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JANNAF Liquid Rocket Combustion Instability Panel Research Recommendations

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JANNAF LIQUID ROCKET COMBUSTION INSTABILITY PANEL RESEARCH RECOMMENDATIONS

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SUMMARY

The Joint Army, Navy, NASA, Air Force (JANNAF) Liquid Rocket Combustion Instability Panel was formed in 1988, drawing its members from industry, academia, and government experts. The panel was chartered to address the needs of near-term engine development programs and to make recommendations whose implementation would provide not only sufficient data but also the analysis capabilities to design stable and efficient engines. The panel was also chartered to make long-term recommendations toward developing mechanistic analysis models that would not be limited by design geometry or operating regime. These models would accurately predict stability and thereby minimize the amount of subscale testing for anchoring.

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The panel has held workshops on Acoustic Absorbing Devices, Combustion Instability Mechanisms, Instability Test Hardware, and Combustion Instability Computational Methods. At these workshops, research projects that would meet the panel's charter were suggested. The JANNAF Liquid Rocket Combustion Instability Panel's conclusions about the work that needs to be done and recommendations on how to approach it, based on evaluation of the suggested research projects, are presented herein.

INTRODUCTION

During the last 40 years, liquid-propellant rocket engine development programs have been hampered by combustion instability. Some of these were the F-1, J-2, J-2S, OMS, LM, XLR-129, and shuttle reaction control system engine development programs. As recently as 1987, an engine that was expected to be stable was unstable (ref. 1).

Because of the many development programs during the Apollo period, most of the combustion stability research data and analytical tools are of the 1950's and 1960's vintage. Although these data and analytical tools were extremely valuable in enabling the success of the Apollo programs, the limited number of development programs since then has curtailed much of the research activity. As a result, the analytical tools failed to evolve and take advantage of the many new technologies, such as computing capabilities and advanced research diagnostics. With today's tight budgets, engine development programs cannot risk an unforeseen stability problem or afford a trial and error approach to solving such a problem.

An unforeseen stability problem can cause program schedule slippage, cost overrun, hardware loss, or facility damage as well as constrain system performance and operating conditions to the point that the planned mission may be compromised. Similarly, using stabilitizing aids to solve the stability problem can add cost, weight, and complexity to the engine. In the past, development programs relied on qualitative analytical tools and full-scale testing to evaluate the stability of a design. Now however, with limited resources, subscale testing and more economical quantitative analysis tools will have to be used.

JANNAF LIQUID ROCKET COMBUSTION INSTABILITY PANEL RECOMMENDATIONS

The JANNAF Liquid Rocket Combustion Instability Panel was formed in 1988. The panel includes experts in combustion stability representing government, industry, and academia. The panel was chartered to address the needs of near-term engine development programs and to make recommendations whose implementation will provide sufficient data and the analysis capabilities to design stable and efficient engines. The panel was also chartered to make recommendations for the long-term objective of developing mechanistic analysis models that will not be limited by design geometry or operating regime. These models should accurately predict stability and minimize the amount of subscale testing for anchoring. A standard model, or set of models, should be produced that will allow the rocket industry to design stable engines and make comprehensive, accurate predictions of the engine's stability. The panel intends to coordinate the funding of such activities through the representatives on the panel. (The names of representives who have attended workshops are included in the appendix.) These representatives decided that the objectives should be pursued through two different approaches (ref. 2): a short-term approach, to quickly upgrade existing stability models and make them more usable to impending development programs; and a long-term approach, to address the issues involved in developing quantitative models.

Short-Term Approach

To address the short-term approach, several tasks were recommended. First, existing stability models should be identified and evaluated to determine their adequacy and accuracy compared to existing data. Second, the various models that prove to be adequate should be put into a modular analysis and design methodology to make them more usable. Third, the models should be evaluated to determine what improvements are required.

Since the panel was formed, some of these recommended tasks have been initiated. Under several government contracts, existing stability models were evaluated to determine their adequacy and accuracy. Under the Oxygen/Hydrocarbon Injector Characterization contract, F04611-85-C-0100, sponsored by the Air Force Astronautics Laboratory, existing models were extended. The objective of this program is to develop and demonstrate an injector design methodology capable of ensuring high combustion efficiency with stable combustion for oxygen/hydrocarbon rocket engines, based only on analysis and properly selected reduced-scale hardware testing. In the Combustion Stability Model Study, NAS 8-36274, sponsored by NASA Marshall Space Flight Center, many of the existing models were evaluated to produce the Generalized Stability (GENSTA) analysis tool, which utilized a single set of existing models to perform stability analysis. And under the LOX/Hydrocarbon Rocket Engine Analytical Design Methodology Development and Validation contract, NAS 3-25556, sponsored by the NASA Lewis Research Center, the existing models were evaluated against existing data.

