Chapter for Theme II: "Creating predictable, high performance, steady state plasmas"

Focusing on panel "Research Requirements and Opportunities"

…from measurements to magnets

Amanda Hubbard, MIT PSFC
Chuck Greenfield, GA
Mark Foster, OFES

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Overall Scope and Goal of Theme II

- Derived directly from "Theme A" of the 2007 FESAC panel report: **Creating predictable, high performance, steady state plasmas:** The state of knowledge must be sufficient for the construction, with high confidence, of a device that permits the creation of sustained plasmas that meet simultaneously, all the conditions required for practical production of fusion energy"

- As with ReNeW in general, the deliverable of our research is the scientific knowledge base to enable *development* of fusion energy.

- As described in the Theme I talk, ITER will be an enormous and necessary step toward this goal, allowing us to learn about burning plasmas – and how to achieve them. However, it is not a prototype for "practical production of fusion energy". A demonstration reactor, generically referred to as DEMO, leading to *economic* energy production would need other features, including:
  - Truly **steady-state** operation, with high reliability, sustained using modest auxiliary heating and current drive. *(for efficient use of generated power)*
  - **Higher fusion power density.** $\sim n^2 T^2 \sim \beta^2 B^4$ *(to reduce needed size)*
  - Many other needed system features, such as tritium breeding, are covered in Theme IV.

Scope of Theme II (con't)

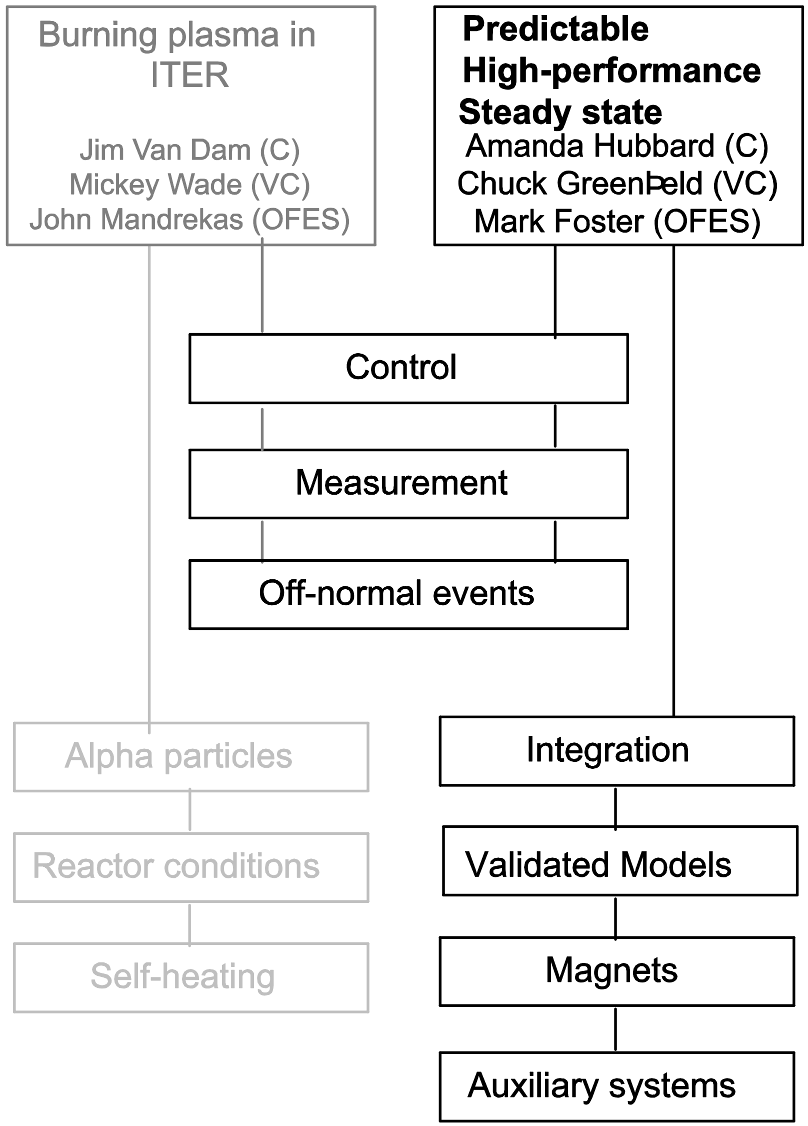
- The issues covered in this Theme are extremely broad, covering a wide spectrum of plasma physics and engineering science (often within a single panel) but major progress on all of them is essential to reach the Theme II goal.

