NASA SBIR 2010 Phase I Solicitation

Aeronautics Research

Aviation Safety Topic A1

The Aviation Safety Program focuses on the Nation's future aviation safety challenges. This vigilance for safety must continue in order to meet the projected increases in air traffic capacity and realize the new capabilities envisioned for the Next Generation Air Transportation System (NextGen). The Aviation Safety Program will conduct research to improve the intrinsic safety attributes of legacy and future aircraft and their operations in the Next Generation Air Transportation system, and to eliminate safety-related technology barriers.

The program has focused on furthering our understanding of the fundamental questions that need to be addressed for mid- and long-term improvements to aviation safety through engineering analysis and technology design. The results at the fundamental level will be integrated at the discipline and multi-discipline levels to ultimately yield system-level integrated capabilities, methods, and tools for analysis, optimization, prediction, and design that will enable improved safety for a range of operating concepts, vehicle classes, and crew configurations. The Aviation Safety Program is divided into four complementary and highly interlinked projects:

- The Aircraft Aging and Durability Project performs foundational research in aging science that will ultimately yield multi-disciplinary analysis and optimization capabilities that will enable system-level integrated methods for the detection, prediction, and mitigation/management of aging-related hazards for future civilian and military aircraft.

- The Integrated Intelligent Flight Deck Project develops tools, methods, principles, guidelines, and technologies for revolutionary flight deck systems that enable transformations toward safer operations.

- The Integrated Resilient Aircraft Control Project conducts research to advance the state of aircraft flight control to provide onboard control resilience for ensuring safe flight in the presence of adverse conditions.

- The Integrated Vehicle Health Management Project develops validated tools, technologies and techniques for automated detection, diagnosis and prognosis that enable mitigation of adverse events during flight.

Examples areas of program interest include research directed at fundamental knowledge of legacy and future aircraft structures and systems durability; on-board detection, diagnosis, prognosis, prediction and mitigation of system failures and faults; monitoring vehicle and airspace issues to identify problems before they become accidents; understanding aircraft dynamics of current and future vehicles in damaged and upset conditions; robust control systems; aircraft guidance for emergency operation; airborne sensors and sensor systems for the detection and monitoring of external hazards to aircraft (e.g., in-flight icing conditions, wake vortices); design of robust collaborative work environments; effective and robust human-automation systems; and information management for effective decision making. In addition, general methods for dramatically advancing the community's capability...
for thorough, cost-effective and time-effective verification and validation of safety-critical systems are of interest to the program as a whole, including rigorous methods for validating design requirements for vehicles and aviation operations, verifying integrated and distributed aircraft and air traffic systems (including assumptions about human performance), and verifying software-intensive systems.

NASA seeks highly innovative proposals that will complement its work in science and technologies that build upon and advance the Agency's unique safety-related research capabilities vital to aviation safety. Additional information is available at [http://www.aeronautics.nasa.gov/programs_avsafe.htm](http://www.aeronautics.nasa.gov/programs_avsafe.htm) [1].

Sub Topics:

**A1.01 Mitigation of Aircraft Aging and Durability-Related Hazards**

**Lead Center:** GRC  
**Participating Center(s):** ARC, LaRC

The mitigation and management of aging and durability-related hazards in future civilian and military aircraft will require advanced materials, concepts, and techniques. NASA is engaged in the research of materials (metals, ceramics, and composites) and characterization/validation test techniques to mitigate aging and durability issues and to enable advanced material suitability and concepts.

Proposals are sought for the development of moisture-resistant resins and new surface treatments/primers. Novel chemistries are sought to improve the durability of aerospace adhesives with potential use on subsonic aircraft. This research opportunity is focused on the development of novel chemistries for coupling agents, surface treatments for adherends and their interfaces, leading to aerospace structural adhesives with improved durability. Work may involve chemical modification and testing of adhesives, coupling agents, surface treatments or combinations thereof and modeling to predict behavior and guide the synthetic approaches. Examples of adhesive characteristics to model and/or test may include, but are not limited to, hydrolytic stability of the interfacial chemistry, moisture permeability at the interface, and hydrophobicity of coupling agents and surface primers. Examples of adherends to model and/or test include carbon fiber/epoxy composites used in structural applications on subsonic aircraft, and aluminum, as well as their respective surface treatments. Additionally, proposals are sought for test techniques to fully characterize aging history and strain rate effects on thermoset and/or thermoplastic resins as well as on advanced composites manufactured of such resins and reinforced with 3D fiber preforms such as the triaxial braid used in advanced composite fan containment structures. Technology innovations may take the form of tools, models, algorithms, prototypes, and/or devices.

Proposals are sought for the development of validated models to capture the evolution of residual stresses and cold work at machined features of compressor and turbine powder metallurgy superalloy disks. This research opportunity is focused on quantifying, modeling and validating residual stress and cold work evolution at stress concentration features during simulated service in aerospace gas turbine engine disk materials. Work may involve use of notched fatigue specimens to simulate stress concentration features utilizing varied surface finish conditions including as-machined, electro-polished, and shot peened surfaces. The simulated load history and temperature gas turbine engine conditions should approximate turbine service history reflective of the new generation of gas turbine engines and include the effect of superimposed dwell cycles. NASA will be an active participant in Phase I of the research effort by providing the notched specimens, and performing the mechanical testing. Technology innovations may take the form of the unique quantification of the effect of service history on residual stress and cold work depth profile evolutions within notches, and include analytical modeling descriptions of the evolution of these parameters as a function of simulated service history. The technology innovations may also include models and algorithms extrapolating the predicted residual stresses and cold work to service conditions outside of those tested during the program.
A1.02 Sensing and Diagnostic Capability for Aircraft Aging and Damage

Lead Center: LaRC

Participating Center(s): AFRC, ARC, GRC, MSFC

Many conventional nondestructive evaluation (NDE) techniques have been used for flaw detection, but have shown little potential for much broader application. One element in NASA’s effort to ensure the integrity of future vehicles is research to identify changes in fundamental material properties as indicators of material aging-related hazards before they become critical. For example, composites can exhibit a number of micromechanisms such as fiber buckling and breakage, matrix cracking and delaminations as precursor to failure. For complex metallic components an inability to determine residual stress state limits the validity of predictions of the fatigue life of the component.

To further these goals, NDE technologies are being sought for the nondestructive characterization of age-related degradation in complex materials and structures. Innovative and novel approaches to using NDE technologies to measure properties related to manufacturing defects, flaws, and material aging. Measurement techniques, models, and analysis methods related to quantifying material thermal properties, elastic properties, density, microcrack formation, fiber buckling and breakage, etc. in complex composite material systems, adhesively bonded/built-up and/or polymer-matrix composite sandwich structures are of particular interest. Other NDE technologies being sought are those that enable the quantitative assessment of the strength of an adhesive region of bonded joints and repairs or enable the rapid, full-field inspection of large area structures. The anticipated outcome of successful proposals would be both a Phase II prototype NDE technology for the use of the developed technique and a demonstration of the technology showing its ability to measure a relevant material property in the advanced materials and structures in subsonic aircraft.

A1.03 Prediction of Aging Effects

Lead Center: LaRC

Participating Center(s): ARC, GRC

In order to assess the long-term effects of potential hazards and aging-related degradation of new and emerging material systems/fabrication techniques, NASA is performing research to anticipate aging and to predict its effects on the designs of future aircraft. To support this predictive capability, structural integrity analytical tools, lifing methods, and material durability prediction tools are being developed. Physics-based and continuum-based models encapsulated as computational methods (software) are needed to provide the basis for these higher level (e.g., design) tools. Proposals are sought that apply innovative computational methods, models and analytic tools to the following specific applications:

- Probabilistic computational code is sought for improved structural analysis of complex metallic and composite airframe components. The methods used in these solutions need to detail the initiation and progression of damage to determine accurate estimates of residual life and/or strength of complex airframe structures.
Software tools are needed to predict the onset and rates of type-II hot corrosion attack in nickel-based turbine disk superalloys that allow for prolonged disk operation at high temperatures. Typically hot corrosion of turbine alloys is a product of molten salt exposure and is manifested by a localized pitting corrosion attack. Prolonged high temperature exposures of turbine disk alloys to sulfur-rich low temperature melting eutectic salts can lead to an onset of Type II hot corrosion attack causing serious degradation to the durability of the turbine components.

Computational software is sought to simulate the response of advanced composite fan case/containment structures in aged conditions to jet engine fan blade-out events using impact mechanics and structural system dynamics modeling techniques.

The anticipated outcome of successful Phase II proposals would be analytic code (software) delivered to NASA suitable for use in material evaluation studies.

A1.04 Aviation External Hazard Sensor Technologies

Lead Center: LaRC
Participating Center(s): AFRC, GRC

A1.05 Crew Systems Technologies for Improved Aviation Safety

Lead Center: LaRC

NASA seeks proposals that will improve aerospace system safety through: the development of highly innovative, crew-centered, technologies that result in effective joint human-automation systems; and improved methods for evaluating such systems in the context of NextGen operations.

We seek proposals for the development of advanced technologies that:

- Effectively convey information and aid decisions which support novel NextGen operational requirements (e.g., 4D trajectory-based operations, visual operations in non-visual meteorological conditions, etc. as described in [http://www.faa.gov/about/initiatives/nextgen/media/NGIP_0130.pdf](http://www.faa.gov/about/initiatives/nextgen/media/NGIP_0130.pdf) [2]);
- Foster the appropriate use of automation and complex information sources by, for example, conveying constraints on automation reliability and information certainty/timeliness;
- Support effective joint cognitive systems by improving the communication and collaboration among multiple intelligent agents (human and automated, proximal and remote);
- Characterize the operational status of the human crewmembers, effectively modulate this state, and/or effectively adapt interfaces and automation in response to functional status (e.g., situationally-aware display
reconfiguration, aiding, and multi-modal presentation of information to maximize system performance and minimize information processing bottlenecks).

We also seek proposals with novel approaches to evaluating joint human-automation systems, particularly with adaptive automation, to assess team (human and automated agents), and system performance and reliability.

Proposals should describe novel technologies and evaluation tools with high potential to serve the objectives of the Operator Performance (http://www.aeronautics.nasa.gov/avsafe/iifd/op.htm [3]) and Operator Characterization (http://www.aeronautics.nasa.gov/avsafe/iifd/ocm.htm [4]) and/or Multimodal Interfaces (http://www.aeronautics.nasa.gov/avsafe/iifd/mmi.htm [5]) elements of NASA's Aviation Safety Integrated Intelligent Flight Deck program (http://www.aeronautics.nasa.gov/avsafe/iifd/index.htm [6]). Successful Phase I proposals should culminate in a final report that specifies, and a Phase II proposal that would realize, technology that improves the effectiveness of joint human-automation systems in aviation, or improves the ability to assess the effectiveness and reliability of such systems.

A1.06 Technologies for Improved Design and Analysis of Flight Deck Systems

Lead Center: ARC
Participating Center(s): LaRC

Information complexity in flight deck systems is increasing exponentially, and flight deck designers need tools to understand, manage, and estimate the performance and safety characteristics of these systems early in the design process - this is particularly true due to the multi-disciplinary nature of these systems. NASA seeks innovative design methods and tools for representing the complex human-automation interactions that will be part of future flight deck systems. In addition, NASA seeks tools and methods for estimating, measuring, and/or evaluating the performance of these designs throughout the lifecycle from preliminary design to operational use - with an emphasis on the early stages of conceptual design. Specific areas of interest include the following:

- Computational/modeling approaches to support determining appropriate human-automation function allocations with respect to safety and reliability. Specifically these methods should focus on metrics that describe the robustness and resilience of a proposed human - automation function allocation;
- Design tools and methods that improve the application of human-centered design principles to the design and certification of mixed human-automated systems;
- Design and analysis methods or tools to better predict and assess human and system performance in relevant operational environments, particularly in regards to procedural errors.

Proposals should describe novel design methods, metrics, and/or tools with high potential to serve the objectives of the System Design and Analysis element of NASA's Aviation Safety Integrated Intelligent Flight Deck program (http://www.aeronautics.nasa.gov/avsafe/iifd/sda.htm [7]). Successful Phase I proposals should culminate in a final report that specifies, and a Phase II proposal that would realize, tools that improve the design process for human-automation systems in aviation, or improves the ability to assess effectiveness of such systems during the design
phase. All proposals should discuss means for verification and validation of proposed methods and tools in operationally valid, or end-user, contexts.

A1.07 Adaptive Aeroservoelastic Suppression

Lead Center: AFRC
Participating Center(s): ARC, LaRC

NASA has initiated an Integrated Resilient Aircraft Control (IRAC) effort under the Aviation Safety Program. The main focus of the effort is to advance the state-of-the-art technology in adaptive controls to provide a design option that allows for increased resiliency to failures, damage, and upset conditions. These adaptive flight control systems will automatically adjust the control feedback and command paths to regain stability, maneuverability, and eventually a safe landing. One potential consequence of changing the control feedback and command paths is that an undesired aeroservoelastic (ASE) interaction could occur. The resulting limit cycle oscillation could result in structural damage or potentially total loss of vehicle control.

Current airplanes with non-adaptive control laws usually include roll-off or notch filters to avoid ASE interactions. These structural mode suppression filters are designed to provide 8 dB of gain attenuation at the structural mode frequency. Ground Vibration Testing (GVT), Structural Mode Interaction (SMI) testing, and finally full scale flight-testing are performed to verify that no adverse ASE interactions occur. Until a significant configuration or control system change occurs, the structural mode suppression filters provide adequate protection.

When an adaptive system changes to respond to off-nominal rigid body behavior, the changes in control can affect the structural mode attenuation levels. In the case of a damaged vehicle, the frequency and damping of the structural modes can change. The combination of changing structural behavior with changing control system gains results in a system with a probability of adverse interactions that is very difficult to predict a priori. An onboard, measurement based method is needed to ensure that the system adjusts to attenuate any adverse ASE interaction before a sustained limit cycle and vehicle damage are encountered. This system must work in concert with the adaptive control system to allow the overall goal of re-gaining rigid body performance as much as possible without exacerbating the situation with ASE interactions.

A1.08 Robust Propulsion Control

Lead Center: GRC

The object of this research topic is to develop approaches for robust propulsion control design to maintain engine operation in the presence of engine icing, foreign object damage such as ice ingestion and bird strikes, or extreme operating conditions such as high angle of attack.
Aircraft engines are designed to operate safely over a wide range of conditions. They can ingest small birds with little or no effect, and they are designed with enough stall margin available that the amount of inlet distortion encountered under normal circumstances is not detrimental. However, there is a limit to the variation that the engine can accept. In the case of larger than normal inlet distortion, large bird ingestion, or internal ice build-up, the engine's operation can be far enough from its design point that stability is compromised. In these cases it might still be possible to maintain basic engine function by moving bleed valves or variable stator vanes off of their nominal schedules. This requires the development of a robust control algorithm that delivers normal engine performance over the traditional operating range, but is capable of maintaining operation beyond normal conditions.

The expected outcome of the research will be a demonstrated robust propulsion control using a realistic engine model such as the NASA-developed Commercial Modular Aero-Propulsion System Simulation (C-MAPSS). Any modifications to the simulation required to accurately model the effects of engine ice, FOD, inlet distortion, etc., will be the responsibility of the contractor, and must be based on physical considerations.

NASA resources available for the research are the publicly available Commercial Modular Aero-Propulsion System Simulation (C-MAPSS) or a similar simulation. C-MAPSS is available upon request to US Citizens and permanent residents.