The task of using the models to create a modular methodology is being addressed by Lewis in the ROCket Combustor Interactive Design (ROCCID) methodology program. The ROCCID code is a modular interactive methodology code that uses existing models to perform a simplified performance analysis and an in-depth stability analysis. The modularity of ROCCID allows for adding or interchanging improved models as they become available. The interactive front end of ROCCID makes it user friendly and simplifies the input procedure. The panel has recommended that the ROCCID methodology be considered a JANNAF standard for combustion stability design and analysis (ref. 3). To enforce this standard when it becomes available, the panel further recommended that government representatives require contractors to use the JANNAF stability analysis standard in their future contracts (ref. 3).

Long-Term Approach

The panel recognized several areas of concern that must be addressed to achieve the long-term objective of developing comprehensive, accurate, quantitative stability models. The panel defined five areas that affect combustion stability: (1) injector/feed system dynamics, (2) atomization, (3) vaporization, (4) mixing, and (5) fluid/wave dynamics (ref. 4). Atomization and vaporization were determined to be the most critical areas, because they provide the initial and boundary conditions to stability analysis and because they can cause significant changes in stability predictions (refs. 4 and 5). The panel recommended exploring CFD techniques and improving numerical techniques to provide an increase in analysis capability (refs. 4 and 5). They recognized that the stability data content and format are not standardly reported and that data have been lost (ref. 2). The panel also recognized that acoustic damping device modeling needs improvement (refs. 5 and 6).

Atomization. - The panel concluded that atomization is the primary area where research and model improvements are required and that detailed atomization rates and drop-size distributions should be obtained (refs. 4 and 5). Because the atomization process determines the initial conditions in the combustor, obtaining an accurate prediction of drop size will benefit stability and performance analyses. Empirical correlations are state of the art, but they were developed using cold-flow testing and may not be accurate for hot-fire conditions. Two correlations developed under hot-fire rocket conditions, are of limited sample size, propellant combinations, and injector type and are not used by the industry (refs. 7 and 8). Therefore, the correlations need to be tested against realistic hot-fire conditions to determine their accuracy. Often, the analyst must extrapolate these correlations because the engine is operating in a different regime. Therefore, new data must be acquired for regions where extrapolation would be required.

In addition to steady-flow correlations, the panel recommended the development of unsteady crossflow atomization models or correlations (ref. 5). When the spray is hit by an acoustic wave in the chamber, flow visualization has shown that the atomization process is broken up and the drops are randomly scattered. The steady-flow atomization correlations become highly inaccurate under these conditions, and modelers have not been able to make adequate corrections for these conditions. Therefore, atomization data must be acquired under crossflow conditions.

The development of "first principles" atomization model was also recommended (ref. 4). This type of model would take the empiricism out of atomization modeling and would avoid the problems associated with extrapolation. Therefore, such a model should be capable of modeling different injector geometries with different fluids under different chamber conditions.

Vaporization. - The panel recommended the development of advanced subcritical and supercritical droplet vaporization models (refs. 4 and 5) as well as, an experimental program for measuring drop size, velocity, species, and temperature, to validate the vaporization models. To make the measurements for atomization and vaporization, high-frequency diagnostic methods with repetition ranges of 10^3 to 10^4 need to be developed.

Numerical modeling. - The panel concluded that computational fluid dynamics (CFD) methods should be introduced into stability modeling in three phases (refs. 4 and 5). Such methods could be applied immediately in several places, such as mixing, steady-state combustion, and atomization stream breakup. The three phases proposed consist of development of a steady-state CFD combustion code, a time-dependent CFD combustion response code, and an integrated CFD wave mechanics/combustion response code. The CFD experts on the panel estimated that it would take 15 years to perform all three modeling phases. In addition, the computational techniques would have to be evaluated for their ability to handle the high-frequency oscillatory flow fields that are common in unstable rocket combustors.

