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SOLID PROPELLANT GAS GENERATORS:

PROCEEDINGS OF THE 1995 WORKSHOP

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ACKNOWLEDGMENTS

The editors would like to express their sincere gratitude to all the speakers (in alphabetical order) whose presentations and participation have made this workshop a successful event: Dr. David Bomse (Southwest Sciences, Inc.), Professor Barry Butler (University of Iowa), Lt. Mark Gillespie (U.S. Air Force Wright Laboratory), Dr. Anthony Hamins (BFRL/NIST), Dr. James Hoover (NAWC, China Lake), Professor Herman Krier (University of Illinois), Professor Kenneth K. Kuo (Pennsylvania State University), Dr. William Pitts (BFRL/NIST), Mr. Philip Renn (NSWC, Indian Head), Dr. Francesco Tamanini (Factory Mutual Research Corporation), and Mr. Marco Tedeschi (NAWC, Lakehurst). The editors would also like to thank Ms. Paula Garrett for her relentless effort in organizing this workshop, Dr. Jack Snell, Fire Program Manager of BFRL/NIST, for the official welcome, despite his busy schedule, Dr. Richard G. Gann, Chief, Fire Science Division, for providing advice in organizing and conducting the workshop, their fellow NIST colleagues, and all the workshop participants. The useful comments and suggestions provided by many participants were also greatly appreciated.

ABSTRACT

A workshop on solid propellant gas generators was held on June 28-29, 1995 at the National Institute of Standards and Technology under the sponsorship of the Building and Fire Research Laboratory. Gas generator technology was first proposed as an alternative to halon 1301 (CF_3Br) for in-flight fire protection. Because the technology is still in a developing stage as a fire suppression method, there is no standard test apparatus for evaluating the performance of gas generators, and there remain many unanswered technical questions for the potential users. The specific objectives of the workshop were (1) to identify certification procedures, (2) to determine which critical parameters were required to characterize the performance of a gas generator, (3) to develop a standard test method for gas generator evaluation, (4) to identify other potential applications, and (5) to search for next generation of propellants. The participants at the workshop included representatives from aircraft and airframe manufacturing industries, airbag and propellant manufacturers, fire fighting equipment companies, military services, government agencies, and universities. The agenda of the workshop encompassed eleven presentations on various topics relevant to the applications of gas generators as a fire fighting tool, followed by several discussion sessions. Various important issues related to the achievement of the objectives set forth were addressed, and recommendations regarding what role NIST should play in this new technology were suggested.

1995 WORKSHOP ON SOLID PROPELLANT GAS GENERATORS

INTRODUCTION

The rapid phase-out of halon 1301 fire protection systems has accelerated the search for other potential technologies as alternate means to suppress fires. Solid propellant gas generators (also known as fire extinguishing pyrotechnics or flame suppressing gas generators), a spin-off from airbag technologies, have recently been demonstrated to suppress certain types of fires, particularly aircraft engine nacelle and dry bay fires. This document summarizes a workshop on solid propellant gas generators held at the National Institute of Standards and Technology (NIST) on June 28-29, 1995 under the auspices of the Building and Fire Research Laboratory.

The intent of the workshop was to bring together gas generator manufacturers, researchers, and potential users to discuss various critical issues related to the evaluation and performance of the gas generators as a fire fighting tool and the search for new propellants. Although standard test apparatus for evaluating the performance of airbags exist, no such equivalence is currently available for evaluating fire suppression performance of gas generators due to the infancy of this technology. The specific objectives of the workshop, which reflected the need for such an apparatus, were:

- identification of certification procedure(s) for gas generators in fire suppression applications,
- determination of critical parameters for evaluating the fire suppression efficiency of various gas generators,
- development of a standard methodology to facilitate testing of gas generators,
- identification of possible applications other than protection of engine nacelles and dry bays,
- identification of a new generation of propellants.

However, the emphasis was placed on the performance and evaluation aspects because it was not possible to discuss the search for new propellants in such a format that certain proprietary propellant ingredients would not be disclosed and that the manufacturers' and researchers' patent-pending rights of the new propellants could be protected.

The workshop participants included propellant and airbag manufacturers, airframe and aircraft manufacturers, military services personnel, researchers from academia, industries, and government laboratories, and potential users.

The agenda of the workshop encompassed presentations on various topics ranging from combustion of solid propellants to flame extinction mechanisms, followed by several discussion sessions. The meeting agenda is listed in **Appendix D** and is briefly summarized as follows. For those who are not familiar with the gas generator technology, **Appendix B**, which is an extended abstract presented by the editors at the 1995 International Conference on Fire Research and Engineering, can serve as an introduction to the subject.