A1.09 Pilot Interactions with Adaptive Control Systems under Off-Nominal Conditions

Lead Center: AFRC

Adaptive control is a promising control technology that can enhance flight safety and performance. Adaptive control has been demonstrated to provide improved performance in many unmanned aerial systems. When operated in an autonomous mode such as in an autopilot, the behavior of an adaptive flight control system can be modeled and simulated with a sufficient degree of repeatability.

The presence of a pilot working in a closed-loop fashion with an adaptive flight control presents an important problem that has not been well addressed. Adaptive control generally requires sufficiently rich input signals to improve parameter convergence, as the adaptive control system adapts to parametric changes in the vehicle dynamics or exogenous disturbances. The condition for rich input signals is known as persistent excitation. During adaptation under off-nominal conditions such as aircraft with damage, the pilot provides persistently exciting signals to the adaptive control system. There is generally a trade-off between adaptation and stability due to persistent excitation. With a high persistent excitation in the pilot inputs, the speed of adaptation increases and in theory better handling performance could be achieved. However, in practice, the high persistent excitation in the control signals can potentially cause significant cross coupling between different flight control axes and or excite unmodeled dynamics such as aeroservoelastic modes. The overall effect of high persistent excitation could aggravate stability robustness of an adaptive flight control system with a pilot in the loop that results in poor handling qualities.

Another aspect of pilot interactions with an adaptive control system is the potential interactions between two adaptive elements in a closed-loop fashion, because the pilot can also be viewed as an adaptive control system.
with a learning ability. With the pilot adaptive element providing high persistently exciting inputs into an adaptive flight control system with a predetermined adaptation rate, the issue of stability can be important and difficult to assess.

To enable an adaptive flight control system to be operated with a pilot in the loop, it is necessary to develop new research techniques that can assess the effects of pilot interactions with an adaptive flight control system. These techniques should address pilot control responses via an adaptive model with features that can capture relevant interactions with an adaptive flight control system. Techniques for assessing pilot interactions via metrics that can quantify the pilot-vehicle system responses with an adaptive flight control system are also needed. Other aspects of the research can include new methods and tools that can provide an advisory function to limit the pilot control inputs in order to trade off between command-following performance and stability robustness.

Research in adaptive control methods will address the system requirements to provide good flying characteristics when the human operator closes the control loop. In the presence of damage, failures, etc. the adaptive system must trade the stability requirements with closed loop handling requirements. Methods for selecting the best achievable handling are needed. The adaptation system needs to find a good compromise between suppression of coupling between the axis (i.e. pitch into roll, etc) and good in-axis behavior. Better metrics to assess cross-coupled (asymmetric) behavior are needed. These metrics could provide a quantitative measurement of the severity of a given failure, as well as a measure of the improvement due to adaptation. As the adaptation changes the flying characteristics of the vehicle, some means of informing the operator is required to ensure that the system is not overdriven by a pilot who is expecting nominal performance.

A1.10 Detection of Aircraft Anomalies

Lead Center: GRC

Participating Center(s): AFRC, ARC, LaRC

Adverse events that occur in aircraft can lead to potentially serious consequences if they go undetected. This effort is to develop the technologies, tools, and techniques to detect in-flight anomalies from adverse events. This involves the integration of novel sensor and advanced analytical technologies for airframe, propulsion systems, and other subsystems within the aircraft. The emphasis of this work is not on diagnosing the exact nature of the failure but on identifying its presence. Proposals are solicited that address aspects of the following topics:

- Analytical and data-driven technologies required to interpret the sensor data to enable the detection of fault and failure events,
- Methods to differentiate sensor failure from actual system or component failure,
- Characterizing, quantifying, and interpreting multi-sensor outputs, and
- New sensors, sensory materials and sensor systems that improve the detection of an adverse event or permit increased sensory coverage for an adverse event.
Emphasis is on novel methods to detect failures in electrical, electromechanical, electronic, structural, and propulsion systems. Along with these system failures, condition sensors are desired for both the detection of internal engine icing as well as composite aircraft lightning strikes (location and intensity). Where possible, a rigorous mathematical framework should be employed to ensure the detection rates and detection time constants are acceptable according to published baselines as characterized by statistical measures. Understanding and addressing validation issues are critical components of this effort.

A1.11 Diagnosis of Aircraft Anomalies

Lead Center: LaRC

Participating Center(s): AFRC, GRC, SSC

The capability to identify faults is critical to determining appropriate mitigation actions to maintain aircraft safety. This effort is to develop innovative methods and tools for the diagnosis of aircraft faults and failures. It includes the development of integrated technologies, tools, and techniques to determine the causal factors, nature, and severity of an adverse event and to distinguish that event from within a family of potential adverse events. These requirements go beyond standard fault isolation techniques. The emphasis is on the development of mathematically rigorous diagnostic technologies that are applicable to structures, propulsion systems, software, and other subsystems within the aircraft. Technologies developed must be able to perform diagnosis given heterogeneous and asynchronous signals coming from the health management components of the vehicle and integrating information from each of these components.

The ability to actively query health management systems, use advanced decision making techniques to perform the diagnosis, and then assess the severity using these techniques are critical. As an example, the mathematical rigor of the diagnosis and severity assessment could be treated through a Bayesian methodology since it allows for characterization and propagation of uncertainties through models of aircraft failure and degradation.

Both computational and prototype hardware implementations of the diagnostic capabilities are expected outcomes of this effort. Other methods could also be employed that appropriately model the uncertainties in the subsystem due to noise, various stresses due to the aerodynamic forces inherent in flight, and other sources of uncertainty. The ability to actively query the underlying health management systems (whether they are related to detection or not) is critical to reducing the uncertainty in the diagnosis. As an example, if there is ambiguity in the diagnosis about the type and location of a particular failure in the aircraft structure, the diagnostic engine should be able to actively query that system or related systems to determine the true location and severity of the anomaly. An important element is the use of structural health monitoring tools based on the application of damage progression models with statistical inference and multivariate decision schemes to aid in the integration of multiple sensors for structural vibration and/or strain measurements in a noisy environment. Where possible, a rigorous mathematical framework should be employed to provide a rank ordered list of diagnoses, an assessment of the severity of each diagnosed event, and a measure of the uncertainty in the diagnosis. Understanding and addressing the system integration and validation issues are critical components of this effort.
A1.12 Prognosis of Aircraft Anomalies

Lead Center: ARC
Participating Center(s): AFRC, GRC, LaRC

The ability to accurately and precisely predict the remaining useful life (RUL) of aircraft components and subsystems enables decision making and action taking that can avert or mitigate failures, thereby enhancing aircraft safety. Furthermore, it can improve operational efficiency by facilitating condition-based maintenance and reducing unscheduled maintenance. This effort addresses the development of innovative methods, technologies, and tools for the prognosis of aircraft faults and failures. The assessment of the RUL could be used by other aircraft systems to place additional restrictions, such as a new operating envelope, on the flight control systems or it could be used by flight or maintenance personnel to take preventative actions. Areas of interest include developing methods for making predictions of RUL, which take into account operational and environmental uncertainties (pure data-driven approaches are discouraged); physics-based models of degradation; generation of aging and degradation datasets on relevant components or subsystems; and development of validation and verification methodologies for prognostics.

Research should be conducted to demonstrate technical feasibility during Phase I and to show a path toward a Phase II technology demonstration. Proposals are solicited that address aspects of the following areas:

- RUL prediction techniques that address a set of fault modes for a device or component, for example by modeling the physics of the most critical fault modes and using (typically less accurate) data-driven methods for the remainder.

- Physics-based damage propagation models for one or more relevant aircraft subsystems such as composite or metallic airframe structures, engine turbomachinery and hot structures, avionics, electrical power systems, electromechanical systems, and electronics. Proposals that focus on technologies envisioned for next generation aircraft are strongly encouraged.

- Uncertainty representation and management (reduction of prediction uncertainty bounds) methods. Proposers are encouraged to consider uncertainties due to measurement noise, imperfect models and algorithms, as well as uncertainties stemming from future anticipated loads and environmental conditions. Methods can also consider the fusion of different techniques but must show how this helps to improve the uncertainty using appropriate metrics.

- Aircraft relevant test beds that can generate aging and degradation datasets for the development and testing of prognostic techniques.

- Verification and validation methods for prognostic algorithms.

If prognostic algorithms are being developed, performance needs to be measured on benchmark data sets using prognostic metrics for accuracy, precision, and robustness. Metrics should include prognostic horizon (PH), alpha-lambda, relative accuracy (RA), convergence, and R_delta.
A1.13 Healing Material System Concepts for IVHM

Lead Center: LaRC
Participating Center(s): AFRC, ARC, GRC

The development of integrated multifunctional self-sensing, self-repairing structures will enable the next generation of lightweight, reliable and damage-tolerant aerospace vehicle designs. Prototype multifunctional composite and/or metallic structures are sought to meet these needs, as are concepts for their analytical and experimental interrogation. Specifically, structural and material concepts are sought to enable in situ monitoring and repair of service damage (e.g., cracks, delaminations) to improve structural durability and enhance safe operation of aerospace structural systems. Emphasis is placed on the development of new materials and systems for the mitigation of structural damage and/or new concepts for activation of healing mechanisms using new or existing materials. These advanced structural and material concepts must be robust, consider all known damage modes for specific material systems and be validated through experiment.

A1.14 Verification and Validation of Flight-Critical Systems

Lead Center: ARC
Participating Center(s): AFRC, LaRC

The purpose of this subtopic is to invest in mid- and long-term research to establish rigorous, systematic, scalable, and repeatable verification and validation methods for flight-critical systems, with a deliberate focus on safety for NextGen (http://www.jpdo.gov/nextgen.asp [8]). This subtopic targets NextGen safety activities and interests encompassing vehicles, vehicle systems, airspace, airspace concept of operations, and air traffic technologies, such as communication or guidance and navigation. Methods for assessing issues with technology, human performance and human-systems integration are all included in this sub-topic, nothing that multi-disciplinary research is required that does not focus on one type of component or phenomenon to the exclusion of other important drivers of safety.

Proposals are sought for the development of:

- Safety-case methods and supporting technologies capable of analyzing the system-wide safety properties suitable for civil aviation vehicles and for complex concepts of operation involving airborne systems, ground systems, human operators and controllers.

- Technologies and mathematical models that enable rigorous, comprehensive analysis of novel integrated, and distributed, systems interacting through various mechanisms such as communication networks and human-automation and human-human interaction.

- Techniques, tools and policies to enable efficient and accurate analysis of safety aspects of software-intensive systems, ultimately reducing the cost of software V&V to the point where it no longer inhibits many safety innovations and NextGen developments.
Tools and techniques that can facilitate the use of formal methods in V&V throughout the lifecycle such as graphical-based development environments (e.g., eclipse plug-ins for static analyzers, model checkers, or theorem provers) or tools facilitating translation from design formats used in industry to formal languages supporting automated reasoning.

This subtopic is intended to address those flight-critical systems that directly conduct flight operations by controlling the aircraft, such as on-board avionics and flight deck systems, and safety-critical ground-based functions such as air traffic control and systems for communication, navigation and surveillance. It is not intended to cover V&V of computational models of physical systems (e.g. CFD codes or finite element analysis).

In Phase II, a functional system shall be delivered to NASA for its retention and ownership.

A1.15 Data Mining

Lead Center: ARC
Participating Center(s): LaRC

The fulfillment of the IVHM project's goal requires the ability to transform the vast amount of data produced by the aircraft and associated systems and people into actionable knowledge that will aid in detection, diagnosis, prognosis, and mitigation at levels ranging from the aircraft-level, to the fleet-level, and ultimately to the level of the national airspace. The vastness of this data means that data mining methods must be efficient and scalable so that they can return results quickly. Additionally, much of this data will be distributed among multiple systems. Data mining methods that can operate on the distributed data where they are is critical because centralizing data will typically be impractical. However, these methods must be provably able to return the same results as what a comparable method would return if the data could be centralized because this is a critical part of verifying and validating these algorithms, which is important for aviation safety applications.

This topic will yield efficient and scalable data-driven algorithms for anomaly detection, diagnosis, prediction, and prognosis that are able to operate at levels ranging from the aircraft level to the fleet level. To that end, the methods must be able to efficiently learn from vast historical time-series datasets (at least 10 TB) that are heterogeneous (contain continuous, discrete, and/or text data). Distributed data-driven algorithms that provably return the same results as a comparable method that requires data to be centralized are also of great interest.
The Fundamental Aeronautics Program (FAP) encompasses the principles of flight in any atmosphere, and at any speed. The program develops focused technological capabilities, starting with the most basic knowledge of underlying phenomena through validation and verification of advanced concepts and technologies at the component and systems level. Physics-based, multidisciplinary design, analysis, and optimization (MDAO) tools will be developed that make it possible to evaluate radically new vehicle designs and to assess, with known uncertainties, the potential impact of innovative technologies and concepts on a vehicle's overall performance. The development of advanced component technologies will realize revolutionary improvements in noise, emissions, and performance. The program also supports NASA's human and robotic exploration missions by advancing knowledge in aeronautical areas critical to planetary Entry, Descent, and Landing. NASA has defined a four-level approach to technology development: conduct foundational research to further our fundamental understanding of the underlying physics and our ability model that physics; leverage the foundational research to develop technologies and analytical tools focused on discipline-based solutions; integrate methods and technologies to develop multi-disciplinary solutions; and solve the aeronautics challenges for a broad range of air vehicles with system-level optimization, assessment and technology integration.

Structurally, the FAP is composed of four projects: hypersonic flight, supersonic flight, subsonic fixed-wing aircraft and subsonic rotary-wing aircraft.

**Hypersonics (HYP)**

- Fundamental research in all disciplines to enable very-high speed flight (for airbreathing launch vehicles) and Entry, Descent and Landing into planetary atmospheres
- High-temperature materials, thermal protection systems (single and multi-use), airbreathing propulsion, aero-thermodynamics, multi-disciplinary analysis and design, guidance, navigation, and control GN&C, advanced experimental capabilities, and supersonic decelerator technologies

**Supersonics (SUP)**

- Eliminate environmental and performance barriers that prevent practical supersonic vehicles (cruise efficiency, noise and emissions, vehicle integration and control)

**Subsonic Fixed Wing (SFW)**

- Develop revolutionary technologies and aircraft concepts with highly improved performance while satisfying strict noise and emission constraints
- Focus on enabling technologies: acoustics predictions, propulsion / combustion, system integration, high-lift concepts, lightweight and strong materials, GNC
Subsonic Rotary Wing (SRW)

- Improve civil potential of rotary wing vehicles (vs. fixed wing) while maintaining their unique benefits
- Key advances in multiple areas through innovation in materials, aeromechanics, flow control, propulsion

Each project addresses specific discipline, multi-discipline, sub-system and system level technology issues relevant to that flight regime. A key aspect of the Fundamental Aeronautics Program is that many technical issues are common across multiple flight regimes and may be best resolved in an integrated coordinated manner. As such, the FAP subtopics are organized by discipline, not by flight regime, with a special subtopic for rotary-wing issues.