Standardized reporting requirements and database. - Since the panel recommended standardizing reporting requirements (ref. 2), the JANNAF Rocket Engine Performance Test Data Acquisition and Interpretation Manual (ref. 9) on data reporting standards is being evaluated and modified to make future data more accessible. When a progress report on the manual was given, the panel recommended that the standards be compared to those used by the ramjet and solid rocket communities (ref. 3).

The panel also concluded that some past data are either lost or inaccessible and that future modelers could not easily utilize the available data. Therefore, the establishment of a centralized, standardized experimental stability and performance database was recommended. The panel, recognizing that not enough fundamental data exist recommended that data be obtained at conditions that are representative of that in a rocket combustor.

Acoustic damping devices. - The panel established that damping devices should be used only as a backup device when engine stability problems are suspected (ref. 6). They estimated that cavity sound speed could be predicted with only 50-percent accuracy (ref. 6). Since the cavity sound speed is crucial to determining acoustic absorber tuning and effectiveness, the panel recommended collecting cavity sound speed data, and using numerical modeling.

Because of the limited capabilities of baffle models, the following additional work in this area (ref. 6) was recommended: the interaction and feedback between the baffles and acoustic cavities should be considered, and the scope of the work should go beyond that of DIST3D (ref. 10); combustion distribution should be treated more rigorously than the simple linear model in DIST3D; a model for the interaction of nonsinusoidal waves with baffles, absorbers, and the nozzle should be developed (ref. 5); experiments should be performed to verify the accuracy of predicting the baffle absorption constant and frequency depression (ref. 6); and since no model exists for evaluating baffles that contain a hub, an effort to develop a baffle/hub model (ref. 5) should be started.

RECOMMENDED RESEARCH

Suggestions of research projects that would meet the general recommendations of the workshops were requested of the panel members. They responded with projects regarding atomization, vaporization, CFD utilization, data base, and baffle cavity modeling.

Atomization Studies

Many projects were proposed to study atomization. The proposed projects apply to impinging, shear coaxial, and swirl coaxial elements.

One proposed project would extend the current data base by performing cold-flow steady-state atomization measurements of injection elements. Suggested measurement techniques included Malvern, phase Doppler, x-ray, neutron radiography, laser-sheet visualization, and laser-induced fluorescence. If these techniques were used, experimental data would consist of mean drop diameters of sprays, drop-size distributions, drop velocities, and jet breakup images. These data could then be correlated with element geometry and size, fluid properties, and operating conditions, to provide generalized relations, and thus, allow description of spray results for arbitrary elements and operating conditions within the ranges of variables tested.

Some work has been started in this area. Woodward, Garner, Cheung, and Kuo (ref. 11) have begun using x-ray radiography and laser-sheet visualization to study the ambient liquid jet breakup, and they plan tests at 6.89×10^6 Pa (1000 psi) in the future. Zaller (ref. 12) is obtaining injector drop sizes by using phase Doppler drop sizing, and plans to test up to 4.13×10^6 Pa (600 psi) in cold flow and 5.51×10^6 Pa (800 psi) in hot-fire conditions. Krulle, Mayer, and Schley (ref. 13) are planning atomization cold-flow tests with a pressurized chamber.

Another suggested project for atomization studies would determine the effect of crossflow on the breakup and atomization processes. The shattering of large drops into small drops can cause the drops to burn rapidly and sustain or amplify a pressure wave. A study of these effects would first require a survey of existing drop-shattering data and correlations. The effects of sinusoidal waves, steep-fronted periodic waves, and single shock waves on the atomization and breakup processes should also be studied. The magnitude and statistical variation of the resulting drop size as a function of the amplitude and frequency of the waves could be produced, thereby developing an empirical correlation. This correlation could be incorporated into existing response models, and the enhanced model should be validated by comparing its predictions to existing stability test data.

Planning and designing are proceeding in this area. Jacobs and Santoro (ref. 14) plan to use an acoustic driver on a liquid jet, and then by laser visualization, to study the effect on jet break-up and atomization. Zaller (ref. 12) plans to determine the crossflow effects on atomization by using a steady cross-flow gas stream on the injection stream.

A suggestion was made that hot-fire atomization data be obtained and compared to cold-flow test data. This project would determine whether the cold-flow correlations that are used to design engines are valid under hot-fire conditions. Determining if less expensive cold-flow atomization testing could be substituted for more expensive hot-fire atomization testing would be a second benefit of this project. Most of the programs to obtain these data are in the planning stages.