The meeting started with an official welcome by Dr. Jack Snell who is the Deputy Director and Fire Program Manager of the Building and Fire Research Laboratory (BFRL) at NIST. Then, Dr. Jiann C. Yang of BFRL/NIST gave a brief overview on the current gas generator technologies for fire suppression. Professor Kenneth K. Kuo of Pennsylvania State University delivered a tutorial on fundamentals of solid propellant combustion. Dr. James Hoover of the Naval Air Warfare Center at China Lake discussed the Navy's in-house research program on fire extinguishing pyrotechnics and the full-scale engine nacelle and dry bay test facilities. Professors Herman Krier of University of Illinois and

Barry Butler of University of Iowa presented their research work on modeling of a generic airbag. Dr. Anthony Hamins of BFRL/NIST discussed various aspects of flame suppression. Dr. William Pitts of BFRL/NIST and Dr. David Bomse of Southwest Sciences, Inc., discussed various species measurement techniques. Lt. Mark Gillespie of the U.S. Air Force Wright Laboratory and Mr. Marco Tedeschi of Naval Air Warfare Center at Lakehurst briefed the audience on the current Air Force and Navy gas generator programs. Mr. Philip Renn of the Naval Surface Warfare Center at Indian Head discussed various gas generator qualification programs. Finally, Dr. Francesco Tamanini of Factory Mutual Research Corporation presented his view on the potential application of gas generator technology to industrial explosion suppression. Copies of their presentations are included in **Appendix E**. Some pages, although presented at the workshop, were intentionally left blank by the speakers when they submitted their copies to the editors due to the preliminary, sensitive, and proprietary nature of the data. These pages were not included in this Appendix.

DISCUSSION AND CONCLUSIONS

There were several discussion sessions at the workshop. The sessions were arranged in such a way that various important issues related to the application of this technology could be addressed. Other useful comments, suggestions, and feed-back from the participants are included in **Appendix A**.

It was not apparent from this workshop that other potential applications, except engine nacelles dry bays, and army vehicles, had been identified because potential end-users among the participants were not broadly represented. For example, representatives from the power utility and telecommunication industries were not present in the workshop. Their absence, however, did not reflect their lack of interest in this technology, but rather it was merely the scheduling and the timing of the workshop that precluded them from attending. It is conceivable that gas generators can be used in a manner similar to a streaming agent for suppressing fires locally or in locations that are difficult to access. Unless sufficient leakage or ventilation is present, total flooding or inerting of an unoccupied space using gas generators may not be feasible because of over-pressurization. In addition, it is also unlikely that gas generators will be used for total flooding in inhabited areas because of complication of possible asphyxiation by inert gases.

Several conceptual designs of test fixtures for evaluating gas generators in fire protection applications were proposed. Since the gas generator technology has its genesis from airbag technologies, some of the proposed test fixtures bore resemblance to those used in the evaluation of airbags. The two apparatus that were discussed the most in the session were several versions of a modified discharge tank and a small-scale wind tunnel. The discharge tank is routinely used in the industry to evaluate the performance of airbags, and the small-scale wind tunnel in which a pool fire is placed behind a bluff body has been used for screening various halon alternatives. The small-scale wind tunnel set-up mimicked a simulated engine nacelle. The schematics of the proposed test fixtures can be found in **Appendix A**.

Because a majority of the participants were from the airframe and aircraft industries and gas generator technology was first proposed as a halon alternative to be used for in-flight aircraft engine and dry bay fire protection, the discussion at the workshop was heavily concentrated on the technical problems that were facing these two applications although similar problems could be encountered when exploring other potential applications of the gas generators. One discussion session was directed to the area of measurements for the purpose of gas generator performance evaluation and certification. Since the effluent product gases depend strongly upon the type of propellant used, it is not feasible and economical to measure the product gases for any arbitrary propellant using various types of instruments. There was consensus among the participants that monitoring of oxygen concentration was probably the most appropriate way to assess the performance of a gas generator used in a dry bay or engine nacelle. In this way, the dependence of effluent product gases on propellant is eliminated (assuming the gases generated are inert). The issue of response time of the measurement technique was also a subject of lengthy discussion. The requirement of 1 ms or less response time for dry bay applications has presented some technical challenges to the researchers. In addition to oxygen concentration measurement, several other parameters were suggested as useful indicators in the evaluation of gas generators, including: pressure, shock, velocity, and temperature.

It was clear that some of the current airbag models could be modified to evaluate gas generator performance. The incorporation of computation fluid dynamics models into the airbag models to study the interaction of exhaust gases from the generator with the geometry of a protected space was suggested.

There was general agreement among the participants that there is an urgent need to develop a certification procedure before gas generators could be considered as a replacement for halon 1301 in engine nacelle and dry bay applications. The lack of a certification process may hinder the deployment of this technology in a timely manner despite many successful full-scale engine nacelle and dry bay fire tests. Still, how to certify a gas generator had not become apparent at the conclusion of the workshop. The major stumbling block appeared to be the identification of certain critical parameters that were required to assess the fire suppression efficiency of an arbitrary gas generator. Such parameters should play important roles in the flame suppression mechanisms. Oxygen concentration emerged as a critical parameter from the discussion. However, detailed flame suppression studies have to be conducted before the role of oxygen in the certification process can be identified.

The lack of a standard laboratory-scale test apparatus for evaluating and screening the fire suppression efficiency of various gas generators may also slow down the advancement of this technology. A test fixture, whose functions and usefulness will be at least similar to that of a standard cup burner used for halon alternative screening studies, needs be developed. The apparatus, in principle, should be relatively simple but at the same time allow enough important information (oxygen concentration, temperature, pressure, *etc.*) to be obtained so that our understanding of the suppression actions of gas generators can be enhanced.

Judging from the responses from the participants during the discussion sessions and their subsequent feed-back, the objectives of the workshop set forth were met with varying degrees of success.

RECOMMENDATIONS

In light of the discussion at the workshop and the current status of gas generator technology for fire suppression, the following recommendations were made.