Additional information: [http://www.aeronautics.nasa.gov/fap/index.html](http://www.aeronautics.nasa.gov/fap/index.html) [9]

Sub Topics:

**A2.01 Materials and Structures for Future Aircraft**

**Lead Center:** GRC

**Participating Center(s):** AFRC, ARC, LaRC

Advanced materials and structures technologies are needed in all four of the NASA Fundamental Aeronautics Program research thrusts (Subsonics Fixed Wing, Subsonics Rotary Wing, Supersonics, and Hypersonics) to enable the design and development of advanced future aircraft. Proposals are sought that address specific design and development challenges associated with airframe and propulsion systems. These proposals should be linked to improvements in aircraft performance indicators such as vehicle weight, fuel consumption, noise, lift, drag, durability, and emissions. In general, the technologies of interest cover five research themes:

- **Fundamental materials development, processing and characterization** - innovative approaches to enhance the durability, processability, performance and reliability of advanced materials (metals, ceramics, polymers, composites, nanostructured materials, hybrids and coatings). In particular, proposals are sought in:
  - Advanced high temperature materials for aircraft engine and airframe components and thermal protection systems, including advanced blade and disk alloys, ceramics and CMCs, polymers and PMCs, nanostructured materials, hybrid materials and coatings to improve environmental durability.
  - Adaptive materials such as piezoelectric ceramics, shape memory alloys, shape memory polymers, and variable stiffness materials and methods to integrate these materials into airframe and/or aircraft engine structures to change component shape, dampen vibrations, and/or attenuate acoustic transmission through the structure.
  - Multifunctional materials and structural concepts for engine and airframe structures, such as novel approaches to power harvesting and thermal management, lightning strike mitigating, self-sensing, and materials for wireless sensing and actuation.
  - New high strength fibers, in particular low density, high strength and stiffness carbon fibers.
  - Innovative processing methods to reduce component manufacturing costs and improve damage tolerance and reliability of ceramics, metals (especially oxide dispersion strengthened nickel-based
alloys), polymers, composites, and hybrids, nanostructured and multifunctional materials and coatings.

- Development of joining and integration technologies including fasteners and/or chemical joining methods for ceramic-to-ceramic, metal-to-metal, and metal-to-ceramic as well as solid state joining methods such as advanced friction stir welding.

- Innovative methods for the evaluation of advanced materials and structural concepts (in particular multifunctional and/or adaptive) under simulated operating conditions, including combinations of electrical, thermal and mechanical loads.

- Nondestructive evaluation (NDE) methods for the detection of as-fabricated flaws and in-service damage for textile polymeric, ceramic and metal matrix composites, nanostructured materials and hybrids. NDE methods that provide quantitative information on residual structural performance are preferred.

- **Structural analysis tools and procedures** - robust and efficient design methods and tools for advanced materials and structural concepts (in particular multifunctional and/or adaptive components) including variable fidelity methods, uncertainty based design and optimization methods, multi-scale computational modeling, and multi-physics modeling and simulation tools. In particular, proposals are sought in:
  
  - Multiscale design tools for aircraft and engine structures that integrate novel materials, mechanism design, and structural subcomponent design into systems level designs.
  
  - Life prediction tools for textile composites including fiber architecture modeling methods that enable the development of physics-based hierarchical analysis methods. Fiber architecture models that address yarn-to-yarn and ply-to-ply interactions covering a wide range of textile preform structures in either a relaxed or compressed deformation state as well as tools to predict debonding and delamination of through thickness reinforced (stitched, z-pinned) composites are of particular interest.
  
  - Tools to predict durability and damage tolerance of new material forms including metallic-composite hybrids, friction stir-welded metallic materials and powder metallurgy-formed materials.
  
  - Meso scale tools to guide materials placement to enable tailored load paths in multifunctional structures for enhanced damage tolerance.

- **Computational materials development tools** - methods to predict properties, damage tolerance, and/or durability of both airframe and propulsion materials, thermal protection systems and ablatives based upon chemistry and processing for conventional as well as functionally graded, nanostructured, multifunctional and adaptive materials. In particular proposals are sought in:
  
  - Ab-initio methods that enable the development of coatings for multiple uses at temperatures above 3000°F in an air environment.
  
  - Computational tool development for structure-property modeling of adaptive materials such as piezoelectric ceramics, shape memory alloys, shape memory polymers to characterize their physical and mechanical behavior under the influence of an external stimulus.
  
  - Computational and analytical tools to enable molecular design of polymeric and/nanostructured materials with tailored multifunctional characteristics.
  
  - Computational microstructural and thermodynamic analysis tools and technique development for designing new lightweight alloy compositions for subsonic airframe and engines from first principles, functionally graded (chemically or microstructurally) materials, and/or novel metals processing
techniques to accelerate materials development and understanding of processing-structure-property relationships.

- Software tools to predict temperature dependent phase chemistries, volume fractions, shape and size distributions, and lattice parameters of phases in a broad range of nickel and iron-nickel based superalloys. Toolset should utilize thermodynamic and kinetic databases and models that are fully accessible, which allow modifications and user-input to expand experimental databases and refine model predictions.

- **Advanced Structural Concepts** - new concepts for airframe and propulsion components incorporating new light weight concepts as well as “smart” structural concepts such as those incorporating self-diagnostics with adaptive materials, multifunctional component concepts to reduce mass and improve durability and performance, lightweight, efficient drive systems and electric motors for use in advanced turboelectric propulsion systems for aircraft, and new concepts for robust thermal protection systems for high-mass planetary entry, descent and landing. In particular, proposals are sought in:

  - Innovative structural concepts, materials, manufacturing and fabrication leading to reliable, entry descent and landing systems including deployable rigid and flexible heat shields and structurally integrated multifunctional systems. Of particular interest are high temperature honeycombs, hat stiffeners, rigid fibrous and foam insulators, as well as high temperature adhesives, films and fabrics for advanced flexible heat shields.

  - Advanced mechanical component technologies including self lubricating coatings, oil-free bearings, and seals.

  - Advanced material and component technologies to enable the development of mechanical and electrical drive system to enable the development of turboelectric propulsion systems, which utilize power from a single turbine engine generator to drive multiple propulsive fans. Innovative concepts are sought for AC-tolerant, low loss (1.5 T field and 500 Hz electrical frequency; and high efficiency (= 30% of Carnot), low mass

  - Novel structural designs for integrated fan cases that combine hardwall composite cases for blade containment with acoustic treatments as well as concepts that integrate the case with the fan inlet to maximize structural, acoustic attenuation and weight benefits.

  - Innovative approaches to structural sensors for extreme environments (>1800°F) including the development and validation of improved methods (i.e. adhesives, plasma spraying techniques, etc.) for attaching sensors to advanced high-temperature materials as well as approaches to measure strain, temperature, heat flux and/or acceleration of structural components.

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**A2.02 Combustion for Aerospace Vehicles**

**Lead Center:** GRC

**Participating Center(s):** LaRC
Active Aeroelastic Wing Shape Tailoring for Aircraft Performance and Control

Modern aircraft are increasingly designed with lightweight, flexible airframe structures. By employing distributed flight control surfaces, a modern wing structure (which implies aircraft wing, horizontal stabilizer, and vertical stabilizer) can be strategically tailored in-flight by actively controlling the wing shape so as to bring about certain desired vehicle characteristics. For example, active aeroelastic wing shape tailoring can be employed to control the wash-out distribution and wing deflection in such a manner that could result in improved aerodynamic performance such as reduced drag during cruise or increased lift during take-off. Another novel use of active aeroelastic wing shape tailoring is for flight control. By actively controlling flexible aerodynamic surfaces differentially or collectively, the motion of an aircraft can be controlled in all three stability axes. In high speed supersonic or hypersonic vehicles, effects of airframe-propulsion-structure interactions can be significant. Thus, propulsion control can play an integral role with active aeroelastic wing shape tailoring control in high speed flight regimes.
This technology area involves the development of various technical elements including:

- Innovative aircraft concepts that can significantly improve aerodynamic performance and control by leveraging active aeroelastic wing shape tailoring.
- Sensor technology that will enable in-flight wing twist and deflection static and dynamic measurements for control development.
- Actuation methods that examine novel modes of actuation for actively controlling wing shape in-flight, and effective placements of distributed control effectors on a wing structure.
- Vehicle dynamic modeling capability for aero-propulsive-servo-elasticity that will provide a knowledge foundation upon which vehicle control and dynamics can be developed.
- Integrated approaches for active aeroelastic wing shape tailoring control with distributed control surfaces that will provide effective advanced control strategies to achieve aerodynamic performance and flight control objectives, taken into account airframe-propulsion-structure interactions that can exist in all three flight regimes.

**Gust Load Alleviation Control**

In a future NextGen operational concept, close separation between aircraft in super density operations could lead to more frequent wake vortex encounters. The increasing use of flexible airframe design in modern aircraft will inherently lead to a potential increase in vehicle dynamic response to turbulence and wake vortices. Gust load alleviation control technology can improve ride qualities and reduce undesired structural dynamic loading on flexible airframes that could shorten aircraft service life. Gust load alleviation control technology can be either reactive or predictive. In a traditional reactive control framework, flight control systems can be designed to provide sufficient aerodynamic damping characteristics that suppress vehicle dynamic response as rapidly as possible upon a turbulence encounter. There is a trade off, however, between increased damping for mode suppression and command-following objectives of a flight control system. Large damping ratios, while desirable for mode suppression, may result in poor flight control performance.

Predictive control can provide a novel gust load alleviation strategy for future aircraft design with lightweight flexible structures. Novel look-ahead sensor technology can measure or estimate turbulent intensity to provide such information to a predictive gust load alleviation control system which in turn would dynamically reconfigure flight control surfaces as an aircraft enters a turbulent atmospheric region. Technology development of predictive gust load alleviation control may include the following:

- Novel sensor technology for Optical Air Data Systems based on LIDAR or other novel detection methods that can measure near-field air turbulent velocity components directly in front of an aircraft in the order of one-body length scale to provide nearly instantaneous predictive capability to significantly improve the effectiveness of a gust load alleviation control system.
- Predictive gust load alleviation control technology that can reliably reconfigure flight control surfaces dynamically based on the sensor information of the near-field turbulence to mitigate the vehicle structural
dynamic response upon a turbulence encounter. The predictive control strategies should be cognizant of potential adverse effects due to potential latency issues that can counteract the objective of gust load alleviation, or potential structural mode interactions due to control input signals that may contain frequencies close to the natural frequencies of the airframe.

Modular and Distributed Control for Propulsion Systems

Modular and flexible control architecture for propulsion systems is an essential technology, which will enable the full realization of turbine engine system performance. Distributed technology can alleviate the thermal constraints on engine control electronics by improving tolerance to elevated temperature and creating opportunities for relocating electronics to a more compatible environment. It will enable the implementation of more complex control law, paving the way for further integration of performance-enhancing control for reduced fuel burn, lower emissions, and operability. Directly, distributed control will reduce engine system weight. This is a multi-disciplinary research area involving high temperature electronics, sensing and actuation, control system integration, and engine system stability.

A2.08 Aircraft Systems Analysis, Design and Optimization

Lead Center: LaRC
Participating Center(s): ARC, GRC

One of the approaches to achieve the NASA Fundamental Aeronautics Program goals is to solve the aeronautics challenges for a broad range of air vehicles with system-level optimization, assessment and technology integration. The needs to meet this approach can be defined by four general themes:

- Design Environment Development;
- Variable Fidelity, Physics-Based Design/Analysis Tools;
- Technology Assessment and Integration; and

Current interdisciplinary design/analysis involves a multitude of tools not necessarily developed to work together, hindering their application to complete system design/analysis studies. Multi-fidelity, multi-disciplinary optimization frameworks, such as Numerical Propulsion System Simulation (NPSS), have been developed by NASA but have limited capabilities to simulate complete vehicle systems. Solicited topics are aligned with these four themes that will support this NASA research area.

Design Environment Development

Technology development is needed to provide complex simulation and modeling capabilities where the computer science details are transparent to the engineer. A framework environment is needed to provide a seamless
integration environment where the engineer need not be concerned with where or how particular codes within the system level simulation will be run. Interfaces and utilities to define, setup, verify, determine the appropriate resources, and launch the system simulation are also needed.

Research challenges include the engineering details needed to numerically zoom (i.e., numerical analysis at various levels of detail) between multi-fidelity components of the same discipline, as well as, multi-discipline components of the same fidelity. A major computer science challenge is developing boundary objects that will be reused in a wide variety of simulations.

Proposals will be considered that enable coupling differing disciplines, numerical zooming within a single discipline, deploying large simulations, and assembling and controlling secure or non-secure simulations.

Variable Fidelity, Physics-Based Design/Analysis Tools

An integrated design process combines high-fidelity computational analyses from several disciplines with advanced numerical design procedures to simultaneously perform detailed Outer Mold Line (OML) shape optimization, structural sizing, active load alleviation control, multi-speed performance (e.g., low takeoff and landing speeds, but efficient transonic cruise), and/or other detailed-design tasks. Current practice still widely uses sequential, single-discipline optimization, at best coupling low-fidelity modeling of other relevant disciplines during the detailed design phase. Substantial performance improvements will be realized by developing closely integrated design procedures coupled with highest-fidelity analyses for use during detailed-design. Design procedures must enable rapid determination of sensitivities (gradients) of a design objective with respect to all design variables and constraints, choose search directions through design space without violating constraints, and make appropriate changes to the vehicle shape (ideally both external OML shape and internal structural element size). Solicitations are for integrated design optimization tools that find combinations of design variables from more than one discipline and can vary synergistically to produce superior performance compared to the results of sequential, single-discipline optimization or repeated cut-and-try analysis.

Technology Assessment and Integration

Improved analysis capability of integrated airframe and propulsion systems would allow more efficient designs to be created that would maximize efficiency and performance while minimizing both noise and emissions. Improved integrated system modeling should allow designers to consider trade-offs between various design and operating parameters to determine the optimum design for various classes of subsonic fixed wing aircraft ranging from personal aircraft to large transports. The modeling would also be beneficial if it had enough fidelity to enable it to analyze both conventional and unconventional systems. Current analysis tools capable of analyzing integrated systems are based on simplified physical and semi-empirical models that are not fully capable of analyzing aircraft and propulsion system parameters that would be required for new or unconventional systems.

Analysis tools are solicited that are capable of analyzing new and unconventional aircraft and propulsion integrated systems. These include: (1) New combustor designs, alternate fuel operation, and the ability to estimate all emissions, and (2) Noise source models (e.g., fan, jet, turbine, core and airframe components). Analyses tools that are scalable, especially to small aircraft, are desired.

Evaluation of Advanced Concepts

Conceptual design and analysis of unconventional vehicle concepts and technologies is needed for technology
portfolio investment planning, development of advanced concepts to provide technology pull, and independent technical assessment of new concepts. This capability will enable "virtual expeditions through the design space" for multi-mission trade studies and optimization. This will require an integrated variable fidelity concept design system. The aerospace flight vehicle conceptual design phase is, in contrast to the succeeding preliminary and detail design phases, the most important step in the product development sequence, because of its predefining function. However, the conceptual design phase is the least well understood part of the entire flight vehicle design process, owing to its high level of abstraction and associated risk, its multidisciplinary design complexity, its permanent shortage of available design information, and its chronic time pressure to find solutions. Currently, the important primary aerospace vehicle design decisions at the conceptual design level (e.g., overall configuration selection) are still made using extremely simple analyses and heuristics. An integrated, variable fidelity system would have large benefits. Higher fidelity tools enabling unconventional configurations to be addressed in the conceptual design process are solicited.

A2.09 Rotorcraft

Lead Center: ARC
Participating Center(s): GRC, LaRC

The challenge of the Subsonic Rotary Wing thrust of the NASA Fundamental Aeronautics Program is to develop validated physics-based multidisciplinary design-analysis-optimization tools for rotorcraft, integrated with technology development, enabling rotorcraft with advanced capabilities to fly as designed for any mission. Technologies of particular interest are as follows:

**Experimental Capabilities: Instrumentation and Techniques for Rotor Blade Measurements**

Instrumentation and measurement techniques are encouraged for assessing scale rotor blade boundary layer state (e.g., laminar, transition, turbulent flow) in simulated hover and forward flight conditions, measurement systems for large-field rotor wake assessment, fast-response pressure sensitive paints applicable to blade surfaces, and methods to measure the rotor tip path plane angle of attack, lateral and longitudinal flapping, and shaft angle in flight and in the wind tunnel. Very low airspeed measurement systems for flight vehicles.

