

Unstable Burning In Solid Propellants – Fame But No Fortune

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This Presentation Is About A Paper That I Wrote With Eric Baum Which Was Published In 1961

I will discuss:

- The unusual way it came into being**
- A brief summary of its contents**
- Background and importance of the problem**
- Community response in first 10 years**
- Lessons learned**

**Much of the material presented was compiled
by Dr. Baum**

My Boss At Aeronutronic Was Dr. David Altman

- Dr. Altman retired as senior vice president of United Technologies in 1981 after 23 years**
- He spent two and a half years at University of California Radiation Laboratory (Manhattan Project)**
- For eleven years he was Chief Chemist at JPL**
- At Aeronutronic he was director of the Vehicle Technology Laboratory**

My Introduction To The Problem

Several times I was present in Dave's office when he brought up the important problem of solid propellant combustion instability

He usually had some famous physicists and other visitors in his office when he discussed the problem

Nobody had a good idea about what controlled the phenomenon

I thought I had a good idea – the transient behavior must be controlled by the solid because its density was much greater than that of the gas

How Our Work Got Started

In addition to being a brilliant scientist Dave was a terrific salesman - We had lots of projects

One day as I was walking to my office one of Dave's project managers stopped me and told me about an unusual problem – his contract was almost over but he did not have any way to spend the money

He asked if I had any ideas

I told him I did, and that is how this work came into being

Solid Propellant Combustion Instability

- **The Problem**

- **Pressure fluctuations are unpredictable and can affect mean burning rate or even threaten structural integrity.**
- **At least 128 motors have experienced instability problems during development, including**
 - **Polaris**
 - **Standard Missile**
 - **Sidewinder**
 - **Harm**
 - **Trident**
 - **Hellfire**
 - **Minuteman**