The results from the foregoing projects would lead to a final project of atomization modeling. Atomization modeling could take place in either of two forms: in the first, correlations from the data would be developed in a way similar to that done in the past; in the second, a CFD model of the atomization process would be developed from first principles. Chuech et al. (ref. 15) are beginning to use CFD methods to predict jet breakup and atomization.

Vaporization Studies

The consensus of workshop attendees was that vaporization should be studied. Toward this end, the following recommendation were made: (1) vaporization testing should include subcritical, near critical, and supercritical test conditions; (2) measurements should be made of single-droplet, dilute-spray, and dense-spray vaporization under conditions that are representative of a rocket combustor; and (3) these measurements should be made under steady and crossflow conditions. A number of research projects have been proposed to fulfill these recommendations. Such projects would generate a data base on droplet vaporization under reacting and nonreacting conditions. These data, in turn, would be used to validate existing models and create new ones as required.

Some work is already proceeding in this area. Yang (ref. 16) is attempting to calculate from first principles the detailed flow structures and gas-droplet interface transport involved in high-pressure droplet vaporization and combustion. Sirignano and Chiang (ref. 17) have been developing techniques to compute the vaporization of drops in gas turbines and have begun to apply these techniques to rockets. Priem (ref. 18) is proposing the Onion Skin method of predicting supercritical drop vaporization. He says that it is simple, sufficiently accurate, and not computer intensive, but notes that experiments at high-Reynolds-number, supercritical conditions need to be performed to validate this theory. Norton, Litchford, and Jeng (ref. 19) are experimenting with the vaporization of a single drop. Santivicca et al. (ref. 20) are experimentally examining the effect of droplet turbulence interaction on the vaporization process.

CFD Utilization

The panel determined that CFD modeling would be a long-term project of about 15 years but that the first step of this long-term project should begin now. The goal is a steady-state combustion code that can handle the two-phase flow, multiple reactions, and compressible flow that are typical in rocket combustors.

Already some work is being done in this area. Some of the researchers mentioned previously (refs. 15 to 17) are attempting to use CFD methods. In addition, Merkle (ref. 21) is using CFD methods to produce a CFD rocket combustor mixing and combustion code. Liang, et al., (ref. 22) wrote the Advanced Rocket Injector Combustion Code (ARICC), and they are trying to improve its predictive and computer-run-time capabilities.

DATA BASE

The panel recommended that a stability data base should be generated to make data accessible and easier to use. To accomplish this a two-part project was suggested: first, a format would be developed for reporting and storing design, performance, stability, and operating characteristics for injector/engine combinations; then, government agencies, engine contractors, and universities would be solicited to provide data related to research, development, and production hardware. This data base would require periodic maintenance.

BAFFLE/CAVITY MODEL

Another suggested project was baffle/cavity modeling. This project would involve developing an integrated baffle/cavity model to include interactive effects of baffles and cavities, and effects of distributed combustion. This new model would go beyond that of DIST3D (ref. 10), taking into consideration the interaction and feedback between the baffles and the acoustic cavities, and addressing the hub baffles. In addition the model would treat combustion distribution more rigorously than the simple linear model in DIST3D. This would allow for a more accurate determination of the interaction between combustion distribution and stability aid placement. Finally, the model would be tested under hot-fire and cold-flow conditions.

SUMMARY OF RECOMMENDATIONS

The panel has recommended that the fundamental mechanisms of stability and their modeling should be the main focus of future liquid rocket combustion stability research. Atomization and vaporization were determined to be the most important mechanisms that must be investigated to improve combustion instability modeling. The panel also concluded that to make the modeling process more efficient, a standardized accessible stability data base should be established; furthermore they recommended that a JANNAF standardized method of analyzing stability should be adopted.

The panel recognizes that CFD modeling has a place in stability analysis and should be pursued over the long term. Therefore, although classical wave mechanics modeling methods must be the mainstay, CFD methods can fill niches in developing mixing, steady-state combustion, and stream breakup codes. These codes would enhance the classical wave mechanics methods. However, since the ideal stability model does not yet exist, the panel recommended continuing work on damping devices.