**Acoustics: Interior and Exterior Rotorcraft Noise Generation, Propagation and Control**

Interior noise topics of interest include, but are not limited to, prediction and/or experimental methods that enhance the understanding of noise generation and transmission mechanisms for cabin noise sources (e.g., power-train noise), active and combined active/passive methods to reduce cabin noise, and novel structural systems or materials to reduce cabin noise without an excessive weight penalty. Exterior noise topics of interest include, but are not limited to, noise prediction and/or experimental methods that address the understanding of issues such as noise generation, propagation, and control. These methods may address topics such as novel or drastically improved source noise prediction methods, novel or drastically improved noise propagation methods (e.g., through the atmosphere), novel or drastically improved experimental techniques (e.g., wind tunnel testing methods, flight testing of noise abatement paths and/or maneuvering acoustics, etc.) to understand and/or control noise sources and their impact on the community. Methods should address one or more of the major noise components such as: harmonic noise, broadband noise, blade-vortex interaction noise, high-speed impulsive noise, interactional noise, and/or low frequency noise (e.g., propagation, psychoacoustic effects, etc).
Rotorcraft Diagnostics and Condition Based Maintenance

Health management of rotorcraft power trains is critical. Predictive, condition-based maintenance improves safety, decreases maintenance costs, and increases system availability. Topics of interest include algorithm development, software tools and innovative sensor technologies to detect and predict the health and usage of rotorcraft dynamic mechanical systems in the engine and drive system. Automatic rotor imbalance detection and rotor smoothing is also of interest. Additionally, rotorcraft health management technologies can include, but are not limited, tools to: increase fault detection coverage and decrease false alarm rates; detect onset of failure, isolate damage, and assess damage severity; predict remaining useful life and maintenance actions required; integration of health monitoring information with maintenance processes and procedures; data management and automated techniques to acquire/process diagnostic information; system models, material failure models and correlation of failure under bench fatigue, seeded fault test and fielded data; data collection/management for analysis of operational data; in-flight pilot cueing and warning of impending catastrophic events.

Proposals on other rotorcraft technologies will also be considered as resources and priorities allow, but the primary emphasis of the solicitation will be on the above three identified technical areas.

A2.10 Propulsion Systems

Lead Center: GRC

This subtopic is divided into two parts. The first part is the Turbomachinery and Heat Transfer and the second part is Propulsion Integration.

Turbomachinery and Heat Transfer

There is a critical need for advanced turbomachinery and heat transfer concepts, methods and tools to enable NASA to reach its goals in the various Fundamental Aeronautics projects. These goals include drastic reductions in aircraft fuel burn, noise, and emissions, as well as an ability to achieve mission requirements for Subsonic Rotary Wing, Subsonic Fixed Wing, Supersonics, and Hypersonics Project flight regimes. In the compression system, advanced concepts and technologies are required to enable high stage loading and wider operating range while maintaining or improving aerodynamic efficiency. Such improvements will enable reduced weight and part count, and will enable advanced variable cycle engines for various missions. In the turbine, the very high cycle temperatures demanded by advanced engine cycles place a premium on the cooling technologies required to ensure adequate life of the turbine component. Reduced cooling flow rates and/or increased cycle temperatures enabled by these technologies have a dramatic impact on the engine performance.

Proposals are sought in the turbomachinery and heat transfer area to provide the following specific items:

- Advanced design concepts to enable increased high stage loading in single and multi-stage axial
compressors while maintaining or improving aerodynamic efficiency and operability. Technologies are sought that would reduce dependence on traditional range extending techniques (such as variable inlet guide vane and variable stator geometry) in compression systems. These may include flow control techniques near the compressor end walls and on the rotor and stator blade surfaces. Technologies are sought to reduce turbomachinery sensitivity to tip clearance leakage effects where clearance to chord ratios are on the order of 5% or above.

- Advanced flow analysis tools to enable design optimization of highly loaded compression systems that can accurately predict aerodynamic efficiency and operability. This includes computer codes with updated models for losses, turbulence, and other models that can simulate the flow through turbomachinery components with advanced design features such as swept and bowed blade shapes, flow range extension techniques, such as flow control and transition control to maintain acceptable operability and efficiency.

- Novel turbine cooling concepts are sought to enable very high turbine cooling effectiveness especially considering the manufacturability of such concepts. These concepts may include film cooling concepts, internal cooling concepts, and innovative methods to couple the film and internal cooling designs. Concepts proposed should have the potential to be produced with current or forthcoming manufacturing techniques. The availability of advanced manufacturing techniques may actually enable improved cooling designs beyond the current state-of-the-art.

- Methods are sought to enable more efficient use of coolant air in the turbine through coolant flow modulation. These methods could consist of open-loop or closed-loop coolant flow modulation. Modulations could be high frequency with frequencies on the order of the turbine blade passing frequency or longer time scales on the order of engine thermal transients. Development of methods to measure turbine local and/or average surface temperatures to enable the closed-loop capability will be considered. Feedback control of the coolant flow rates and/or methods to produce modulation in actual turbine thermal environments are desired. Finally, a description of how the proposed technology will work in a vision modulated turbine cooling turbine system will be needed.

**Propulsion Integration**

Proposals for Propulsion Integration will address engine and engine integration topics as outlined in this section in support of the Fundamental Aeronautics Program.

One objective of the Subsonic Fixed Wing Project is to develop verified analysis capabilities for the key technical issues related to integrating embedded propulsion systems for "N+2" hybrid wing/body configurations. These key technical issues include: inlet technologies for distorted engine inflows related to embedded engines with boundary layer ingestion; fan-face flow distortion and its effects on fan efficiency and operability, noise, flutter stability and aeromechanical stress and life; wide operability of the fan and core with a variable area nozzle; issues related to the implementation of a thrust vectoring variable area nozzle; and duct losses related to long flow paths associated with embedded engines. Specifically, proposals are sought to provide advanced technology, prediction methods and tools. The supersonics project would like proposals to develop tools and propulsion technologies that will enable the design of high performance fans; high-efficiency, low-boom, and stable inlets; high-performance, low-noise exhaust nozzles; and intelligent sensors and actuators for supersonic aircraft. The supersonics project is interested in both computational and experimental research, aimed at evaluating and analyzing promising technologies as well as understanding the fundamental flow physics that will enable improved prediction methods.

A mission class of interest to the Hypersonics Project is the Reusable Airbreathing Launch Vehicle (RALV). The RALV mission was chosen to build on work started in NASA's Next Generation Launch Technology (NGLT) Program to provide new vehicle architectures and technologies to dramatically increase the reliability of future launch vehicles. The design of reusable entry vehicles that provide low-cost access to space is challenging in several technology areas. The development of hypersonic air-breathing propulsion systems and the integration of the propulsion system with the airframe impact vehicle performance and controllability and drive the need for an integrated physics-based design methodology.
For Propulsion Integration, topics will be solicited for design concepts and analysis tools that enable:

- Technologies and/or concepts to enable integrated, high-performance, lightweight supersonic inlets and nozzles that have minimal impact on an aircraft's sonic boom signature.
- Technologies and/or concepts to enable high-pressure recovery, low distortion and low-weight subsonic diffusers.
- Practical, validated CFD models for flow control devices such as micro-ramps, vaned vortex generators, air jets, or synthetic jets.
- The reduction of system complexity of turbine-based combined-cycle propulsion systems.
- The rapid assessment of CFD solutions (e.g. automatically interpolating numerical solutions to the measurement locations, generating "metrics of goodness" for parameters of interest, etc.).
- Develop methodologies that provide installed propulsion performance, specifically nozzle conceptual level design/analysis methods, capable of addressing conventional and unconventional nozzle geometries. Geometries should be valid for subsonic, supersonic, and hypersonic flight applications. Documentation of methodologies should include: underlying theory and mathematical models, computational solution methods, source-code, validation data, and limitations.

Airspace Systems Topic A3

NASA’s Airspace Systems Program (ASP) is investing in the development, validation and transfer of advanced innovative concepts, technologies and procedures to support the development of the Next Generation Air Transportation System (NextGen). This investment includes partnerships with other government agencies represented in the Joint Planning and Development Office (JPDO), including the Federal Aviation Administration (FAA) and joint activities with the U.S. aeronautics industry and academia. As such, ASP will develop and demonstrate future concepts, capabilities, and technologies that will enable major increases in air traffic management effectiveness, flexibility, and efficiency, while maintaining safety, to meet capacity and mobility requirements of NextGen. ASP integrates the two projects NextGen Concepts and Technology Development (CTD) and NextGen Systems Analysis Integration and Evaluation (SAIE), to directly address the fundamental research needs of NextGen vision in partnership with the member agencies of the JPDO. The CTD develops and explores fundamental concepts, algorithms, and air-borne and ground-based technologies to increase capacity and throughput of the national airspace system, to address demand-capacity imbalances, and achieve high efficiency in the use of resources such as airports, en route and terminal airspace. The SAIE Project is responsible for facilitating the Research and Development maturation of integrated concepts through evaluation in relevant environments, providing integrated solutions, characterizing airspace system problem spaces, defining innovative approaches, and assessing the potential system impacts and design ramifications of the program's portfolio.
Together, the projects will also focus NASA’s technical expertise and world-class facilities to address the question of where, when, how and the extent to which automation can be applied to moving air traffic safely and efficiently through the NAS and technologies that address optimal allocation of ground and air technologies necessary for NextGen. Additionally, the roles and responsibilities of humans and automation influence in the ATM will be addressed by both projects. Key objectives of NASA’s AS Program are to:

- Improve mobility, capacity, efficiency and access of the airspace system;
- Improve collaboration, predictability, and flexibility for the airspace users;
- Enable accurate modeling and simulation of air transportation systems;
- Accommodate operations of all classes of aircraft; and
- Maintain system safety and environmental protection.

Sub Topics:

**A3.01 Concepts and Technology Development (CTD)**

*Lead Center: ARC*

*Participating Center(s): AFRC, LaRC*

**A3.02 Systems Analysis Integration Evaluation (SAIE)**

*Lead Center: LaRC*

*Participating Center(s): AFRC, ARC*

**Atmospheric Hazards**

- Common situational awareness between flight deck and ground automation systems for weather avoidance
- Integrating weather products into decision support tools
- Airspace capacity estimation in presence of weather
- Development of wake vortex detection and hazard metric tools

**System Level Concepts Development**

- System safety assessment, graceful degradation and recovery
Trajectory Modeling and Uncertainty Prediction

- Analysis of growth of uncertainty as a function of look-ahead time on different phases of flight
- Development of methods to determine, for a target concept/system, the TP accuracy needed to be able to achieve the minimum acceptable system/concept performance as well as identify sources of errors
- Development of methods for managing/reducing trajectory uncertainty to meet specified performance requirements
- Identify critical aircraft behavior data for exchange for interoperability

Roles and Responsibilities in NextGen

- Means to measure controller and pilots workloads in order to optimize air-ground functional allocation
- Means to measure controller and pilots workloads in order to optimize human-automation functional allocation

Modeling and Simulation

- Developing probabilistic or dynamic methods of calculating airspace workload capacity

Aeronautics Test Technologies Topic A4

The Aeronautics Test Program (ATP) ensures the long term availability and health of NASA's major wind tunnels/ground test facilities and flight operations/test infrastructure that support NASA, DoD and U.S. industry research and development (R&D) and test and evaluation (T&E) requirements. Furthermore, ATP provides rate stability to the aforementioned user community. The ATP facilities are located at four NASA Centers made up of the Ames Research Center, Dryden Flight Research Center, Glenn Research Center and Langley Research Center. Classes of facilities within the ATP include low speed, transonic, supersonic, and hypersonic wind tunnels, hypersonic propulsion integration test facilities, air-breathing engine test facilities, the Western Aeronautical Test Range (WATR), support and test bed aircraft, and the simulation and loads laboratories. A key component of ensuring a test facility's long term viability is to implement and continually improve on the efficiency and effectiveness of that facility's operations along with developing new technologies to address the nation's future aerospace challenges. To operate a facility in this manner requires the use of state-of-the-art test technologies and test techniques, creative facility performance capability enhancements, and novel means of acquiring test data. NASA is soliciting proposals in the areas of instrumentation, test measurement technology, test techniques and facility development that apply to the ATP facilities to help in achieving the ATP goals of sustaining and improving
our test capabilities. Proposals that describe products or processes that are transportable across multiple facility classes are of special interest. The proposals will also be assessed for their ability to develop products that can be implemented across government-owned, industry and academic institution test facilities. Additional information is available at [http://www.aeronautics.nasa.gov/atp/index.html](http://www.aeronautics.nasa.gov/atp/index.html) [10].

Sub Topics:

**A4.01 Ground Test Techniques and Measurement Technology**

Lead Center: GRC

Participating Center(s): ARC, GRC

NASA is seeking highly innovative and commercially viable test measurement technologies, test techniques, and facility performance technologies that would increase efficiency, capability, productivity for ground test facilities.

The types of technology solutions sought, but not limited to, are: skin friction measurement techniques; improved flow transition and quality detection methodologies; non-intrusive measurement technologies for velocity, pressure, temperature, and strain measurements; force balance measurement technology development; and improvement of current cutting edge technologies, such as Particle Based Velocimetry (LDV, PIV), Pressure Sensitive Paint (PSP), and focusing acoustic measurements that can be used more reliably in a production wind tunnel environment. Instrumentation solutions used to characterize ground test facility performance are being sought in the area of aerodynamics performance characterization (flow quality, turbulence intensity, mach number measurement, etc.). Of interest are subsonic, transonic, supersonic, and hypersonic speed regimes. Specialized areas may include cryogenic conditions, icing conditions, and rotating turbo machinery. Proposals that are applicable specifically to the ATP facilities (see [http://www.aeronautics.nasa.gov/atp](http://www.aeronautics.nasa.gov/atp) [11]) and across multiple facility classes are especially important. The proposals will also be assessed for their ability to develop products that can be used in other aerospace ground test facilities.

**A4.02 Flight Test Techniques and Measurement Technology**

Lead Center: AFRC

Participating Center(s): ARC, GRC

NASA's aeronautical flight test capabilities are reliant on a combination of both ground and flight research facilities. By using state-of-the-art test techniques, measurement technologies, and data acquisition systems to enhance and modernize these test facilities, NASA will be able to meet the needs of cutting-edge flight research and development programs for the nation.

Proposals submitted to this subtopic should address innovative methods and advanced technologies that would improve the health and test capabilities of NASA's ground and flight facilities. Flight regimes of interest range from atmospheric low-speed, to high-altitude long-endurance to supersonic, to hypersonic and access-to-space. Ground support facilities include: the Western Aeronautical Test Range (WATR), Flight Loads Laboratory (FLL), and laboratories that conduct simulation and verification & validation (V&V) of flight systems including hardware-in-the-loop testing. Flight facilities include both piloted and unmanned test aircraft with various ranges of flight performance and capable of operating over a broad span of flight regimes.

NASA is committed to improve the ATP facility effectiveness to support and conduct flight research. This includes developing test techniques that improve the control of both ground-based and in-flight test conditions, expanding measurement and analysis methodologies, and improving test data acquisition and management with sensors and
systems that have fast response, low volume, minimal intrusion, and high accuracy and reliability.

NASA requires improved measurement and analysis techniques for acquisition of real-time, in-flight data used to determine aerodynamic, structural, flight control, and propulsion system performance characteristics. These data will also be used to provide test conductors the information to safely expand the flight and test envelopes of aerospace vehicles and components. This requirement includes the development of sensors to enhance the monitoring of test aircraft safety and atmospheric conditions during flight testing.