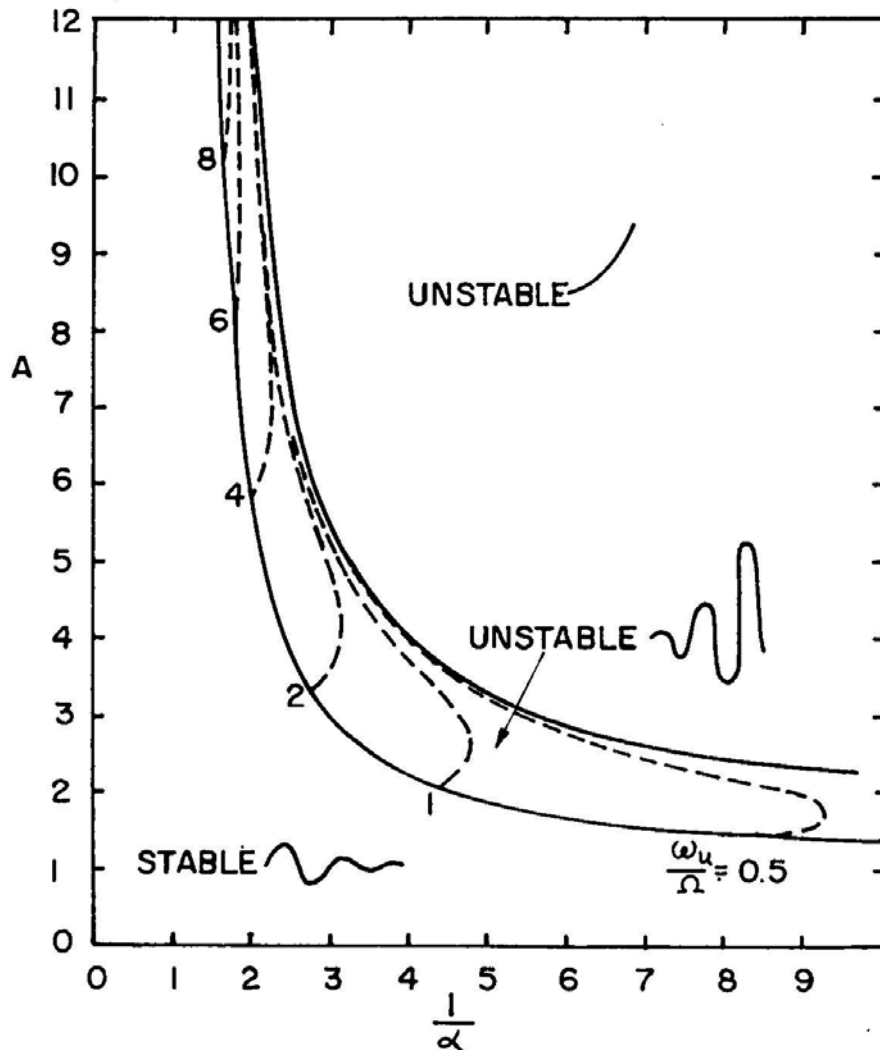
Denison-Baum Model Origins

- **Denison:**
 - **Aeronutronic Dept. Mgr. with experience in modeling chemically reacting boundary layers**
 - **Major project: simulation of solid propellant reaction products using gas/liq reactants for testing nozzles (Navy-funded)**
 - **Began thinking about instability problem before funding became available**
- **Baum:**
 - **New-hire in another dept. with thesis experience doing stability analyses**
 - **Hired to work in navy-sponsored lab-scale studies of unstable burning in solid propellants (in planning stage)**
 - **Was asked to check work Denison had started and apply linear stability analysis**

The Model

- Time lags in the gas phase neglected while transient conduction in the solid takes place
- Results obtained by a perturbation of laminar flame conditions and transient heat conduction in the solid
- Burning rate and heat flux developed from conservation equations
- Assumptions include homogeneous propellant, Lewis number of unity, single step reaction of any order, no reactions in solid state, vaporization according to an Arrhenius law, and no erosive burning
- Because resulting equations are linear a Laplace transform method of solution was used – results are analytic

Results



Stability conditions indicate three regions:

- Unbounded nonoscillatory mode
- Unstable oscillatory mode
- Stable oscillatory mode

$$A = (E_w / RT_w)(1 - T_i / T_w)$$

$$\alpha = c_p T_f / [c_s (T_w - T_i) \xi]$$

$$\text{where } \xi = (n + 2)/2 + E_f / 2RT_f$$

Rational Approach To Solving A Technologic Problem Impacting Several Large Systems

- **Define Problem, Allocate Resources, Assign Technical Directors**
 - **Panel Of Reps From Affected Services/Weapon-Programs**
- **Technical Direction**
 - **Top Level Oversight**
 - **Panel Of Best And Brightest Researchers**
 - **Recommend Direction Of Research**
 - **Evaluate Completed Or In-process Work Via Periodic Meetings**
 - **Individual Project Oversight**
 - **Assigned By Funding Agency**

Organization Of The Combustion Instability Research Effort

- **(1958)Polaris Program Mgrs. & DOD Committee On Large Motors Recommend Setting Up *Ad Hoc* Committee That Then Recommends An Enhanced Coordinated Research Program To Be Implemented By A Tri-service Committee (ONR, AFOSR, ARO & ARPA)**
- **F.T. McClure (APL) Assigned To Coordinate Effort As Head Of What Was The Forerunner Of The JANNAF Combustion Subcommittee**

PROS/CONS Of Assigning McClure To Run The Top-Level Oversight Committee

- **PRO: McClure Was Among The Best & Brightest**
 - **McClure, Hart, Cantrell, ... At APL Were Doing The Best Work At The Time e.g.**
 - **Hart, RW & McClure, FT, “Combustion Instability; Acoustic Interaction With A Burning Propellant Surface”, J. Chem. Phys 30, 1504 (1959)**
- **CON: There Were Conflicts Of Interest**
 - **APL Continued To Work The Problem For The Navy Internally While The Oversight Committee Judged Both The APL Work And Outside Work Funded By Participating Sponsors**
 - **APL Acted As Technical Director For Navy-Sponsored Work Outside Of APL**

Advantages Of Denison-Baum Vs. Hart-McClure

- **Hart-McClure**
 - **Rigorous**
 - **Result: 11 Independent Dimensionless Parameters**

- **Denison-Baum**
 - **Many Simplifying Approximations**
 - **Result: 2 Independent Dimensionless Parameters**