- A key *difference* of ReNeW from the Greenwald report is that FESAC presumed success of ITER and the current program, and examined gaps to DEMO. Our research needs to start NOW, and presume little.

- Theme I focuses primarily on the needs of ITER. Theme II looks more broadly at needs for higher performance, steady state, self-sustained burning plasmas. Clearly, issues overlap, hence several joint panels.
  - Where ITER issues are well covered in Theme I (eg Measurements, Control), the Theme II chapter gives *additional* research requirements for DEMO.
  - Where topics are not covered (eg validated theory and modeling, auxiliary systems), the panels also included requirements for ITER.

- *Can give here only examples of selected issues* – much more in Theme II Chapter (on the forum) and in Theme workshop presentations (linked to the ReNeW website)!

Organization of Theme II



Many thanks to all the ~65 members of these panels, and especially these leaders, for 6+ months of hard work!

Panel Leads

Dave Humphreys, John Ferron

Jim Terry, Réjean Boivin

Rich Hawryluk, Jon Menard, Steve Knowlton

Ed Synakowski → Chuck Kessel

George Tynan

Joe Minervini

Randy Wilson

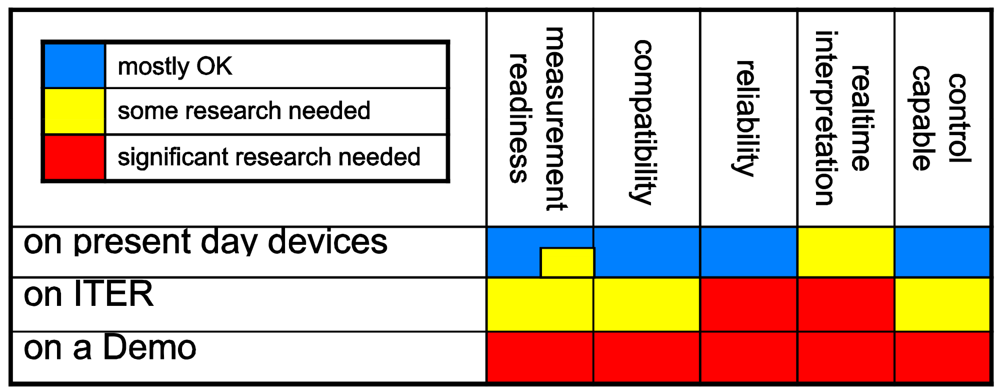
Measurement (joint)

Importance for Theme II goal:

- Measurements are crucial both for obtaining the **scientific understanding**, and for creating and **controlling** the steady state, high performance burning plasmas**.**

- Panel assessment found major additional challenges in moving from ITER to DEMO! Eg
  - 100 x fluence,
  - 650^{o} walls
  - Calibration for steady state

As examples, if ITER diags were put on DEMO, lifetimes would be:
~ 13 weeks for magnetic sensors
~ 1 week for bolometers
~ a few hours for VUV windows
~ a few hours for pressure gauges



Measurement:
Key Research Requirements and Opportunities

- **Development of the necessary compatibility of the measurements, calibration strategies, and reliability requirements with the expected difficult environment .** Opportunities include:
  - R&D for measurements where present techniques do NOT transfer. (eg, optical 1st mirrors are unlikely to work).
  - Develop creative, robust diagnostic techniques.
  - Physics engineering for monitoring in nuclear environment (eg 'smart tiles', blanket instrumentation) for detectors and for windows.
  - Research and development for calibration techniques (in situ, and/or during D-T burn)

- **Development of the necessary degree of real-time interpretation & analysis of measurements** (Critical for Control, reliability.)
  - Key needed advances over ITER are for steady state, needing real-time analysis.

Long time scale for such advances requires near-term R&D, adequate test facilities.