Also of interest to NASA are innovative methods and analysis techniques to improve the correlation of data from ground test to flight test.

Integrated System Research Project (ISRP) Topic A5

The Integrated Systems Research Program (ISRP), a new program effort that began in FY10, will conduct research at an integrated system-level on promising concepts and technologies and explore, assess or demonstrate their benefits in a relevant environment. The integrated system-level research in this program will be coordinated with ongoing long-term, foundational research within the three other research programs, as well as efforts within other Federal Government agencies. As the NextGen evolves to meet the projected growth in demand for air transportation, researchers must address the national challenges of mobility, capacity, safety, and energy and the environment in order to meet the expected growth in air traffic. In particular, the environmental impacts of noise and emissions are a growing concern and could limit the ability of the system to accommodate growth. ISRP will explore and assess new vehicle concepts and enabling technologies through system-level experimentation to simultaneously reduce fuel burn, noise and emissions, and will focus specifically on maturing and integrating technologies in major vehicle systems/subsystems for accelerated transition to practical application.

ISRP is comprised of one project - the Environmentally Responsible Aviation (ERA) Project.

Environmentally Responsible Aviation (ERA)

The project's primary goal is to select vehicle concepts and technologies that can simultaneously reduce fuel burn, noise and emissions; it contains three subprojects: Airframe Technology, Propulsion Technology and Vehicle Systems Integration.
- Testing unconventional aircraft configurations that have higher lift to drag ratio, reduced drag and reduced noise around airports;
- Achieving drag reduction through laminar flow;
- Developing composite (nonmetallic) structural concepts to reduce weight and improve fuel burn; and
- Testing advanced, fuel-flexible combustor technologies that can reduce engine NOx emissions.

Sub Topics:

**A5.01 Laminar Flow Ground Testing**

**Lead Center: LaRC**

Laminar flow enabling technologies are required to allow the Environmentally Responsible Aviation (ERA) Project to simultaneously achieve its aggressive fuel burn, noise, and emissions goals for the N+2 timeframe. To achieve these breakthrough achievements related to drag reduction, the system level requirements for viable aircraft configurations utilizing laminar flow technologies must be established. Although numerous flight tests have proven the aerodynamic possibilities, such flight tests are much too expensive to allow for extensive parametric exploration and optimization to reduce the risks. Therefore, one of the key contributions needed to further advance the technology readiness level of laminar flow technologies integrated into vehicle concepts is the ability to conduct ground-based testing at relevant chord and unit Reynolds numbers. To achieve this need, the ERA Project plans to use the National Transonic Facility (NTF). The NTF is a pressurized, cryogenic wind tunnel capable of approximately 45 million chord Reynolds numbers at transonic speeds.

To date, testing has been done on a Natural Laminar Wing Model with mixed results. The preliminary results indicate contaminants in the flow path of the wind tunnel contributed to early boundary layer transition on the model. These contaminants are suspected to be a combination of minute frost particles, oil droplets, and dust. Based on the surface quality requirements for laminar flow testing at the conditions of the NTF contaminants as small as a few microns are sufficient to disrupt the stability of the boundary layer.

This solicitation seeks proposals to develop:

- Wind tunnel circuit cleaning techniques/processes to remove oil and dust contaminates from the NTF and other similar facilities. Because of the cryogenic testing requirements for dry test circuits water-based approaches are discouraged. The proposed process needs to demonstrate that particles and oil at the micron level can be sufficiently captured and removed from the test environment.

- Methods to polish, clean, and protect the surface quality of a wind tunnel model leading edge to sufficient levels to enable successful laminar flow testing at the NTF.

**A5.02 Open Rotor Installed Thrust**

**Lead Center: AFRC**

NASA’s Environmentally Responsible Aviation (ERA) project seeks simultaneous, aggressive reductions in noise, emissions and fuel burn for transport category aircraft in the N+2 timeframe. A significant reduction in Specific Fuel Consumption (SFC) will be required to meet the goal of a 50% reduction in fuel burn.
One path that engine manufactures are proposing to meet the required SFC improvements is a return to the open rotor technology first tested in the 1980’s. Many challenges to using open rotors on future generations of aircraft exist, both from the design and operations standpoint. One of the design challenges of the open rotor is determining the in-flight installed thrust of the open rotor on the aircraft.

Current practice with turbofans involves an extensive series of ground tests that determine corrections for the installed engine thrust relative to its measured uninstalled configuration. Currently, there is no acceptable method that has been proven to duplicate this for open rotors. Additionally, there is currently no way to directly measure thrust during flight on an installed engine for this class of aircraft.

This solicitation seeks proposals to develop and validate:

Develop methods and techniques to correct ground tested thrust measurements for installed, in-flight effects of an open rotor propulsion system.

Develop methods and conceptual designs for hardware that would allow for the direct measurement of thrust in flight, throughout the full flight envelope. This measurement system must be robust enough to withstand the full flight and maneuvering envelop used during flight testing of a new aircraft while being precise enough to measure the thrust at all power settings.

A5.03 Variable Cycle Propulsion

Lead Center: GRC

Proposals for the variable cycle propulsion subtopic will address engine and engine integration topics as outlined in this section in support of the Integrated System Research Program.

Variable cycle propulsion concepts can potentially help the Environmentally Responsible Aviation (ERA) Project reach its aggressive fuel burn, noise, and emissions goals for the N+2 timeframe by taking advantage of engine and engine/airframe integration concepts that allow the system to optimize over the entire flight envelope. For example, a variable cycle concept may allow the aircraft system to fly efficiently at multiple flight speeds or altitudes, shift noise and emissions production to less critical phases of the mission, or allow for more efficient operation within airspace constraints.
Proposals are solicited that address this opportunity by developing system analysis tools and applying them to variable cycle engine concepts that can address the mission fuel burn, noise, and emissions goals for the ERA Project. Proposed efforts should identify one or more specific variable cycle concepts and assess their impact upon all three ERA metrics (fuel burn, noise, and emissions) for at least one representative long range, subsonic transport, passenger or cargo mission profile (60,000 to 100,000 lbs equivalent payload carried for 6000 nmi, at approximately 0.78-0.85 Mach number). System analysis tools should be developed and employed to adequately capture the combined effects of engine architecture concepts and their integration into airframe designs envisioned for the N+2 timeframe. Specific enabling technologies for these variable cycle system concepts should be identified and prioritized for future development. Such enabling technologies may include, but are not limited to concepts related to engine inlet, fan, compressor, combustor, turbine, nozzle components and their integration.

Mitigation of Aircraft Aging and Durability-Related Hazards Topic A1.01
The mitigation and management of aging and durability-related hazards in future civilian and military aircraft will require advanced materials, concepts, and techniques. NASA is engaged in the research of materials (metals, ceramics, and composites) and characterization/validation test techniques to mitigate aging and durability issues and to enable advanced material suitability and concepts.

Proposals are sought for the development of moisture-resistant resins and new surface treatments/primers. Novel chemistries are sought to improve the durability of aerospace adhesives with potential use on subsonic aircraft. This research opportunity is focused on the development of novel chemistries for coupling agents, surface treatments for adherends and their interfaces, leading to aerospace structural adhesives with improved durability. Work may involve chemical modification and testing of adhesives, coupling agents, surface treatments or combinations thereof and modeling to predict behavior and guide the synthetic approaches. Examples of adhesive characteristics to model and/or test may include, but are not limited to, hydrolytic stability of the interfacial chemistry, moisture permeability at the interface, and hydrophobicity of coupling agents and surface primers. Examples of adherends to model and/or test include carbon fiber/epoxy composites used in structural applications on subsonic aircraft, and aluminum, as well as their respective surface treatments. Additionally, proposals are sought for test techniques to fully characterize aging history and strain rate effects on thermoset and/or thermoplastic resins as well as on advanced composites manufactured of such resins and reinforced with 3D fiber preforms such as the triaxial braid used in advanced composite fan containment structures. Technology innovations may take the form of tools, models, algorithms, prototypes, and/or devices.

Proposals are sought for the development of validated models to capture the evolution of residual stresses and cold work at machined features of compressor and turbine powder metallurgy superalloy disks. This research opportunity is focused on quantifying, modeling and validating residual stress and cold work evolution at stress concentration features during simulated service in aerospace gas turbine engine disk materials. Work may involve use of notched fatigue specimens to simulate stress concentration features utilizing varied surface finish conditions including as-machined, electro-polished, and shot peened surfaces. The simulated load history and temperature gas turbine engine conditions should approximate turbine service history reflective of the new generation of gas
turbine engines and include the effect of superimposed dwell cycles. NASA will be an active participant in Phase I of the research effort by providing the notched specimens, and performing the mechanical testing. Technology innovations may take the form of the unique quantification of the effect of service history on residual stress and cold work depth profile evolutions within notches, and include analytical modeling descriptions of the evolution of these parameters as a function of simulated service history. The technology innovations may also include models and algorithms extrapolating the predicted residual stresses and cold work to service conditions outside of those tested during the program.

Sub Topics:
Sensing and Diagnostic Capability for Aircraft Aging and Damage Topic A1.02
Many conventional nondestructive evaluation (NDE) techniques have been used for flaw detection, but have shown little potential for much broader application. One element in NASA’s effort to ensure the integrity of future vehicles is research to identify changes in fundamental material properties as indicators of material aging-related hazards before they become critical. For example, composites can exhibit a number of micromechanisms such as fiber buckling and breakage, matrix cracking and delaminations as precursor to failure. For complex metallic components an inability to determine residual stress state limits the validity of predictions of the fatigue life of the component.

To further these goals, NDE technologies are being sought for the nondestructive characterization of age-related degradation in complex materials and structures. Innovative and novel approaches to using NDE technologies to measure properties related to manufacturing defects, flaws, and material aging. Measurement techniques, models, and analysis methods related to quantifying material thermal properties, elastic properties, density, microcrack formation, fiber buckling and breakage, etc. in complex composite material systems, adhesively bonded/built-up and/or polymer-matrix composite sandwich structures are of particular interest. Other NDE technologies being sought are those that enable the quantitative assessment of the strength of an adhesive region of bonded joints and repairs or enable the rapid, full-field inspection of large area structures. The anticipated outcome of successful proposals would be both a Phase II prototype NDE technology for the use of the developed technique and a demonstration of the technology showing its ability to measure a relevant material property in the advanced materials and structures in subsonic aircraft.

Sub Topics:
Prediction of Aging Effects Topic A1.03
In order to assess the long-term effects of potential hazards and aging-related degradation of new and emerging material systems/fabrication techniques, NASA is performing research to anticipate aging and to predict its effects on the designs of future aircraft. To support this predictive capability, structural integrity analytical tools, lifing methods, and material durability prediction tools are being developed. Physics-based and continuum-based models encapsulated as computational methods (software) are needed to provide the basis for these higher level (e.g., design) tools. Proposals are sought that apply innovative computational methods, models and analytic tools to the following specific applications:

- Probabilistic computational code is sought for improved structural analysis of complex metallic and composite airframe components. The methods used in these solutions need to detail the initiation and progression of damage to determine accurate estimates of residual life and/or strength of complex airframe structures.
Software tools are needed to predict the onset and rates of type-II hot corrosion attack in nickel-based turbine disk superalloys that allow for prolonged disk operation at high temperatures. Typically hot corrosion of turbine alloys is a product of molten salt exposure and is manifested by a localized pitting corrosion attack. Prolonged high temperature exposures of turbine disk alloys to sulfur-rich low temperature melting eutectic salts can lead to an onset of Type II hot corrosion attack causing serious degradation to the durability of the turbine components.

Computational software is sought to simulate the response of advanced composite fan case/containment structures in aged conditions to jet engine fan blade-out events using impact mechanics and structural system dynamics modeling techniques.

The anticipated outcome of successful Phase II proposals would be analytic code (software) delivered to NASA suitable for use in material evaluation studies.

Sub Topics:
Aviation External Hazard Sensor Technologies Topic A1.04

Sub Topics:
Crew Systems Technologies for Improved Aviation Safety Topic A1.05
NASA seeks proposals that will improve aerospace system safety through: the development of highly innovative, crew-centered, technologies that result in effective joint human-automation systems; and improved methods for evaluating such systems in the context of NextGen operations.

We seek proposals for the development of advanced technologies that:

- Effectively convey information and aid decisions which support novel NextGen operational requirements (e.g., 4D trajectory-based operations, visual operations in non-visual meteorological conditions, etc. as described in [http://www.faa.gov/about/initiatives/nextgen/media/NGIP_0130.pdf](http://www.faa.gov/about/initiatives/nextgen/media/NGIP_0130.pdf)[2]);

- Foster the appropriate use of automation and complex information sources by, for example, conveying constraints on automation reliability and information certainty/timeliness;

- Support effective joint cognitive systems by improving the communication and collaboration among multiple intelligent agents (human and automated, proximal and remote);

- Characterize the operational status of the human crewmembers, effectively modulate this state, and/or effectively adapt interfaces and automation in response to functional status (e.g., situationally-aware display reconfiguration, aiding, and multi-modal presentation of information to maximize system performance and minimize information processing bottlenecks).

We also seek proposals with novel approaches to evaluating joint human-automation systems, particularly with adaptive automation, to assess team (human and automated agents), and system performance and reliability.

Proposals should describe novel technologies and evaluation tools with high potential to serve the objectives of the

Sub Topics:

Technologies for Improved Design and Analysis of Flight Deck Systems Topic A1.06

Information complexity in flight deck systems is increasing exponentially, and flight deck designers need tools to understand, manage, and estimate the performance and safety characteristics of these systems early in the design process - this is particularly true due to the multi-disciplinary nature of these systems. NASA seeks innovative design methods and tools for representing the complex human-automation interactions that will be part of future flight deck systems. In addition, NASA seeks tools and methods for estimating, measuring, and/or evaluating the performance of these designs throughout the lifecycle from preliminary design to operational use - with an emphasis on the early stages of conceptual design. Specific areas of interest include the following:

- Computational/modeling approaches to support determining appropriate human-automation function allocations with respect to safety and reliability. Specifically these methods should focus on metrics that describe the robustness and resilience of a proposed human - automation function allocation;
- Design tools and methods that improve the application of human-centered design principles to the design and certification of mixed human-automated systems;
- Design and analysis methods or tools to better predict and assess human and system performance in relevant operational environments, particularly in regards to procedural errors.

Proposals should describe novel design methods, metrics, and/or tools with high potential to serve the objectives of the System Design and Analysis element of NASA's Aviation Safety Integrated Intelligent Flight Deck program ([http://www.aeronautics.nasa.gov/avsafe/iifd/sda.htm](http://www.aeronautics.nasa.gov/avsafe/iifd/sda.htm)[7]). Successful Phase I proposals should culminate in a final report that specifies, and a Phase II proposal that would realize, tools that improve the design process for human-automation systems in aviation, or improves the ability to assess effectiveness of such systems during the design phase. All proposals should discuss means for verification and validation of proposed methods and tools in operationally valid, or end-user, contexts.

Sub Topics:

Adaptive Aeroservoelastic Suppression Topic A1.07

NASA has initiated an Integrated Resilient Aircraft Control (IRAC) effort under the Aviation Safety Program. The main focus of the effort is to advance the state-of-the-art technology in adaptive controls to provide a design option that allows for increased resiliency to failures, damage, and upset conditions. These adaptive flight control systems will automatically adjust the control feedback and command paths to regain stability, maneuverability, and eventually a safe landing. One potential consequence of changing the control feedback and command paths is that an undesired aeroservoelastic (ASE) interaction could occur. The resulting limit cycle oscillation could result in
structural damage or potentially total loss of vehicle control.