- A standard test fixture for evaluating fire suppression efficiency of gas generators should be developed. NIST is capable of supporting these efforts.

- The identification of a new class of next generation propellants (*e.g.*, cool and high nitrogen content in the effluent) and the characterization of thermophysical properties of propellants should remain the realm of propellant manufacturers and researchers because of their expertise in this field.

- Certification processes should be developed because they are critical to the advancement of the technology. The development may require extensive cooperation among various parties and many strategy sessions as more full-scale test results become available. NIST can act as a coordinator in such an effort, and if deemed necessary, NIST will sponsor workshops to address the certification issues.

- In view of its involvement in fire modeling and computational fluid dynamics, NIST should play an active role in the modeling effort to study gas generator performance.

- The push for the gas generator technology to other areas of applications requires the promotion of public awareness of such technology, and in this regard, NIST should be in a favorable position to play such role to identify other potential users because of its constant communication and interaction with the fire protection community.

APPENDIX A

Comments/Suggestions for Future Gas Generator Related R & D from Workshop Participants

(In alphabetical order)

Mr. Glenn Harper, McDonnell Douglas

General: The following suggestions/comments for future Gas Generator fire fighting R & D have been prepared as a result of the USN and NIST sponsored workshops at NIST in June 1995. The primary requirements appear to be: understanding the extinguishing mechanisms, defining the concentration/distribution *vs*. time, simplified modeling to gain insight into concentration/distribution, verification of the applicability of small scale lab tests, additional applications, prioritization/allocation of R & D funds, and adequate interaction of the various interested parties. There appear to be two primary goals: understanding the process, and developing reasonably accurate engineering prediction tools for each technology in order to select the optimum technologies for deployment.

(1) Gas Generator Combustion: There was much discussion regarding the need for detailed research into the combustion process inside the generator. Although there is always more to learn about this process, much more is known about this subject than about hot inert gas distribution or the extinguishing mechanism. Future R & D should concentrate on the issues least understood because those are the areas of greatest risk.

(2) Extinguishing Mechanism: The F/A-18 E/F Engine Bay fire extinguishing tests at China Lake in 1994, though successful, are not fully understood. The first priority for future Gas Generator R & D should be to better understand the fire extinguishing phenomenon for those series of tests and also for the Dry Bay tests. To this end I suggest the following for all future Engine Bay testing until the process is well understood:

(a) Continue to push for the 100 ms response concentration sensor ASAP, for the 1995 V-22 tests if possible. If the local concentration of inert gases in the area of the fire are well below the minimum inerting concentrations, then the mechanism is not inerting and other measurements must be made to determine how the fire is extinguished. I would even accept slower response if that was all that was available. (This conclusion presumes that the 100 ms response time is adequate, which may be a false assumption.)

(b) Insure good time correlation between the video coverage and the extinguishing sequence.

(c) If possible, install high response instrumentation in the area of the fire to record pressures, temperature, velocity, flow direction, etc. Enough instrumentation to determine the extinguishing mechanism(s) should be installed if at all possible.

(d) If possible, instrument to sense a shock in the area of the fire.

(3) Concentration Sensor: O_2 sensing, over a broad range of concentrations, is preferred since the same device could then be used for any agent or generator; however, if sensing O_2 is much less sensitive,takes much longer to develop, or cost much more, it might be preferable to sense some other gases, especially for the near term testing. The 100 ms response seems fast enough to learn a lot about distribution in the next test series, especially since it is the only system currently available. Faster might be better but if

it is too late it is of no value. A study to really determine the required response time assuming both inerting and mechanical extinguishing might be valuable since current estimates seem to be based more on experience than analysis. We may need the 1 ms system for Dry Bay ballistic testing and even that may not be adequate.

(4) Modeling: There appears to be a real need for appropriate modeling to better understand the distribution process, to resolve the wide variation in test results between test site, and the ability to make reasonably accurate engineering predictions for sizing and trade studies. A simplified model that allows one to look at the general trends and provides ROM values is much more valuable now than a detailed CFD model that provides high accuracy but takes several man years to develop. A simplified model based on first order effects to address mixing, cooling, buoyancy, ventilation, transport time, etc. would be very helpful in all future Engine Bay testing, this fall if possible. (I would like to see the results of NIST modeling for Mr. Mike Bennett when they become available.) Perhaps a more complex CFD model could be developed to provide insight as a research tool, but if it takes as much time as Dr. Krier indicated it will be of little or no help to the industry. This is another area where the appropriate balance of resources is required. We must have some modeling, but determining the appropriate levels of expenditure, accuracy, and detail is the challenge.

(5) Small Scale Tests: The discussion of the Turbulent Spray Burner and the Turbulent Pool Burner (I believe Dr. Hamins used different names.) test results were interesting. I think working with Mike Bennett and NAVAIR to verify the applicability of these test approaches for evaluating both chemical agents and, if possible, adapting them to Gas Generators would be helpful in quickly developing and evaluating new propellants. In reality, most Engine Bay fires are a combination of both spray and pool fires and combining the results of both tests may provide the best correlation with full scale tests.

(6) Other Applications: There are likely to be applications for Gas Generators for fuel tank protection and perhaps for weapons bay protection, although one should check with the U.S. Army first to see the results of their ammunition bay testing.