Validated Theory and Predictive Modeling

Importance for Theme II goal:

- Theme is charged with creating **predictable**, high performance, steady state plasmas. **Theoretical understanding, predictive simulations and experimental validation** are all essential components in obtaining the needed knowledge base.
- Predictive capability is a major overall goal of OFES.

- The panel has taken a broad, multifaceted approach to this "grand challenge", including
  - basic theory,
  - first-principles computational simulations,
  - experimental validation,
  - reduced models.
- Emphasizing *integration* across topical science areas.

Validated Theory and Predictive Modeling:

Key Research Requirements and Opportunities

Panel considered *key science opportunities* in each topical area:

(few of many examples given here)

- Core Transport & MHD stability. *Rotation, particle transport, coupling to RF models.*
- Edge, SOL and Divertor plasma physics. *First-principles models. RF sheaths*.
- Energetic Particle physics. *Energetic ion loss, generation of instabilities*.
- Disruptions. *Nonlinear MHD models, including mitigation techniques*.
- Pedestal and Edge Localized Modes. *Predicting pedestals, L-H, ELM loads.*
- RF Heating and current drive. *Alpha absorption, flow drive, edge propagation.*
- Integrated modeling*. Reduced models for simulation of scenarios, eg ITER.*

General emphasis, for all topics, on **integration of topical physics models**, and systematic **verification and validation** of models, including **new diagnostics and experimental facilities** of varying types and scales.

Plasma modification by auxiliary systems

Importance for Theme II goal:

- Reactor-grade plasmas will require means of **heating, current drive, fueling and other control actuators** which are a major advance from today's experiments, in a much more challenging environment.
- *Require auxiliary systems that can provide power, particles, current and rotation at the appropriate locations in the plasma at the appropriate intensity.*
- Panel assessed the advances needed in all areas, for ITER and to DEMO. Identified specific research requirements – both science and engineering - for **fueling, electron cyclotron Heating and Current Drive, ion cyclotron and lower hybrid H&CD, neutral beams.**

Key Research Requirements and Opportunities

- **Fueling:**
  - Steady state, deep core, fueling and pumping; high speed pellets, CTs.
  - Improve and validate models of fueling, tritium burnup.
  - Assess fueling compatibility with ELMs and MHD.
  - Explore advanced operating scenarios with pellet fueling.

Plasma modification by auxiliary systems

Key Research Requirements and Opportunities (con't)

Electron Cyclotron Heating and Current Drive.

Basic physics now well understood. Key opportunities to:

- Study physics of electron heated plasmas, to simulate burning plasmas.
- Develop higher power, higher (tunable?) f, high efficiency gyrotrons for DEMO.
- Robust launcher required; current designs are unsuitable for DEMO.

Ion Cyclotron and Lower Hybrid Heating and Current Drive.

Major recent advances in core propagation and absorption understanding. Key remaining needs include:

- Understanding wave propagation and effects through plasma *edge.*
- Predictive, physics based launcher design. *Get away from 'trial and error'!*
- Developments of antennas, sources, and external components.

Neutral Beam Injection.

- ITER need is for reliable, high energy (1 MeV) negative ion beams. *EU and JA.*
- New DEMO need for continuous operation; *US opportunity in Li jet neutralizers*.

Control (joint panel)

Importance for Theme II goal:

- Maintaining a **steady state** plasma at high performance **(near its operating limits)** requires an unprecedented degree of control.
  How high performance can be reliably maintained?

- For Theme II, panel took a long view, assessing the control needs of a fusion power plant. These build on the needs of ITER, and many are shared by nearer term steady state, high performance experiments which would help meet the requirements.
- DEMO will require:
  - Sustained, high reliability control operation (many months…)
  - Virtually failure-free, commercial-level economics, full nuclear licensing constraints

Examples of new challenges include:

- Control of j(r) with high (90%?) bootstrap fraction.
- Burn control and power regulation for reactor operation.
- Suppression of multiple core and edge instabilities.
- Response to all potential fault events (impurity flake, H&CD trip…)