Current airplanes with non-adaptive control laws usually include roll-off or notch filters to avoid ASE interactions. These structural mode suppression filters are designed to provide 8 dB of gain attenuation at the structural mode frequency. Ground Vibration Testing (GVT), Structural Mode Interaction (SMI) testing, and finally full scale flight-testing are performed to verify that no adverse ASE interactions occur. Until a significant configuration or control system change occurs, the structural mode suppression filters provide adequate protection.

When an adaptive system changes to respond to off-nominal rigid body behavior, the changes in control can affect the structural mode attenuation levels. In the case of a damaged vehicle, the frequency and damping of the structural modes can change. The combination of changing structural behavior with changing control system gains results in a system with a probability of adverse interactions that is very difficult to predict a priori. An onboard, measurement based method is needed to ensure that the system adjusts to attenuate any adverse ASE interaction before a sustained limit cycle and vehicle damage are encountered. This system must work in concert with the adaptive control system to allow the overall goal of re-gaining rigid body performance as much as possible without exacerbating the situation with ASE interactions.

Sub Topics:
Robust Propulsion Control Topic A1.08
The object of this research topic is to develop approaches for robust propulsion control design to maintain engine operation in the presence of engine icing, foreign object damage such as ice ingestion and bird strikes, or extreme operating conditions such as high angle of attack.

Aircraft engines are designed to operate safely over a wide range of conditions. They can ingest small birds with little or no effect, and they are designed with enough stall margin available that the amount of inlet distortion encountered under normal circumstances is not detrimental. However, there is a limit to the variation that the engine can accept. In the case of larger than normal inlet distortion, large bird ingestion, or internal ice build-up, the engine's operation can be far enough from its design point that stability is compromised. In these cases it might still be possible to maintain basic engine function by moving bleed valves or variable stator vanes off of their nominal schedules. This requires the development of a robust control algorithm that delivers normal engine performance over the traditional operating range, but is capable of maintaining operation beyond normal conditions.

The expected outcome of the research will be a demonstrated robust propulsion control using a realistic engine model such as the NASA-developed Commercial Modular Aero-Propulsion System Simulation (C-MAPSS). Any modifications to the simulation required to accurately model the effects of engine ice, FOD, inlet distortion, etc., will be the responsibility of the contractor, and must be based on physical considerations.

NASA resources available for the research are the publicly available Commercial Modular Aero-Propulsion System Simulation (C-MAPSS) or a similar simulation. C-MAPSS is available upon request to US Citizens and permanent residents.
Adaptive control is a promising control technology that can enhance flight safety and performance. Adaptive control has been demonstrated to provide improved performance in many unmanned aerial systems. When operated in an autonomous mode such as in an autopilot, the behavior of an adaptive flight control system can be modeled and simulated with a sufficient degree of repeatability.

The presence of a pilot working in a closed-loop fashion with an adaptive flight control presents an important problem that has not been well addressed. Adaptive control generally requires sufficiently rich input signals to improve parameter convergence, as the adaptive control system adapts to parametric changes in the vehicle dynamics or exogenous disturbances. The condition for rich input signals is known as persistent excitation. During adaptation under off-nominal conditions such as aircraft with damage, the pilot provides persistently exciting signals to the adaptive control system. There is generally a trade-off between adaptation and stability due to persistent excitation. With a high persistent excitation in the pilot inputs, the speed of adaptation increases and in theory better handling performance could be achieved. However, in practice, the high persistent excitation in the control signals can potentially cause significant cross coupling between different flight control axes and or excite unmodeled dynamics such as aeroservoelastic modes. The overall effect of high persistent excitation could aggravate stability robustness of an adaptive flight control system with a pilot in the loop that results in poor handling qualities.

Another aspect of pilot interactions with an adaptive control system is the potential interactions between two adaptive elements in a closed-loop fashion, because the pilot can also be viewed as an adaptive control system with a learning ability. With the pilot adaptive element providing high persistently exciting inputs into an adaptive flight control system with a predetermined adaptation rate, the issue of stability can be important and difficult to assess.

To enable an adaptive flight control system to be operated with a pilot in the loop, it is necessary to develop new research techniques that can assess the effects of pilot interactions with an adaptive flight control system. These techniques should address pilot control responses via an adaptive model with features that can capture relevant interactions with an adaptive flight control system. Techniques for assessing pilot interactions via metrics that can quantify the pilot-vehicle system responses with an adaptive flight control system are also needed. Other aspects of the research can include new methods and tools that can provide an advisory function to limit the pilot control inputs in order to trade off between command-following performance and stability robustness.

Research in adaptive control methods will address the system requirements to provide good flying characteristics when the human operator closes the control loop. In the presence of damage, failures, etc. the adaptive system must trade the stability requirements with closed loop handling requirements. Methods for selecting the best achievable handling are needed. The adaptation system needs to find a good compromise between suppression of coupling between the axis (i.e. pitch into roll, etc) and good in-axis behavior. Better metrics to assess cross-coupled (asymmetric) behavior are needed. These metrics could provide a quantitative measurement of the severity of a given failure, as well as a measure of the improvement due to adaptation. As the adaptation changes the flying characteristics of the vehicle, some means of informing the operator is required to ensure that the system is not overdriven by a pilot who is expecting nominal performance.
Adverse events that occur in aircraft can lead to potentially serious consequences if they go undetected. This effort is to develop the technologies, tools, and techniques to detect in-flight anomalies from adverse events. This involves the integration of novel sensor and advanced analytical technologies for airframe, propulsion systems, and other subsystems within the aircraft. The emphasis of this work is not on diagnosing the exact nature of the failure but on identifying its presence. Proposals are solicited that address aspects of the following topics:

- Analytical and data-driven technologies required to interpret the sensor data to enable the detection of fault and failure events,
- Methods to differentiate sensor failure from actual system or component failure,
- Characterizing, quantifying, and interpreting multi-sensor outputs, and
- New sensors, sensory materials and sensor systems that improve the detection of an adverse event or permit increased sensory coverage for an adverse event.

Emphasis is on novel methods to detect failures in electrical, electromechanical, electronic, structural, and propulsion systems. Along with these system failures, condition sensors are desired for both the detection of internal engine icing as well as composite aircraft lightning strikes (location and intensity). Where possible, a rigorous mathematical framework should be employed to ensure the detection rates and detection time constants are acceptable according to published baselines as characterized by statistical measures. Understanding and addressing validation issues are critical components of this effort.

The capability to identify faults is critical to determining appropriate mitigation actions to maintain aircraft safety. This effort is to develop innovative methods and tools for the diagnosis of aircraft faults and failures. It includes the development of integrated technologies, tools, and techniques to determine the causal factors, nature, and severity of an adverse event and to distinguish that event from within a family of potential adverse events. These requirements go beyond standard fault isolation techniques. The emphasis is on the development of mathematically rigorous diagnostic technologies that are applicable to structures, propulsion systems, software, and other subsystems within the aircraft. Technologies developed must be able to perform diagnosis given heterogeneous and asynchronous signals coming from the health management components of the vehicle and integrating information from each of these components.

The ability to actively query health management systems, use advanced decision making techniques to perform the diagnosis, and then assess the severity using these techniques are critical. As an example, the mathematical rigor of the diagnosis and severity assessment could be treated through a Bayesian methodology since it allows for characterization and propagation of uncertainties through models of aircraft failure and degradation.

Both computational and prototype hardware implementations of the diagnostic capabilities are expected outcomes of this effort. Other methods could also be employed that appropriately model the uncertainties in the subsystem due to noise, various stresses due to the aerodynamic forces inherent in flight, and other sources of uncertainty.
The ability to actively query the underlying health management systems (whether they are related to detection or not) is critical to reducing the uncertainty in the diagnosis. As an example, if there is ambiguity in the diagnosis about the type and location of a particular failure in the aircraft structure, the diagnostic engine should be able to actively query that system or related systems to determine the true location and severity of the anomaly. An important element is the use of structural health monitoring tools based on the application of damage progression models with statistical inference and multivariate decision schemes to aid in the integration of multiple sensors for structural vibration and/or strain measurements in a noisy environment. Where possible, a rigorous mathematical framework should be employed to provide a rank ordered list of diagnoses, an assessment of the severity of each diagnosed event, and a measure of the uncertainty in the diagnosis. Understanding and addressing the system integration and validation issues are critical components of this effort.

Sub Topics:

Prognosis of Aircraft Anomalies Topic A1.12
The ability to accurately and precisely predict the remaining useful life (RUL) of aircraft components and subsystems enables decision making and action taking that can avert or mitigate failures, thereby enhancing aircraft safety. Furthermore, it can improve operational efficiency by facilitating condition-based maintenance and reducing unscheduled maintenance. This effort addresses the development of innovative methods, technologies, and tools for the prognosis of aircraft faults and failures. The assessment of the RUL could be used by other aircraft systems to place additional restrictions, such as a new operating envelope, on the flight control systems or it could be used by flight or maintenance personnel to take preventative actions. Areas of interest include developing methods for making predictions of RUL, which take into account operational and environmental uncertainties (pure data-driven approaches are discouraged); physics-based models of degradation; generation of aging and degradation datasets on relevant components or subsystems; and development of validation and verification methodologies for prognostics.

Research should be conducted to demonstrate technical feasibility during Phase I and to show a path toward a Phase II technology demonstration. Proposals are solicited that address aspects of the following areas:

- **RUL prediction techniques** that address a set of fault modes for a device or component, for example by modeling the physics of the most critical fault modes and using (typically less accurate) data-driven methods for the remainder.

- **Physics-based damage propagation models** for one or more relevant aircraft subsystems such as composite or metallic airframe structures, engine turbomachinery and hot structures, avionics, electrical power systems, electromechanical systems, and electronics. Proposals that focus on technologies envisioned for next generation aircraft are strongly encouraged.

- **Uncertainty representation and management** (reduction of prediction uncertainty bounds) methods. Proposers are encouraged to consider uncertainties due to measurement noise, imperfect models and algorithms, as well as uncertainties stemming from future anticipated loads and environmental conditions. Methods can also consider the fusion of different techniques but must show how this helps to improve the uncertainty using appropriate metrics.

- **Aircraft relevant test beds** that can generate aging and degradation datasets for the development and testing of prognostic techniques.

- **Verification and validation methods** for prognostic algorithms.
If prognostic algorithms are being developed, performance needs to be measured on benchmark data sets using prognostic metrics for accuracy, precision, and robustness. Metrics should include prognostic horizon (PH), alpha-lambda, relative accuracy (RA), convergence, and $R_{\Delta\Delta}$.

Sub Topics:
The development of integrated multifunctional self-sensing, self-repairing structures will enable the next generation of lightweight, reliable and damage-tolerant aerospace vehicle designs. Prototype multifunctional composite and/or metallic structures are sought to meet these needs, as are concepts for their analytical and experimental interrogation. Specifically, structural and material concepts are sought to enable in situ monitoring and repair of service damage (e.g., cracks, delaminations) to improve structural durability and enhance safe operation of aerospace structural systems. Emphasis is placed on the development of new materials and systems for the mitigation of structural damage and/or new concepts for activation of healing mechanisms using new or existing materials. These advanced structural and material concepts must be robust, consider all known damage modes for specific material systems and be validated through experiment.

Sub Topics:
Verification and Validation of Flight-Critical Systems Topic A1.14
The purpose of this subtopic is to invest in mid- and long-term research to establish rigorous, systematic, scalable, and repeatable verification and validation methods for flight-critical systems, with a deliberate focus on safety for NextGen ([http://www.jpdo.gov/nextgen.asp](http://www.jpdo.gov/nextgen.asp) [8]). This subtopic targets NextGen safety activities and interests encompassing vehicles, vehicle systems, airspace, airspace concept of operations, and air traffic technologies, such as communication or guidance and navigation. Methods for assessing issues with technology, human performance and human-systems integration are all included in this sub-topic, nothing that multi-disciplinary research is required that does not focus on one type of component or phenomenon to the exclusion of other important drivers of safety.

Proposals are sought for the development of:

- Safety-case methods and supporting technologies capable of analyzing the system-wide safety properties suitable for civil aviation vehicles and for complex concepts of operation involving airborne systems, ground systems, human operators and controllers.
- Technologies and mathematical models that enable rigorous, comprehensive analysis of novel integrated, and distributed, systems interacting through various mechanisms such as communication networks and human-automation and human-human interaction.
- Techniques, tools and policies to enable efficient and accurate analysis of safety aspects of software-intensive systems, ultimately reducing the cost of software V&V to the point where it no longer inhibits many safety innovations and NextGen developments.
- Tools and techniques that can facilitate the use of formal methods in V&V throughout the lifecycle such as graphical-based development environments (e.g., eclipse plug-ins for static analyzers, model checkers, or
theorem provers) or tools facilitating translation from design formats used in industry to formal languages supporting automated reasoning.

This subtopic is intended to address those flight-critical systems that directly conduct flight operations by controlling the aircraft, such as on-board avionics and flight deck systems, and safety-critical ground-based functions such as air traffic control and systems for communication, navigation and surveillance. It is not intended to cover V&V of computational models of physical systems (e.g. CFD codes or finite element analysis).

In Phase II, a functional system shall be delivered to NASA for its retention and ownership.

Sub Topics:

Data Mining Topic A1.15
The fulfillment of the IVHM project's goal requires the ability to transform the vast amount of data produced by the aircraft and associated systems and people into actionable knowledge that will aid in detection, diagnosis, prognosis, and mitigation at levels ranging from the aircraft-level, to the fleet-level, and ultimately to the level of the national airspace. The vastness of this data means that data mining methods must be efficient and scalable so that they can return results quickly. Additionally, much of this data will be distributed among multiple systems. Data mining methods that can operate on the distributed data where they are critical because centralizing data will typically be impractical. However, these methods must be provably able to return the same results as what a comparable method would return if the data could be centralized because this is a critical part of verifying and validating these algorithms, which is important for aviation safety applications.

This topic will yield efficient and scalable data-driven algorithms for anomaly detection, diagnosis, prediction, and prognosis that are able to operate at levels ranging from the aircraft level to the fleet level. To that end, the methods must be able to efficiently learn from vast historical time-series datasets (at least 10 TB) that are heterogeneous (contain continuous, discrete, and/or text data). Distributed data-driven algorithms that provably return the same results as a comparable method that requires data to be centralized are also of great interest.

Sub Topics:

Materials and Structures for Future Aircraft Topic A2.01
Advanced materials and structures technologies are needed in all four of the NASA Fundamental Aeronautics Program research thrusts (Subsonics Fixed Wing, Subsonics Rotary Wing, Supersonics, and Hypersonics) to enable the design and development of advanced future aircraft. Proposals are sought that address specific design and development challenges associated with airframe and propulsion systems. These proposals should be linked
to improvements in aircraft performance indicators such as vehicle weight, fuel consumption, noise, lift, drag, durability, and emissions. In general, the technologies of interest cover five research themes:

- **Fundamental materials development, processing and characterization** - innovative approaches to enhance the durability, processability, performance and reliability of advanced materials (metals, ceramics, polymers, composites, nanostructured materials, hybrids and coatings). In particular, proposals are sought in:
  
  - Advanced high temperature materials for aircraft engine and airframe components and thermal protection systems, including advanced blade and disk alloys, ceramics and CMCs, polymers and PMCs, nanostructured materials, hybrid materials and coatings to improve environmental durability.
  
  - Adaptive materials such as piezoelectric ceramics, shape memory alloys, shape memory polymers, and variable stiffness materials and methods to integrate these materials into airframe and/or aircraft engine structures to change component shape, dampen vibrations, and/or attenuate acoustic transmission through the structure.
  
  - Multifunctional materials and structural concepts for engine and airframe structures, such as novel approaches to power harvesting and thermal management, lightning strike mitigating, self-sensing, and materials for wireless sensing and actuation.
  