(7) Broad Interaction: I encourage NIST to insure that the research/academic organizations involved in NIST out year programs have a mechanism in place to insure adequate interaction with the airframe, engine, fire extinguishing, government pyrotechnic, and Survivability & Vulnerability (S & V) communities to insure their R & D activities can be applied to our specific areas of concern in a timely manner with appropriate limits on the levels of complexity, effort, and accuracy.

(8) Prioritization: I encourage NIST to resist spending a disproportionate amount of NIST limited resources in detailed research on things already fairly well understood (Combustion inside the Generator for example.) as opposed to gaining insight into those areas about which little is known (Extinguishing mechanism or distribution of effluent gases thorough the bay for example.). it is better to obtain the first 50 % knowledge in an unknown area than the last 5 % knowledge in an area already fairly well explored.

(9) Other Issues: The impact of discharging Gas Generators into Engine Bays containing engines worth $3 to $ 10 mil. must continue to be considered. Clean-up, corrosion (especially in salt atmosphere, landing after post-shutdown cold soak, etc.), the "Blast Effect" on maintenance crews if accidental discharged, toxicity all need to be considered. Testing over broad range of temperatures, vibration/shock, etc. is also required since the combustion characteristics of all propellants are temperature dependent, some more than others, and there is some risk of "cracked grains" due to shock, temperature cycling, vibration, etc. which may result in severe over pressure when ignited.

Dr. J.M. Heimerl, Army Research Laboratory

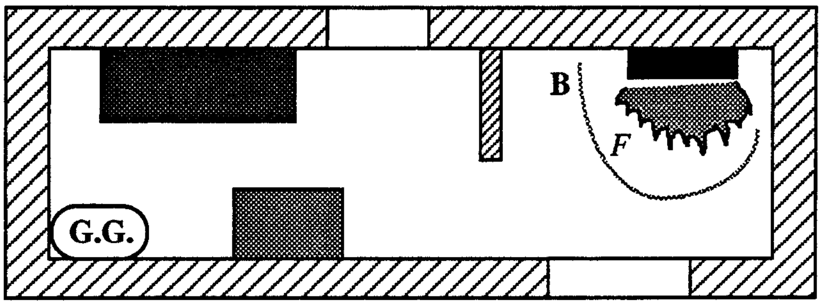
A Method to Attack Practical Extinguishment Problems

The flow diagram of Dr. Bill Grosshandler and the "living room" fire schematic of Prof. Herman Krier suggested the methodology to be discussed below.

Bill Grosshandler suggested that the overall problem could be broken down into a series of events such as:

Gas Generator ⇒ spatial & temporal flow ⇒ fire extinguishment.

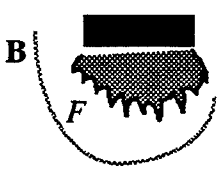
Herman Krier presented a "living room" fire as an example of the complexities of a real life fire scenario.



The fire, *F*, is to be put out by the gas generator **GG**. There is some complex flow path that the extinguishing gases must take to reach the fire.

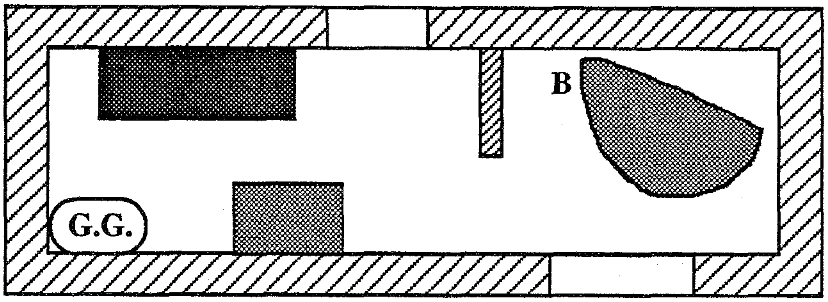
The proposed methodology isolates the fire from the rest of the environment and divides the original problem into two parts.

(1) Isolate the fire by inscribing a boundary, **B**.



Determine what values (or range of values) of critical parameters must be present at **B** to extinguish the fire. The parameters might include: temperature, pressure, species concentration (*e.g.*, diluent or "superagent"), and flow velocity. The extinguishing properties could be determined from experiment, modeling, or previous experience.

(2) Then, other flow codes (or perhaps, even experiments) could be used to determine the values of the parameters at the boundary, **B**,



and answer:

(1) whether the given, fixed **GG** could extinguish the flame, *F* (this answer relates to drop-in replacement for a current halogen extinguisher); or

(2) what arrangement of **GG** (*i.e.*, type of solid propellant, amount per container, number of containers, their locations) would extinguish *F*; or

(3) what is the best arrangement (*e.g.*, with cost, time or total amount of propellant as constraints) to extinguish *F*.

The advantages of this methodology are:

(1) it separates the system and its fire from the environment that contains the gas generator. To handle them together, either experimentally or in a code, can be a complex, expensive undertaking.

(2) it allows the user (of the system to be protected) to define the problem in a way that allows a relatively rapid solution. Detailed specifications of the system need not be present in codes (or experiments) employed to determine solution.

(3) even if the fire is so large or so hot that it strongly couples with and severely affects the flow contours in the surrounding environment, the methodology might still be useful if one were to include in the model a "black box" heat source bounded by **B**.

One might think that a possible disadvantage of this methodology is the requirement the values of the critical parameters at **B** must be known. This may prove to be difficult in practice. However, one would have to know this information (or its equivalent) to determine whether **GG** is solution.