CONCLUDING REMARKS

Clearly, much work needs to be done to produce models that will accurately predict stability for engines under development. The panel members felt that there are an overwhelming number of issues to be addressed, but that such issues can be solved methodically if a sufficient and steady level of resources is committed. Because stability is vaporization-limited, atomization and vaporization processes control most of the instabilities encountered. These processes set the initial and boundary conditions for stability models. Therefore, the recommendation to seek, greater insight into atomization and vaporization is expected to provide the greatest payoff in improving stability modeling.

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Appendix - Liquid Rocket Combustion Instability Workshop Attendees.
AAttendees and their affiliations at the time of the workshops were as follows:

Mark D. Klem, Chairman	NASA Lewis Research Center
Carl A. Aukerman	NASA Lewis Research Center
Kevin J. Breisacher	NASA Lewis Research Center
Kenneth J. Davidian	NASA Lewis Research Center
Michelle M. Zaller	Sverdrup Tech., Inc. Lewis Research Center Group
John Hutt	NASA Marshall Space Flight Center
P. Kevin Tucker	NASA Marshall Space Flight Center
Tim Edwards	Air Force Astronautics Laboratory
Phillip Kessel	Air Force Astronautics Laboratory
Al Kudlach	Air Force Astronautics Laboratory
Jay Levine	Air Force Astronautics Laboratory
Jim Nichols	Air Force Astronautics Laboratory
Larry Quinn	Air Force Astronautics Laboratory
Lt Ken Philippart	Air Force Astronautics Laboratory
Lt Jim Rymarcsuk	Air Force Astronautics Laboratory
Elizabeth Slimak	Air Force Astronautics Laboratory
Mitat A. Birkan	Air Force Office of Scientific Research
Peter J. O'Rourke	Los Alamos National Laboratory
William Anderson	Aerojet Propulsion Division
Jeffery Muss	Aerojet Propulsion Division
Thong V. Nguyen	Aerojet Propulsion Division
Jerry L. Pieper	Aerojet Propulsion Division
Richard Walker	Aerojet Propulsion Division
Subra V. Sankar	Aerometrics, Inc.
Andrej Przekwas	CFD Research Corporation
Alan Hersh	Hersh Acoustical Engineering
Richard J. Priem	Priem Consultants, Inc.
James J. Fang	Rocketdyne Division
Robert J. Jensen	Rocketdyne Division
Pak Liang	Rocketdyne Division
Thomas Coultas	Schafer Associates Inc
Curtis Johnson	Software & Engineering Associates
Gary R. Nickerson	Software & Engineering Associates
Robert Glick	Talley Defense Systems
B. B. Stokes	Thiokol Corporation
James D. Sterling	TRW Corporation
Robert Carrol	United Technologies Pratt & Whitney
George B. Cox, Jr	United Technologies Pratt & Whitney
D. Lee Hill	United Technologies Pratt & Whitney
Gregory M. Dobbs	United Technologies Research Center
Donald J. Hautman	United Technologies Research Center
Thomas J. Rosfjord	United Technologies Research Center
Fred Culick	California Institute of Technology
Frederick H. Reardon	California State University at Sacramento
Bill Sirignano	University of California at Irvine
Charles Mitchell	Colorado State University
John W. Daily	University of Colorado
Charles Merkle	Pennsylvania State University
H. Robert Jacobs	Pennsylvania State University
Vigor Yang	Pennsylvania State University
Robert J. Santoro	Pennsylvania State University
San-Mou Jeng	University of Tennessee Space Institute

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15. Supplementary Notes

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16. Abstract

The Joint Army, Navy, NASA, Air Force (JANNAF) Liquid Rocket Combustion Instability Panel was formed in 1988, drawing its members from industry, academia, and government experts. The panel was chartered to address the needs of near-term engine development programs and to make recommendations whose implementation would provide not only sufficient data but also the analysis capabilities to design stable and efficient engines. The panel was also chartered to make long-term recommendations toward developing mechanistic analysis models that would not be limited by design geometry or operating regime. These models would accurately predict stability and thereby minimize the amount of subscale testing for anchoring. The panel has held workshops on Acoustic Absorbing Devices, Combustion Instability Mechanisms, Instability Test Hardware, and Combustion Instability Computational Methods. At these workshops, research projects that would meet the panel's charter were suggested. The JANNAF Liquid Rocket Combustion Instability Panel's conclusions about the work that needs to be done and recommendations on how to approach it, based on evaluation of the suggested research projects, are presented herein.

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