Consequences

- Denison-Baum Paper Submitted To ARS Journal Nov. 1960
- Publication Clearance Request Sent To APL
- Paper Cleared & Published
 - Denison, MR & Baum, E, “A Simplified Model Of Unstable Burning In Solid Propellants”, ARS J., 1112-1122 (Aug. 1961)
- APL Contract Monitor Ordered Any Similar “Out-of-Scope” Theoretical Work To Stop

Community Response: First 10 Years

- **Never Presented To JANNAF Combustion Meeting**
- **R.W Hart And F.T McClure, “Theory Of Acoustic Instability In Solid Propellant Rocket Combustion”, 10th Symposium On Combustion, 1965, Also See Proceedings Of The 1st ICRPG Combustion Instability Conference 1965**
 - **Admits D-B Results Very Similar To Their Own & May Be Of More General Validity At Low Frequencies**
- **M. Imber, “Transient Effects In Solid Propellant Burning”, AIAA J. May 1965**
 - **Extends D-B To Ignition Period**
- **M. Imber, “Thermal Conductivity: A Parameter In Solid Propellant Burning”, AIAA J. Sept 1966**
 - **Extends D-B To Include Temp. Dependence Of Conductivity**

Community Response: First 10 Years (Cont.)

- **R.L. Coates, N.S. Cohen & L.R. Harvill, “An Interpretation Of L* Combustion Instability In Terms Of Acoustic Instability Theory”, AIAA J. June 1967**
 - **Applies D-B To An Acoustic Model Of A Rocket Motor & Claims Good Agreement With Data**
- **R.S. Brown, R.J. Muzzy & M.E. Steinle, “Effect Of Surface Reactions On Acoustic Response Of Solid Propellants”, AIAA J. Sept. 1967**
 - **Applies An Alternate Flame Model To D-B**
- **C.L. Oberg, “Combustion Instability: The Relation Between Acoustic And Nonacoustic Instability”, AIAA J. Feb 1968**
 - **Compares D-B Favorably With Data**

Community Response: First 10 Years (Cont.)

- **H. Krier, J.S. T'ien, W.A. Sirignano & M. Summerfield, “Nonsteady Burning Phenomena Of Solid Propellants ...”, AIAA J. Feb. 1968**
 - **Applies Alternate Flame Model To D-B**
- **R.S. Brown, R.J. Muzzy & M.E. Steinle, “Surface Reaction Effects On The Acoustic Response Of Composite Solid Propellants”, AIAA J. March 1968**
 - **Applies Alternate Flame Model To D-B**
- **G.A. Marxman & C.E. Wooldridge, “The Effect Of Surface Reactions On The Solid Propellant Response Function”, AIAA J. Mar. 1968**
 - **Applies Alternate Flame Model To D-B**

Community Response: First 10 Years (Cont.)

- **F.E. Culick, “A Review Of Calculations For Unsteady Burning Of A Solid Propellant”, AIAA J. Dec. 1968**
 - **Review Says All Of The Alternate Flame Models Are Wrong Including D-B**
- **J.S.T'ien, W.A. Sirignano & M. Summerfield, “Theory Of L-star Combustion Instability With Temperature Oscillations”, AIAA J. Jan. 1970**
 - **Applies Alternate Flame Model To D-B**
- **F.A. Williams, “Quasi-steady Gas-phase Flame Theory In Unsteady Burning Of A Homogeneous Solid Propellant”, AIAA J. Sept. 1973**
 - **Shows That Of All Of The ‘Alternate’ Flame Models, The Original D-B Modeling Remains The Best**

Subsequent History

- **Hart-McClure is a historical footnote**
- **Denison-Baum is still used (50 yrs later) as basis for models relaxing the approximations or as the limiting case for non-linear models**
- **When I would meet some scientist for the first time I was often asked, “Are you the Denison of Denison and Baum? I thought you were dead” – Fame but no fortune**

Lessons Learned

- **The “Best And Brightest” Had Both The Direct And The Top Level Oversight Of The D-B Modeling But Failed To Recognize Its Value Until 5 Years Later**
- **This Is In Part Because Confidence In The Somewhat Arcane Mathematics Grows With Each Successful Subsequent Application**
- **Perhaps More Effort Would Have Been Put Into Understanding The Model If APL Had Not Been So Confident That They Had The Modeling Well In Hand**
- **We Never Could Have Done This Work At All If We Had To Write A Proposal**