Prof. Herman Krier, University of Illinois, Urbana-Champaign
Prof. Barry Butler, University of Iowa

Key Concepts for Modeling Strategies

- Solid Propellant Gas Generator models exist, have been validated, and can be applied to "new" systems.

Input	Output
* Propellant information	* Mass flow (t)
* Hardware parameters	* Velocity (t)
* Combustion behavior	* Temperature (t)
•	* Species concentration (t)
•	•
•	•
etc.	etc.

- Fires to be extinguished are flow specific (*i.e.*, wide variety of different flow conditions).

    * Geometry (engine nacelles *vs*. dry bays *vs*. others)
    * In-flow/out-flow
    * Chemistry of flame (Damköhler number)
        - •
        - •
        - etc.

- The <u>first</u> is input to the <u>second</u> (gas generator output is choked flow).

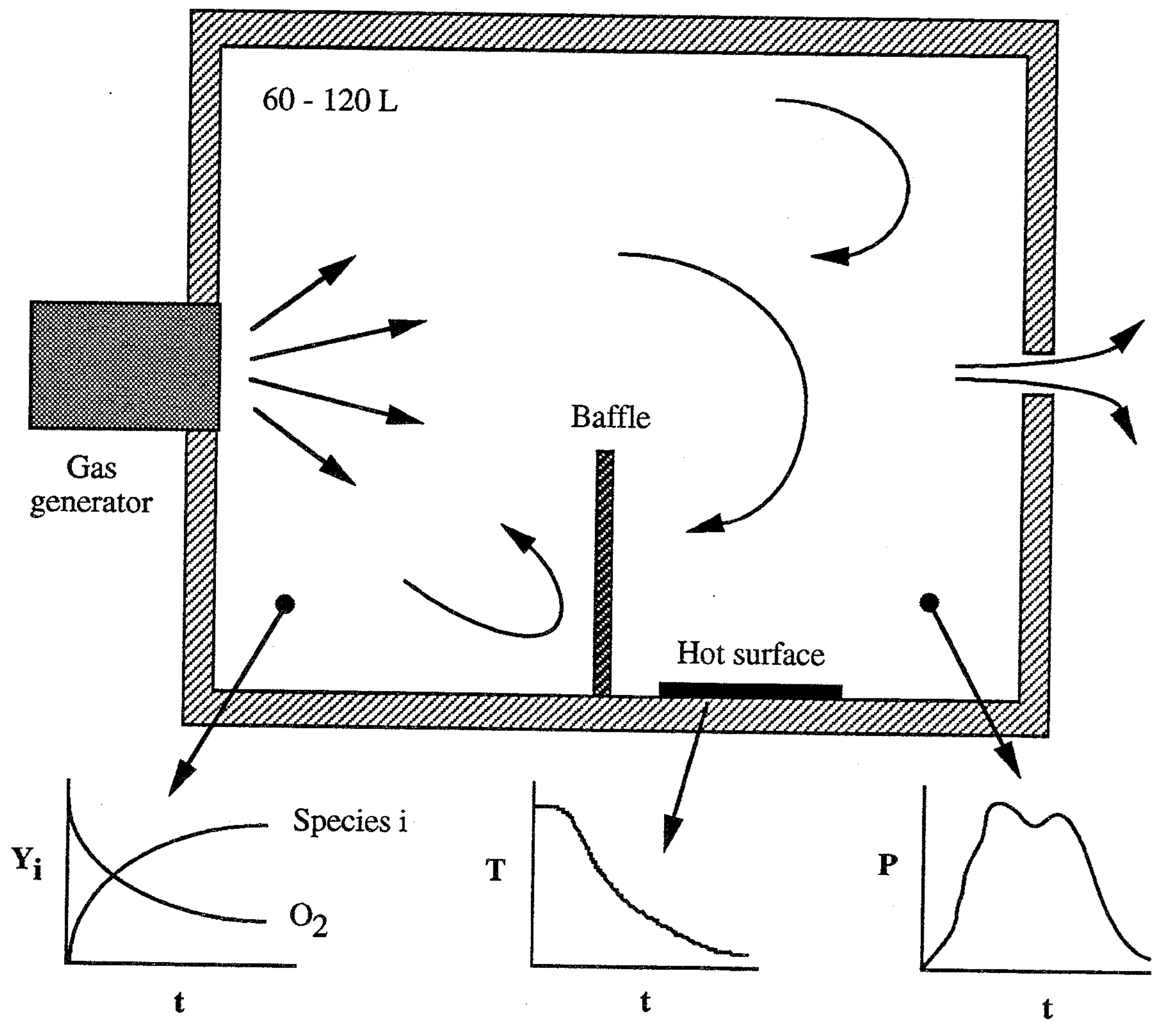
- CFD codes for chemically reacting, high turbulence flow exist and are routinely used.

- Based on combustion fundamentals, criteria for extinguishment must be specified.

- Solve the 2-D, unsteady, chemically reacting flow specific to each "problem".