  - New high strength fibers, in particular low density, high strength and stiffness carbon fibers.
  
  - Innovative processing methods to reduce component manufacturing costs and improve damage tolerance and reliability of ceramics, metals (especially oxide dispersion strengthened nickel-based alloys), polymers, composites, and hybrids, nanostructured and multifunctional materials and coatings.
  
  - Development of joining and integration technologies including fasteners and/or chemical joining methods for ceramic-to-ceramic, metal-to-metal, and metal-to-ceramic as well as solid state joining methods such as advanced friction stir welding.
  
  - Innovative methods for the evaluation of advanced materials and structural concepts (in particular multifunctional and/or adaptive) under simulated operating conditions, including combinations of electrical, thermal and mechanical loads.
  
  - Nondestructive evaluation (NDE) methods for the detection of as-fabricated flaws and in-service damage for textile polymeric, ceramic and metal matrix composites, nanostructured materials and hybrids. NDE methods that provide quantitative information on residual structural performance are preferred.

- **Structural analysis tools and procedures** - robust and efficient design methods and tools for advanced materials and structural concepts (in particular multifunctional and/or adaptive components) including variable fidelity methods, uncertainty based design and optimization methods, multi-scale computational modeling, and multi-physics modeling and simulation tools. In particular, proposals are sought in:
  
  - Multiscale design tools for aircraft and engine structures that integrate novel materials, mechanism design, and structural subcomponent design into systems level designs.
  
  - Life prediction tools for textile composites including fiber architecture modeling methods that enable the development of physics-based hierarchical analysis methods. Fiber architecture models that address yarn-to-yarn and ply-to-ply interactions covering a wide range of textile preform structures.
in either a relaxed or compressed deformation state as well as tools to predict debonding and delamination of through thickness reinforced (stitched, z-pinned) composites are of particular interest.

- Tools to predict durability and damage tolerance of new material forms including metallic-composite hybrids, friction stir-welded metallic materials and powder metallurgy-formed materials.
- Meso scale tools to guide materials placement to enable tailored load paths in multifunctional structures for enhanced damage tolerance.

**Computational materials development tools** - methods to predict properties, damage tolerance, and/or durability of both airframe and propulsion materials, thermal protection systems and ablatives based upon chemistry and processing for conventional as well as functionally graded, nanostructured, multifunctional and adaptive materials. In particular proposals are sought in:

- Ab-initio methods that enable the development of coatings for multiple uses at temperatures above 3000°F in an air environment.
- Computational tool development for structure-property modeling of adaptive materials such as piezoelectric ceramics, shape memory alloys, shape memory polymers to characterize their physical and mechanical behavior under the influence of an external stimulus.
- Computational and analytical tools to enable molecular design of polymeric and/nanostructured materials with tailored multifunctional characteristics.
- Computational microstructural and thermodynamic analysis tools and technique development for designing new lightweight alloy compositions for subsonic airframe and engines from first principles, functionally graded (chemically or microstructurally) materials, and/or novel metals processing techniques to accelerate materials development and understanding of processing-structure-property relationships.
- Software tools to predict temperature dependent phase chemistries, volume fractions, shape and size distributions, and lattice parameters of phases in a broad range of nickel and iron-nickel based superalloys. Toolset should utilize thermodynamic and kinetic databases and models that are fully accessible, which allow modifications and user-input to expand experimental databases and refine model predictions.

**Advanced Structural Concepts** - new concepts for airframe and propulsion components incorporating new light weight concepts as well as "smart" structural concepts such as those incorporating self-diagnostics with adaptive materials, multifunctional component concepts to reduce mass and improve durability and performance, lightweight, efficient drive systems and electric motors for use in advanced turboelectric propulsion systems for aircraft, and new concepts for robust thermal protection systems for high-mass planetary entry, descent and landing. In particular, proposals are sought in:

- Innovative structural concepts, materials, manufacturing and fabrication leading to reliable, entry descent and landing systems including deployable rigid and flexible heat shields and structurally integrated multifunctional systems. Of particular interest are high temperature honeycombs, hat stiffeners, rigid fibrous and foam insulators, as well as high temperature adhesives, films and fabrics for advanced flexible heat shields.
- Advanced mechanical component technologies including self lubricating coatings, oil-free bearings, and seals.
- Advanced material and component technologies to enable the development of mechanical and electrical drive system to enable the development of turboelectric propulsion systems, which utilize
power from a single turbine engine generator to drive multiple propulsive fans. Innovative concepts are sought for AC-tolerant, low loss (1.5 T field and 500 Hz electrical frequency; and high efficiency (= 30% of Carnot), low mass (1).

- Novel structural designs for integrated fan cases that combine hardwall composite cases for blade containment with acoustic treatments as well as concepts that integrate the case with the fan inlet to maximize structural, acoustic attenuation and weight benefits.

- Innovative approaches to structural sensors for extreme environments (>1800°F) including the development and validation of improved methods (i.e. adhesives, plasma spraying techniques, etc.) for attaching sensors to advanced high-temperature materials as well as approaches to measure strain, temperature, heat flux and/or acceleration of structural components.

Sub Topics:
Combustion for Aerospace Vehicles Topic A2.02

Sub Topics:
Aero-Acoustics Topic A2.03

Sub Topics:
Aeroelasticity Topic A2.04

Sub Topics:
Aerodynamics Topic A2.05

Sub Topics:
Aerothermodynamics Topic A2.06

Sub Topics:
Flight and Propulsion Control and Dynamics Topic A2.07

**Active Aeroelastic Wing Shape Tailoring for Aircraft Performance and Control**

Modern aircraft are increasingly designed with lightweight, flexible airframe structures. By employing distributed flight control surfaces, a modern wing structure (which implies aircraft wing, horizontal stabilizer, and vertical stabilizer) can be strategically tailored in-flight by actively controlling the wing shape so as to bring about certain desired vehicle characteristics. For example, active aeroelastic wing shape tailoring can be employed to control the wash-out distribution and wing deflection in such a manner that could result in improved aerodynamic performance such as reduced drag during cruise or increased lift during take-off. Another novel use of active aeroelastic wing shape tailoring is for flight control. By actively controlling flexible aerodynamic surfaces differentially or collectively, the motion of an aircraft can be controlled in all three stability axes. In high speed supersonic or hypersonic vehicles, effects of airframe-propulsion-structure interactions can be significant. Thus, propulsion control can play an integral role with active aeroelastic wing shape tailoring control in high speed flight regimes.

This technology area involves the development of various technical elements including:
• Innovative aircraft concepts that can significantly improve aerodynamic performance and control by leveraging active aeroelastic wing shape tailoring.

• Sensor technology that will enable in-flight wing twist and deflection static and dynamic measurements for control development.

• Actuation methods that examine novel modes of actuation for actively controlling wing shape in-flight, and effective placements of distributed control effectors on a wing structure.

• Vehicle dynamic modeling capability for aero-propulsive-servo-elasticity that will provide a knowledge foundation upon which vehicle control and dynamics can be developed.

• Integrated approaches for active aeroelastic wing shape tailoring control with distributed control surfaces that will provide effective advanced control strategies to achieve aerodynamic performance and flight control objectives, taken into account airframe-propulsion-structure interactions that can exist in all three flight regimes.

**Gust Load Alleviation Control**

In a future NextGen operational concept, close separation between aircraft in super density operations could lead to more frequent wake vortex encounters. The increasing use of flexible airframe design in modern aircraft will inherently lead to a potential increase in vehicle dynamic response to turbulence and wake vortices. Gust load alleviation control technology can improve ride qualities and reduce undesired structural dynamic loading on flexible airframes that could shorten aircraft service life. Gust load alleviation control technology can be either reactive or predictive. In a traditional reactive control framework, flight control systems can be designed to provide sufficient aerodynamic damping characteristics that suppress vehicle dynamic response as rapidly as possible upon a turbulence encounter. There is a trade off, however, between increased damping for mode suppression and command-following objectives of a flight control system. Large damping ratios, while desirable for mode suppression, may result in poor flight control performance.

Predictive control can provide a novel gust load alleviation strategy for future aircraft design with lightweight flexible structures. Novel look-ahead sensor technology can measure or estimate turbulent intensity to provide such information to a predictive gust load alleviation control system which in turn would dynamically reconfigure flight control surfaces as an aircraft enters a turbulent atmospheric region. Technology development of predictive gust load alleviation control may include the following:

• Novel sensor technology for Optical Air Data Systems based on LIDAR or other novel detection methods that can measure near-field air turbulent velocity components directly in front of an aircraft in the order of one-body length scale to provide nearly instantaneous predictive capability to significantly improve the effectiveness of a gust load alleviation control system.

• Predictive gust load alleviation control technology that can reliably reconfigure flight control surfaces dynamically based on the sensor information of the near-field turbulence to mitigate the vehicle structural dynamic response upon a turbulence encounter. The predictive control strategies should be cognizant of potential adverse effects due to potential latency issues that can counteract the objective of gust load alleviation, or potential structural mode interactions due to control input signals that may contain frequencies close to the natural frequencies of the airframe.
Modular and Distributed Control for Propulsion Systems

Modular and flexible control architecture for propulsion systems is an essential technology, which will enable the full realization of turbine engine system performance. Distributed technology can alleviate the thermal constraints on engine control electronics by improving tolerance to elevated temperature and creating opportunities for relocating electronics to a more compatible environment. It will enable the implementation of more complex control law, paving the way for further integration of performance-enhancing control for reduced fuel burn, lower emissions, and operability. Directly, distributed control will reduce engine system weight. This is a multi-disciplinary research area involving high temperature electronics, sensing and actuation, control system integration, and engine system stability.

Sub Topics:
Aircraft Systems Analysis, Design and Optimization Topic A2.08
One of the approaches to achieve the NASA Fundamental Aeronautics Program goals is to solve the aeronautics challenges for a broad range of air vehicles with system-level optimization, assessment and technology integration. The needs to meet this approach can be defined by four general themes:

- Design Environment Development;
- Variable Fidelity, Physics-Based Design/Analysis Tools;
- Technology Assessment and Integration; and

Current interdisciplinary design/analysis involves a multitude of tools not necessarily developed to work together, hindering their application to complete system design/analysis studies. Multi-fidelity, multi-disciplinary optimization frameworks, such as Numerical Propulsion System Simulation (NPSS), have been developed by NASA but have limited capabilities to simulate complete vehicle systems. Solicited topics are aligned with these four themes that will support this NASA research area.

Design Environment Development

Technology development is needed to provide complex simulation and modeling capabilities where the computer science details are transparent to the engineer. A framework environment is needed to provide a seamless integration environment where the engineer need not be concerned with where or how particular codes within the system level simulation will be run. Interfaces and utilities to define, setup, verify, determine the appropriate resources, and launch the system simulation are also needed.

Research challenges include the engineering details needed to numerically zoom (i.e., numerical analysis at various levels of detail) between multi-fidelity components of the same discipline, as well as, multi-discipline components of the same fidelity. A major computer science challenge is developing boundary objects that will be reused in a wide variety of simulations.
Proposals will be considered that enable coupling differing disciplines, numerical zooming within a single discipline, deploying large simulations, and assembling and controlling secure or non-secure simulations.

**Variable Fidelity, Physics-Based Design/Analysis Tools**

An integrated design process combines high-fidelity computational analyses from several disciplines with advanced numerical design procedures to simultaneously perform detailed Outer Mold Line (OML) shape optimization, structural sizing, active load alleviation control, multi-speed performance (e.g., low takeoff and landing speeds, but efficient transonic cruise), and/or other detailed-design tasks. Current practice still widely uses sequential, single-discipline optimization, at best coupling low-fidelity modeling of other relevant disciplines during the detailed design phase. Substantial performance improvements will be realized by developing closely integrated design procedures coupled with highest-fidelity analyses for use during detailed-design. Design procedures must enable rapid determination of sensitivities (gradients) of a design objective with respect to all design variables and constraints, choose search directions through design space without violating constraints, and make appropriate changes to the vehicle shape (ideally both external OML shape and internal structural element size). Solicitations are for integrated design optimization tools that find combinations of design variables from more than one discipline and can vary synergistically to produce superior performance compared to the results of sequential, single-discipline optimization or repeated cut-and-try analysis.

**Technology Assessment and Integration**

Improved analysis capability of integrated airframe and propulsion systems would allow more efficient designs to be created that would maximize efficiency and performance while minimizing both noise and emissions. Improved integrated system modeling should allow designers to consider trade-offs between various design and operating parameters to determine the optimum design for various classes of subsonic fixed wing aircraft ranging from personal aircraft to large transports. The modeling would also be beneficial if it had enough fidelity to enable it to analyze both conventional and unconventional systems. Current analysis tools capable of analyzing integrated systems are based on simplified physical and semi-empirical models that are not fully capable of analyzing aircraft and propulsion system parameters that would be required for new or unconventional systems.

Analysis tools are solicited that are capable of analyzing new and unconventional aircraft and propulsion integrated systems. These include: (1) New combustor designs, alternate fuel operation, and the ability to estimate all emissions, and (2) Noise source models (e.g., fan, jet, turbine, core and airframe components). Analyses tools that are scalable, especially to small aircraft, are desired.

**Evaluation of Advanced Concepts**

Conceptual design and analysis of unconventional vehicle concepts and technologies is needed for technology portfolio investment planning, development of advanced concepts to provide technology pull, and independent technical assessment of new concepts. This capability will enable "virtual expeditions through the design space" for multi-mission trade studies and optimization. This will require an integrated variable fidelity concept design system. The aerospace flight vehicle conceptual design phase is, in contrast to the succeeding preliminary and detail design phases, the most important step in the product development sequence, because of its predefining function. However, the conceptual design phase is the least well understood part of the entire flight vehicle design process, owing to its high level of abstraction and associated risk, its multidisciplinary design complexity, its permanent shortage of available design information, and its chronic time pressure to find solutions. Currently, the important primary aerospace vehicle design decisions at the conceptual design level (e.g., overall configuration selection) are still made using extremely simple analyses and heuristics. An integrated, variable fidelity system would have large
benefits. Higher fidelity tools enabling unconventional configurations to be addressed in the conceptual design process are solicited.

Sub Topics:

**Rotorcraft Topic A2.09**
The challenge of the Subsonic Rotary Wing thrust of the NASA Fundamental Aeronautics Program is to develop validated physics-based multidisciplinary design-analysis-optimization tools for rotorcraft, integrated with technology development, enabling rotorcraft with advanced capabilities to fly as designed for any mission. Technologies of particular interest are as follows:

**Experimental Capabilities: Instrumentation and Techniques for Rotor Blade Measurements**

Instrumentation and measurement techniques are encouraged for assessing scale rotor blade boundary layer state (e.g., laminar, transition, turbulent flow) in simulated hover and forward flight conditions, measurement systems for large-field rotor wake assessment, fast-response pressure sensitive paints applicable to blade surfaces, and methods to measure the rotor tip path plane angle of attack, lateral and longitude flapping, and shaft angle in flight and in the wind tunnel. Very low airspeed measurement systems for flight vehicles.

**Acoustics: Interior and Exterior Rotorcraft Noise Generation, Propagation and Control**

Interior noise topics of interest include, but are not limited to, prediction and/or experimental methods that enhance the understanding of noise generation and transmission mechanisms for cabin noise sources (e.g., power-train noise), active and combined active/passive methods to reduce cabin noise, and novel structural systems or materials to reduce cabin noise without an excessive weight penalty. Exterior noise topics of interest include, but are not limited to, noise prediction and/or experimental methods that address the understanding of issues such as noise generation, propagation, and control. These methods may address topics such as novel or drastically improved source noise prediction methods, novel or drastically improved noise propagation methods (e.g., through the atmosphere), novel or drastically improved experimental techniques (e.g., wind tunnel testing methods, flight testing of noise abatement paths and/or maneuvering acoustics, etc.) to understand and/or control noise sources and their impact on the community. Methods should address one or more of the major noise components such as: harmonic noise, broadband noise, blade-vortex interaction noise, high-speed impulsive noise, interactional noise, and/or low frequency noise (e.g., propagation, psychoacoustic effects, etc).