Control:
Key Research Requirements

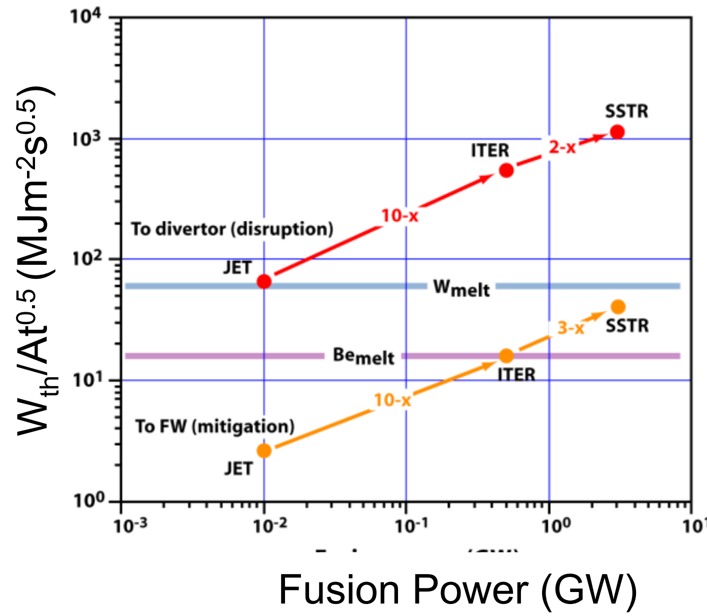
- Development of **control-level models**
  - Eg., plasma/actuator responses and instabilities
  - Derived from detailed physics codes
  - Required for model-based design and quantifying robust control
- Development of **control algorithms** for robust achievement of high performance plasma regimes
  - Engagement and integration of control mathematics community
  - Robust controllers with quantified performance reliability
- **Experimental validation of control models and verification of control solution performance** (coupled with measurements, auxiliary systems).
  - **Near term:** expansion of control research on operating devices: model-based control solutions are already essential for AT operation beyond no-wall beta limit
  - **Medium term:** demonstration of sustained robust performance on long pulse superconducting devices
  - **Long term:** control research with ITER and a sustained operation burning plasma facility

Off-normal Events

Importance for Theme II goal :

- Events such as **disruptions** would put an *end* to steady state plasmas, and even **damaging transients** must be avoided or mitigated.
- While the research needed for ITER will enable huge progress in this area, the panel's assessment shows it will NOT be sufficient.

- BAD NEWS: The *problems* for DEMO are more difficult than ITER. Eg.
  - Need 100-1000 x lower disruptivity, ie higher reliability. (longer pulses, higher energy, thick structure incompatible with breeding).
  - ELM mitigation must also be more reliable. Are RMP coils feasible?



- GOOD NEWS: Larger range of potential *solutions* Eg.
  - Other magnetic configurations, eg 3-D shaping.
  - New ELM-free regimes.
  - "Off-normal tolerant walls", such as liquid Li capillary-pore.

Off-normal Events

Key Research Requirements and Opportunities:

Disruptions:

- **Prediction and avoidance:** Determine the level of steady-state performance that tokamaks and STs can achieve and remain disruption free. *Needs high performance long pulse experiments.*
- **3-D shaping:** Determine the pressure limits in stellarators, and study thermal collapse. Determine the level of 3D shaping needed to avoid disruptions in tokamaks.

Large ELMs:

- Increase emphasis on *complete* ELM suppression/avoidance.
- Evaluate whether RMP coils are viable in DEMO.
- Study ELMs in stellarators.

Alpha particles ejected by plasma instabilities: Study in stellarators.

Off-normal event tolerant walls: Study liquid lithium walls, including impact of disruptions, runaways, impact on pedestal and core.

Integration of high performance, steady state, burning plasmas

Importance to Theme II Goals:

- The title is nearly identical to that of the Theme, with the addition of "burning". This is the central panel charged with *Integrating* the requirements from other panels, plus many from Theme III!
- Greenwald issue is: "*Creation, on a routine basis, of core, edge and SOL plasmas in S-S, with the combined performance characteristics of DEMO*".

Panel identified two major focus areas requiring experimental demonstration:

1. Dynamics of a self-consistent burning core plasma, with $P\alpha$ >> Pin.
2. Consistent solutions for core plasmas and DEMO-relevant boundary.