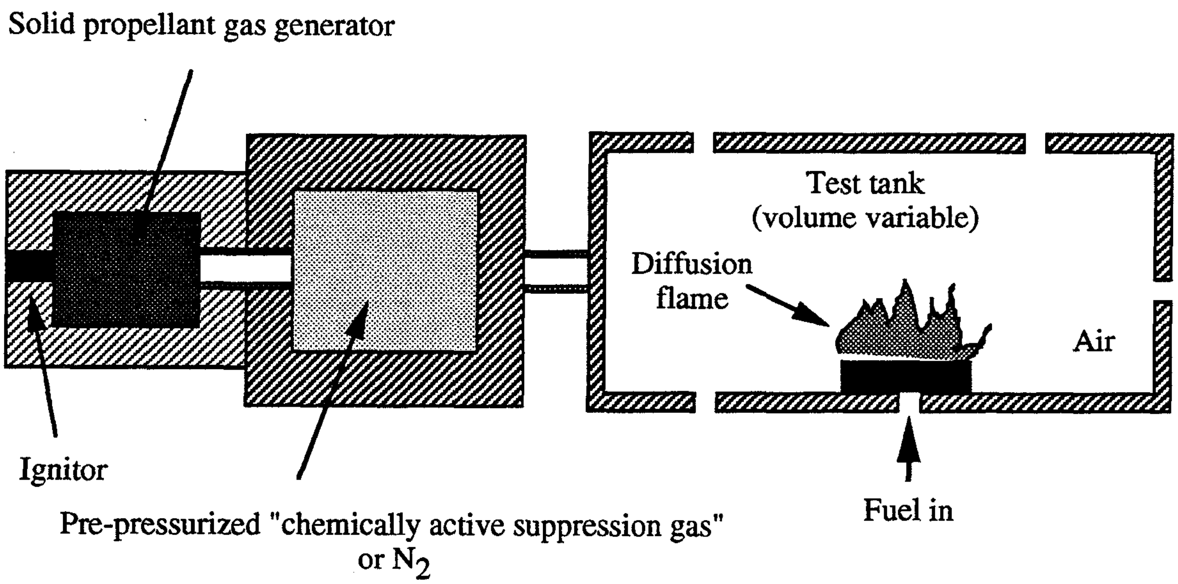
    * Cold flow
    * Hot flow

Modified Tank Test

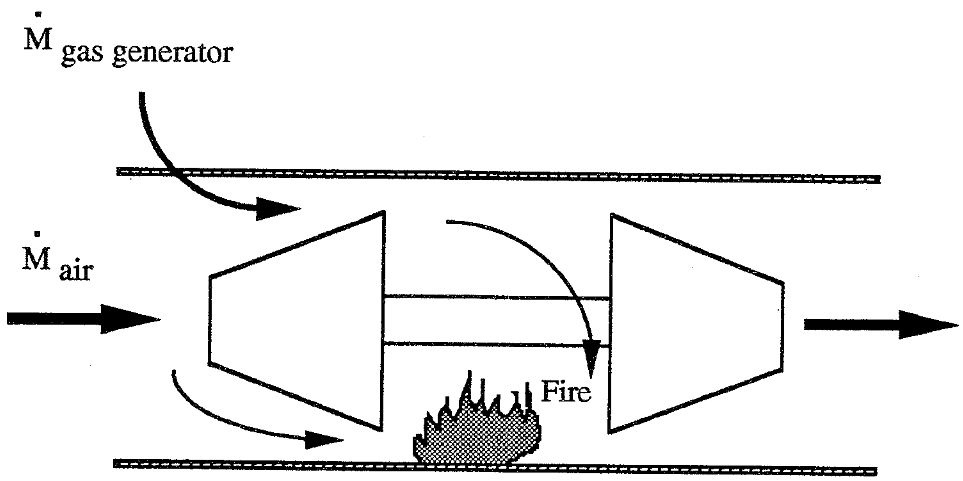


- Small scale
- Fundamental understanding - Yes
- Product development - Yes
- Certification - No
- Inexpensive - Yes
- Repeatable - Yes