**Rotorcraft Diagnostics and Condition Based Maintenance**

Health management of rotorcraft power trains is critical. Predictive, condition-based maintenance improves safety, decreases maintenance costs, and increases system availability. Topics of interest include algorithm development, software tools and innovative sensor technologies to detect and predict the health and usage of rotorcraft dynamic mechanical systems in the engine and drive system. Automatic rotor imbalance detection and rotor smoothing is also of interest. Additionally, rotorcraft health management technologies can include, but are not limited to, tools to: increase fault detection coverage and decrease false alarm rates; detect onset of failure, isolate damage, and assess damage severity; predict remaining useful life and maintenance actions required; integration of health monitoring information with maintenance processes and procedures; data management and automated techniques to acquire/process diagnostic information; system models, material failure models and correlation of failure under bench fatigue, seeded fault test and fielded data; data collection/management for analysis of operational data; in-flight pilot cueing and warning of impending catastrophic events.
Proposals on other rotorcraft technologies will also be considered as resources and priorities allow, but the primary emphasis of the solicitation will be on the above three identified technical areas.

Sub Topics:
   Propulsion Systems Topic A2.10
This subtopic is divided into two parts. The first part is the Turbomachinery and Heat Transfer and the second part is Propulsion Integration.

Turbomachinery and Heat Transfer

There is a critical need for advanced turbomachinery and heat transfer concepts, methods and tools to enable NASA to reach its goals in the various Fundamental Aeronautics projects. These goals include drastic reductions in aircraft fuel burn, noise, and emissions, as well as an ability to achieve mission requirements for Subsonic Rotary Wing, Subsonic Fixed Wing, Supersonics, and Hypersonics Project flight regimes. In the compression system, advanced concepts and technologies are required to enable high stage loading and wider operating range while maintaining or improving aerodynamic efficiency. Such improvements will enable reduced weight and part count, and will enable advanced variable cycle engines for various missions. In the turbine, the very high cycle temperatures demanded by advanced engine cycles place a premium on the cooling technologies required to ensure adequate life of the turbine component. Reduced cooling flow rates and/or increased cycle temperatures enabled by these technologies have a dramatic impact on the engine performance.

Proposals are sought in the turbomachinery and heat transfer area to provide the following specific items:

- Advanced design concepts to enable increased high stage loading in single and multi-stage axial compressors while maintaining or improving aerodynamic efficiency and operability. Technologies are sought that would reduce dependence on traditional range extending techniques (such as variable inlet guide vane and variable stator geometry) in compression systems. These may include flow control techniques near the compressor end walls and on the rotor and stator blade surfaces. Technologies are sought to reduce turbomachinery sensitivity to tip clearance leakage effects where clearance to chord ratios are on the order of 5% or above.

- Advanced flow analysis tools to enable design optimization of highly loaded compression systems that can accurately predict aerodynamic efficiency and operability. This includes computer codes with updated models for losses, turbulence, and other models that can simulate the flow through turbomachinery components with advanced design features such as swept and bowed blade shapes, flow range extension techniques, such as flow control and transition control to maintain acceptable operability and efficiency.

- Novel turbine cooling concepts are sought to enable very high turbine cooling effectiveness especially considering the manufacturability of such concepts. These concepts may include film cooling concepts, internal cooling concepts, and innovative methods to couple the film and internal cooling designs. Concepts proposed should have the potential to be produced with current or forthcoming manufacturing techniques. The availability of advanced manufacturing techniques may actually enable improved cooling designs beyond the current state-of-the-art.

- Methods are sought to enable more efficient use of coolant air in the turbine through coolant flow
modulation. These methods could consist of open-loop or closed-loop coolant flow modulation. Modulations could be high frequency with frequencies on the order of the turbine blade passing frequency or longer time scales on the order of engine thermal transients. Development of methods to measure turbine local and/or average surface temperatures to enable the closed-loop capability will be considered. Feedback control of the coolant flow rates and/or methods to produce modulation in actual turbine thermal environments are desired. Finally, a description of how the proposed technology will work in a vision modulated turbine cooling turbine system will be needed.

Propulsion Integration

Proposals for Propulsion Integration will address engine and engine integration topics as outlined in this section in support of the Fundamental Aeronautics Program.

One objective of the Subsonic Fixed Wing Project is to develop verified analysis capabilities for the key technical issues related to integrating embedded propulsion systems for "N+2" hybrid wing/body configurations. These key technical issues include: inlet technologies for distorted engine inflows related to embedded engines with boundary layer ingestion; fan-face flow distortion and its effects on fan efficiency and operability, noise, flutter stability and aeromechanical stress and life; wide operability of the fan and core with a variable area nozzle; issues related to the implementation of a thrust vectoring variable area nozzle; and duct losses related to long flow paths associated with embedded engines. Specifically, proposals are sought to provide advanced technology, prediction methods and tools. The supersonics project would like proposals to develop tools and propulsion technologies that will enable the design of high performance fans; high-efficiency, low-boom, and stable inlets; high-performance, low-noise exhaust nozzles; and intelligent sensors and actuators for supersonic aircraft. The supersonics project is interested in both computational and experimental research, aimed at evaluating and analyzing promising technologies as well as understanding the fundamental flow physics that will enable improved prediction methods.

A mission class of interest to the Hypersonics Project is the Reusable Airbreathing Launch Vehicle (RALV). The RALV mission was chosen to build on work started in NASA's Next Generation Launch Technology (NGLT) Program to provide new vehicle architectures and technologies to dramatically increase the reliability of future launch vehicles. The design of reusable entry vehicles that provide low-cost access to space is challenging in several technology areas. The development of hypersonic air-breathing propulsion systems and the integration of the propulsion system with the airframe impact vehicle performance and controllability and drive the need for an integrated physics-based design methodology.

For Propulsion Integration, topics will be solicited for design concepts and analysis tools that enable:

- Technologies and/or concepts to enable integrated, high-performance, lightweight supersonic inlets and nozzles that have minimal impact on an aircraft’s sonic boom signature.
- Technologies and/or concepts to enable high-pressure recovery, low distortion and low-weight subsonic diffusers.
- Practical, validated CFD models for flow control devices such as micro-ramps, vaned vortex generators, air jets, or synthetic jets.
- The reduction of system complexity of turbine-based combined-cycle propulsion systems.
- The rapid assessment of CFD solutions (e.g. automatically interpolating numerical solutions to the
measurement locations, generating "metrics of goodness" for parameters of interest, etc.).

- Develop methodologies that provide installed propulsion performance, specifically nozzle conceptual level design/analysis methods, capable of addressing conventional and unconventional nozzle geometries. Geometries should be valid for subsonic, supersonic, and hypersonic flight applications. Documentation of methodologies should include: underlying theory and mathematical models, computational solution methods, source-code, validation data, and limitations.

Sub Topics:
Concepts and Technology Development (CTD) Topic A3.01

Sub Topics:
Systems Analysis Integration Evaluation (SAIE) Topic A3.02

Atmospheric Hazards

- Common situational awareness between flight deck and ground automation systems for weather avoidance
- Integrating weather products into decision support tools
- Airspace capacity estimation in presence of weather
- Development of wake vortex detection and hazard metric tools

System Level Concepts Development

- System safety assessment, graceful degradation and recovery

Trajectory Modeling and Uncertainty Prediction

- Analysis of growth of uncertainty as a function of look-ahead time on different phases of flight
- Development of methods to determine, for a target concept/system, the TP accuracy needed to be able to achieve the minimum acceptable system/concept performance as well as identify sources of errors
- Development of methods for managing/reducing trajectory uncertainty to meet specified performance requirements
- Identify critical aircraft behavior data for exchange for interoperability
Roles and Responsibilities in NextGen

- Means to measure controller and pilots workloads in order to optimize air-ground functional allocation
- Means to measure controller and pilots workloads in order to optimize human-automation functional allocation

Modeling and Simulation

- Developing probabilistic or dynamic methods of calculating airspace workload capacity

Sub Topics:

Ground Test Techniques and Measurement Technology Topic A4.01

NASA is seeking highly innovative and commercially viable test measurement technologies, test techniques, and facility performance technologies that would increase efficiency, capability, productivity for ground test facilities.

The types of technology solutions sought, but not limited to, are: skin friction measurement techniques; improved flow transition and quality detection methodologies; non-intrusive measurement technologies for velocity, pressure, temperature, and strain measurements; force balance measurement technology development; and improvement of current cutting edge technologies, such as Particle Based Velocimetry (LDV, PIV), Pressure Sensitive Paint (PSP), and focusing acoustic measurements that can be used more reliably in a production wind tunnel environment. Instrumentation solutions used to characterize ground test facility performance are being sought in the area of aerodynamics performance characterization (flow quality, turbulence intensity, mach number measurement, etc.). Of interest are subsonic, transonic, supersonic, and hypersonic speed regimes. Specialized areas may include cryogenic conditions, icing conditions, and rotating turbo machinery. Proposals that are applicable specifically to the ATP facilities (see http://www.aeronautics.nasa.gov/atp [11]) and across multiple facility classes are especially important. The proposals will also be assessed for their ability to develop products that can be used in other aerospace ground test facilities.

Sub Topics:

Flight Test Techniques and Measurement Technology Topic A4.02

NASA's aeronautical flight test capabilities are reliant on a combination of both ground and flight research facilities. By using state-of-the-art test techniques, measurement technologies, and data acquisition systems to enhance and modernize these test facilities, NASA will be able to meet the needs of cutting-edge flight research and development programs for the nation.

Proposals submitted to this subtopic should address innovative methods and advanced technologies that would improve the health and test capabilities of NASA's ground and flight facilities. Flight regimes of interest range from atmospheric low-speed, to high-altitude long-endurance to supersonic, to hypersonic and access-to-space.
support facilities include: the Western Aeronautical Test Range (WATR), Flight Loads Laboratory (FLL), and laboratories that conduct simulation and verification & validation (V&V) of flight systems including hardware-in-the-loop testing. Flight facilities include both piloted and unmanned test aircraft with various ranges of flight performance and capable of operating over a broad span of flight regimes.

NASA is committed to improve the ATP facility effectiveness to support and conduct flight research. This includes developing test techniques that improve the control of both ground-based and in-flight test conditions, expanding measurement and analysis methodologies, and improving test data acquisition and management with sensors and systems that have fast response, low volume, minimal intrusion, and high accuracy and reliability.

NASA requires improved measurement and analysis techniques for acquisition of real-time, in-flight data used to determine aerodynamic, structural, flight control, and propulsion system performance characteristics. These data will also be used to provide test conductors the information to safely expand the flight and test envelopes of aerospace vehicles and components. This requirement includes the development of sensors to enhance the monitoring of test aircraft safety and atmospheric conditions during flight testing.

Also of interest to NASA are innovative methods and analysis techniques to improve the correlation of data from ground test to flight test.

Sub Topics:
Laminar Flow Ground Testing Topic A5.01
Laminar flow enabling technologies are required to allow the Environmentally Responsible Aviation (ERA) Project to simultaneously achieve its aggressive fuel burn, noise, and emissions goals for the N+2 timeframe. To achieve these breakthrough achievements related to drag reduction, the system level requirements for viable aircraft configurations utilizing laminar flow technologies must be established. Although numerous flight tests have proven the aerodynamic possibilities, such flight tests are much too expensive to allow for extensive parametric exploration and optimization to reduce the risks. Therefore, one of the key contributions needed to further advance the technology readiness level of laminar flow technologies integrated into vehicle concepts is the ability to conduct ground-based testing at relevant chord and unit Reynolds numbers. To achieve this need, the ERA Project plans to use the National Transonic Facility (NTF). The NTF is a pressurized, cryogenic wind tunnel capable of approximately 45 million chord Reynolds numbers at transonic speeds.

To date, testing has been done on a Natural Laminar Wing Model with mixed results. The preliminary results indicate contaminants in the flow path of the wind tunnel contributed to early boundary layer transition on the model. These contaminants are suspected to be a combination of minute frost particles, oil droplets, and dust. Based on the surface quality requirements for laminar flow testing at the conditions of the NTF contaminants as small as a few microns are sufficient to disrupt the stability of the boundary layer.
This solicitation seeks proposals to develop:

Wind tunnel circuit cleaning techniques/processes to remove oil and dust contaminants from the NTF and other similar facilities. Because of the cryogenic testing requirements for dry test circuits water-based approaches are discouraged. The proposed process needs to demonstrate that particles and oil at the micron level can be sufficiently captured and removed from the test environment.

Methods to polish, clean, and protect the surface quality of a wind tunnel model leading edge to sufficient levels to enable successful laminar flow testing at the NTF.

Sub Topics:
Open Rotor Installed Thrust Topic A5.02
NASA’s Environmentally Responsible Aviation (ERA) project seeks simultaneous, aggressive reductions in noise, emissions and fuel burn for transport category aircraft in the N+2 timeframe. A significant reduction in Specific Fuel Consumption (SFC) will be required to meet the goal of a 50% reduction in fuel burn.

One path that engine manufactures are proposing to meet the required SFC improvements is a return to the open rotor technology first tested in the 1980’s. Many challenges to using open rotors on future generations of aircraft exist, both from the design and operations standpoint. One of the design challenges of the open rotor is determining the in-flight installed thrust of the open rotor on the aircraft.

Current practice with turbofans involves an extensive series of ground tests that determine corrections for the installed engine thrust relative to its measured uninstalled configuration. Currently, there is no acceptable method that has been proven to duplicate this for open rotors. Additionally, there is currently no way to directly measure thrust during flight on an installed engine for this class of aircraft.

This solicitation seeks proposals to develop and validate:

Develop methods and techniques to correct ground tested thrust measurements for installed, in-flight effects of an open rotor propulsion system.

Develop methods and conceptual designs for hardware that would allow for the direct measurement of thrust in flight, throughout the full flight envelope. This measurement system must be robust enough to withstand the full flight and maneuvering envelop used during flight testing of a new aircraft while being precise enough to measure the thrust at all power settings.
Variable cycle propulsion concepts can potentially help the Environmentally Responsible Aviation (ERA) Project reach its aggressive fuel burn, noise, and emissions goals for the N+2 timeframe by taking advantage of engine and engine/airframe integration concepts that allow the system to optimize over the entire flight envelope. For example, a variable cycle concept may allow the aircraft system to fly efficiently at multiple flight speeds or altitudes, shift noise and emissions production to less critical phases of the mission, or allow for more efficient operation within airspace constraints.

Proposals are solicited that address this opportunity by developing system analysis tools and applying them to variable cycle engine concepts that can address the mission fuel burn, noise, and emissions goals for the ERA Project. Proposed efforts should identify one or more specific variable cycle concepts and assess their impact upon all three ERA metrics (fuel burn, noise, and emissions) for at least one representative long range, subsonic transport, passenger or cargo mission profile (60,000 to 100,000 lbs equivalent payload carried for 6000 nmi, at approximately 0.78-0.85 Mach number). System analysis tools should be developed and employed to adequately capture the combined effects of engine architecture concepts and their integration into airframe designs envisioned for the N+2 timeframe. Specific enabling technologies for these variable cycle system concepts should be identified and prioritized for future development. Such enabling technologies may include, but are not limited to concepts related to engine inlet, fan, compressor, combustor, turbine, nozzle components and their integration.