Supported by increased efforts on two critical areas:

- Increased capability in predictive simulation *(reducing need to demonstrate all parameters simultaneously before DEMO)*
- Focus on PMI and material evolution *(giving a boundary solution to integrate).*

Integration of high performance, steady state, burning plasmas:

Key Issues and Research Requirements:

1. **Dynamics of a self-consistent burning core plasma, with Pα >> Pext.**
   - *Is there a desirable self-consistent solution* for *kinetic and current profiles in strongly coupled burning plasma when* ***most*** *heat comes from alphas,* ***most*** *current is bootstrap driven?? What maximum stability properties will be possible with low rotation, fast alphas, strong pedestals? What heating and CD sources will be most effective, as P_{ext} is reduced?*
   - **Requires an experimental test**, with key parameters:

     $P_{alpha}/P_{input} \approx 4\text{-}9$ $0.65 < (I_{bootstrap}/I_{plasma}) < 0.90$ 100% non-inductive

     $\beta_N^{\text{no wall}} < \beta_N < \beta_N^{\text{with wall}}$ $\tau_{pulse} > 5\ \tau_{CR}$
2. **Consistent solutions for core plasmas and DEMO-relevant boundary.**
   - *What solutions exist for high heat loads, consistent with such plasmas, given strong couplings of SOL, pedestal and core? How are fuel and impurities controlled? How will hot walls, evolving materials affect core?*
   - Again, **need experimental tests**. Much could be learned with a non-nuclear, high heat flux, long pulse facility.
3. Ultimately, need to integrate boundary solutions with high Q from 1.

Magnets

Importance for Theme II goal:

- 'High Performance' ⇒ high β^2 $\mathbf{B^4}$.
- **Steady state, high field** magnets are critical! Improved, lower cost magnets would bring 'practical production of fusion energy' much closer. Higher field could enable more compact devices, and/or allow operation at lower β, easing Control requirements and likelihood of Off-normal events.
- Benefits for near-term experimental facilities span *all* ReNeW Themes.

- Magnets panel focused on **High Temperature Superconductors** as the research opportunity with the greatest potential:
  - Revolutionary materials like YBCO have huge potential for higher B, current density, at higher T (~ 40-60 K) and lower cooling cost.
  - Great recent progress spurred by other DOE research (HEP, power transmission) timely opportunity to leverage this.
  - May already be close to ready for applications for lower B fusion experiments or non-planar coils (eg ST or stellarator).

Magnets:

Key Research Opportunities

Despite promise, HTS is a young technology, and major advances in several areas are needed for steady, high B fusion applications:

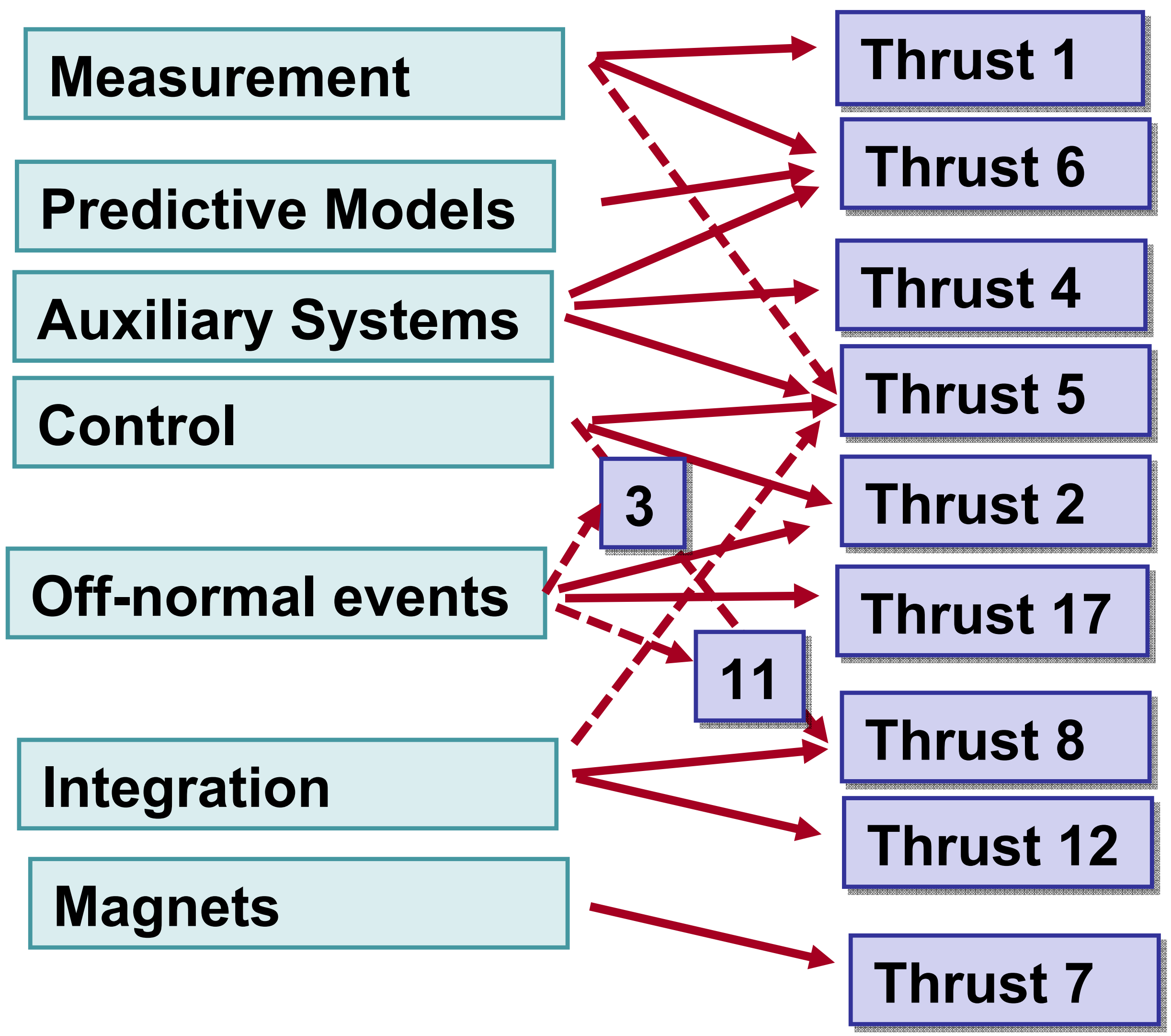
- **Superconducting wires and cables:** *Need much higher current density (~30-70 kA), piece length, strength etc.*
- **Mechanical support structure**, both external and conductor. Key to accuracy, which is crucial for ***3-D applications***. Integration of HTS tapes?
- **Insulation:** Improvements needed for all magnet types; radiation damage. Explore alternative approaches, such as new nanodielectric materials.
- **Joints:** HTS offers prospects for ***demountable superconducting coils***. This would be enormously helpful for both near-term facilities (eg, a fusion nuclear science facility or core-edge integration facility, which need to change out components) and for maintainability of a fusion DEMO.
- **Quench detection** and instrumentation

Magnet research for fusion is currently getting very modest effort.

High Temperature Superconductor development is a potential "game changer" for the fusion research program – IF there is a new, focused, effort. Would also have benefits outside fusion.

Research Requirements of Theme II panels are met by *multiple* ReNeW Thrusts.

Panels Thrusts (incomplete!)



Details are in table at the end of Theme II chapter.

- Most proposed Thrusts span Themes (ie do NOT just look at Thrusts 5-8 for Theme II needs!)
- Several Thrusts contribute ReNeW-wide. (eg predictive capability, measurements, magnets).
- Many links *among* thrusts.

Appreciation, and call for feedback.

- The work of Theme II has been a huge effort from a large number of busy people! **The interest and response has been overwhelming.**
  - **7 panels** (3 joint)
  - **65 members** (28 joint) from **20 institutions.**
  - **82 White Papers**, from members and non-members. (a ReNeW record!).
  - **120 attendees** at Theme I+II workshop – thanks to GA for hosting. *http://fusion.gat.com/global/Renewt12*
- Theme II leaders echo Jim's appreciation to all who have contributed, and are contributing to Thrusts as leaders, co-authors or reviewers.

- **Full credit for the Theme II chapter goes to the panel leaders and members!**

- Drafts are posted on the Forum, under "Theme II- Renew performance chapter, latest revision"
- Feedback and suggestions from all ReNeWers for improvement are welcome, now, in today's breakout session, and/or in writing to panel or section leaders.