A Potential Test Fixture

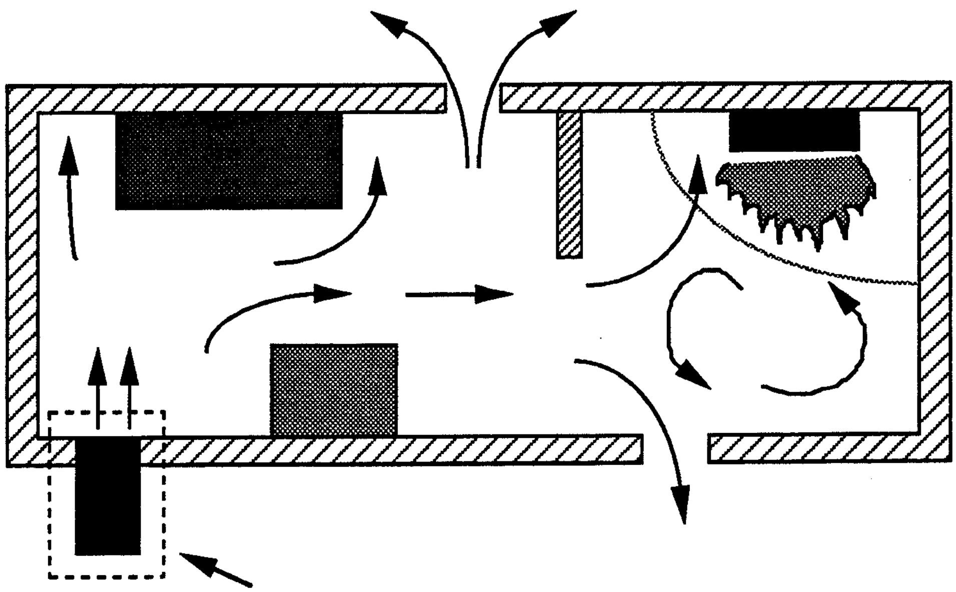


ENGINE FIRE



Key : $\dfrac{\dot{M}_{\text{gas generator}}}{\dot{M}_{\text{air}}} \lll 1$

DRY BAY FIRE



Gas generator

$\dot{M}\ (t), T(t), V(t), Y_i\ (t)$

Prof. Kenneth K. Kuo, Pennsylvania State University

Fundamental Data Required

- Characterization of gas generator propellant burning behavior including:
  - Steady-state burning rate and product concentration
    - $r_b = r_b\,(P,T_i)$
    - Burning surface temperature, $T_s = T_s\,(P,T_i)$
    - Temperature sensitivity, $\sigma_p = \sigma_p\,(P)$
    - Combustion product concentration
  - Transient burning behavior
    - The effect of chamber pressure variations on burning rate
    - Characterization of pertinent combustion instability parameters such as $(\partial T_s/\partial T_i)_P$, acoustic admittance, etc.

Contributions from Participants in the Discussion Session moderated by Dr. William M. Pitts, NIST

Parameters of interest

- Shock measurements
- Velocity
- Pressure
- Concentration
- Temperature
- Flow visualization
- Radicals
- Flame/flow interaction
- Thermal cooling

APPENDIX B

Solid Propellant Gas Generators: An Overview and Their Application to Fire Suppression[1]

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ABSTRACT

A solid propellant gas generator is essentially an airbag inflator without a bag. That is, the gas generated is discharged directly into ambience rather than into a bag. A typical solid propellant gas generator consists of solid propellant tablets which will, upon ignition, rapidly react to generate gas-phase combustion products and particulates, an ignitor to initiate the combustion of the propellant, a filter system to prevent or minimize the release of the particulates from the combustion reactions into the ambience, a heat transfer mechanism (normally the filter itself) to cool the high temperature combustion gas before being discharged into the ambience, and an exhaust mechanism to disperse the gas efficiently. In this article, an overview of the current status on solid propellant gas generators will be discussed, and potential areas for future research will be suggested.

The solid propellant used in an airbag inflator typically contains sodium azide (NaN_3), iron oxide (Fe_2O_3), and small amount of other proprietary additives. The principle gas-phase product as the result of the combustion of the NaN_3/Fe_2O_3 propellant is nitrogen, and the resulting temperature is in the neighborhood of 1300 K. Solid species such as sodium oxide (Na_2O) and ferrous oxide (FeO) are also generated during the combustion process. Since the product gas is mainly nitrogen, the extension of airbag inflator technologies to suppress fires is ideal and logical. The suppression action of a solid propellant gas generator is believed to be due mainly to the effects of oxygen displacement (dilution) by nitrogen and gas discharge dynamics (flame stretch). To a lesser extent, a thermal effect also plays a role. However, the actual extinguishment mechanism(s) are not precisely known. It is possible that the extinguishment mechanism depends on the distance between the gas generator and the fire. If the location of the gas generator is very close to the fire, the extinguishment mechanism is likely to be attributable to blowing out the fire by the exhaust from the gas generator.

There are basically two types of airbag inflator systems: (1) the conventional and (2) the pre-pressurized or gas-assisted. In a conventional system, the gas that is used to inflate the bag depends entirely on the combustion gas generated by the solid propellant. However, in a pre-pressurized or gas-assisted system, the high temperature gas as a result of the combustion of the propellant is first mixed with a pre-pressurized inert gas at ambient temperature before being discharged into a bag. Similarly, one can also conveniently classify solid propellant gas generators into two categories, depending upon their functions: (1) conventional and (2) hybrid. When a gas generator is used alone for fire suppression, it is termed

[1]presented at the 1995 International Conference on Fire Research & Engineering, September 10-15, Orlando, Florida

"conventional." When it is used together with other liquid or powdered fire suppressing agents, it is termed "hybrid." In a hybrid system, the gas generator normally is used as a means to provide sufficient pressurization so that the expulsion of liquid or powdered agent from a storage vessel can be facilitated.

A typical sequence of events that occurs during gas generation for fire suppression using solid propellants can be described as follows. Upon detection of a fire, the ignitor located in the combustion chamber of the solid propellant gas generator is activated. The ignitor, which contains a small amount of pyrotechnic materials (*e.g.*, $Zr/KClO_4$), immediately releases high temperature gas and hot particulates *via* thermally initiated, exothermic chemical reactions of the pyrotechnic materials. The resulting temperature and pressure rises then initiate the solid propellant reactions near the ignitor, and a deflagration front rapidly propagates throughout the solid propellant bed. Very frequently, booster propellants, ignited by the ignitor, are used to facilitate the combustion of the main solid propellants. The high temperature and high pressure combustion gases, together with the condensed-phase products, then exit the combustion chamber through a filter before discharging into the ambience.

The attractiveness of using solid propellant gas generators in fire suppression applications lies in the fact that the system, when used alone, is considered to have no ozone depletion and global warming potential, and is physically very compact. Being a derivative from the airbag inflator technologies, there are voluminous research materials available in the literature. Another advantage is that since gases are generated *via* solid propellant reactions, the system can, in principle, be tailored to function over a period of few milliseconds (*e.g.*, for aircraft dry bay fire protection) to few seconds (*e.g.*, for aircraft engine nacelle applications) by manipulating the parameters that control the combustion mechanisms. In addition, the gas generators have very extended storage and service life. However, the toxicity of some of the by-products can not be ignored.

A review of previous research literature on airbag inflator technologies has suggested, through parallelism, the following areas for future research on solid propellant gas generators: (1) continuing search for better solid propellants, (2) better understanding of the suppression mechanism(s) of the product gases, (3) modeling and simulation of the thermochemistry and gas discharge dynamics, and (4) hardware optimization.

Sodium azide, which is used in the preparation of herbicides and in various organic syntheses, is the current principal chemical used in solid propellants for gas generators. Because of its potential health hazards (*e.g.*, its potential to lower blood pressure), current research has been focused on the "non-azide based" propellants by the airbag manufacturers. The pertinent thermochemical and thermophysical properties to be considered for any new propellant should include (1) propellant thermochemistry (flame temperature and chemical composition of combustion products) and stoichiometry (moles of gas produced per mole of propellant burnt), (2) propellant ignitability and burning rates under various conditions, (3) toxicity of combustion products, (4) stability of propellent during storage and transport, and (5) propellant thermal properties. In addition, the grain size and shape of the propellant and how the propellant is packed in the gas generator also play important roles in the performance of the gas generator.
The suppression mechanisms of the combustion gases are the least understood because of the complexity of the gas discharge dynamics and turbulence interaction of the suppressants with the fires. Current practice for studying the suppression efficiency of the propellent, at least in the dry bay and engine nacelle applications, is to use trial and error to determine the amount of propellants required to put out a specific fire. A better understanding of the suppression mechanisms would therefore be needed in order to determine the required amount of propellants in a systematic way.

Current computer codes for simulating airbag inflator performance may be used with some modifications to evaluate the performance of gas generators. Note that existing computer codes address almost exclusively the simulation of internal performance of airbag inflators and that chemical equilibrium is assumed to determine the products of combustion and flame temperatures. Since the gas generation processes are extremely rapid and over in such a short duration, chemical equilibrium may not be reached, and simplified or detailed chemical kinetics should be considered in future code development. In addition, the interaction of the exhaust gas from the gas generator with the ambience has to be taken into account in the modified codes.

Current or future airbag inflator technologies can definitively benefit the hardware optimization of gas generators. Current active areas of research on airbag inflator hardware appear to be focused on the improvement of filter design and gas cooling system. For solid propellant gas generators, research should also be focused on how to disperse the gas effectively upon leaving the generator.

Presently, the gas generator technique has been proposed to be used in uninhabited areas because of the detrimental effects of oxygen depletion and nitrogen inerting on humans. Current interest has been focused on the application of the technique to aircraft dry bay and engine nacelle fires. Recently, tests performed at the Naval Air Warfare Center in China Lake, California and Wright Laboratory in Dayton, Ohio have demonstrated the feasibility of using solid propellant gas generators to suppress simulated aircraft dry bay fires. Other potential areas of application have also been suggested by the manufacturers. These include, to name a few, warehouse fire protection, industrial explosion prevention, and race car and shipboard engines.

APPENDIX C

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APPENDIX D

Meeting Agenda

SOLID PROPELLANT GAS GENERATOR WORKSHOP
June 28-29, 1995

National Institute of Standards and Technology
Building 101, Lecture Room D
Gaithersburg, MD 20899 USA

June 28, 1995

8:00-8:30 AM	Coffee
8:30 AM	Jack Snell, Fire Program Manager Building and Fire Research Laboratory, NIST *Welcome*
8:40 AM	Jiann C. Yang, NIST *Introductory Remarks*
9:00 AM	Kenneth Kuo, Pennsylvania State University *Fundamentals of Solid Propellant Combustion*
9:50 AM	James Hoover Naval Air Warfare Center, China Lake *Fire Extinguishing Pyrotechnics*
10:20 AM	Break
10:40 AM	Herman Krier, University of Illinois Barry Butler, University of Iowa *Modeling and Experimental Validation of Gas Generators*
11:40 AM	Anthony Hamins, NIST *Flame Extinction and Suppression*
12:10 PM	Lunch
1:15 PM	William Pitts, NIST *Species Concentration Measurements*
1:45 PM	David Bomse, Southwest Sciences *Oxygen Concentration Measurements*

2:15 PM	Mark Gillespie, Wright Laboratory *U.S. Air Force Inert Gas Generator Program*
2:45 PM	Marco Tedeschi, Naval Air Warfare Center, Lakehurst *Inert Gas Generators Used for Fire Suppression Abroad U.S. Naval Aircraft*
3:15 PM	Break
3:35 PM	Philip Renn, Naval Surface Warfare Center, Indian Head *Navy Qualification of Solid Propellant Gas Generators for Aircraft Fire Suppression*
4:05 PM	Francesco Tamanini, Factory Mutual Research Corporation *Explosion Suppression for Industrial Applications*
4:35 PM	Moderator: Jiann C. Yang, NIST *Discussion I: Other Potential Applications?*
5:15 PM	Meeting Adjourn

June 29, 1995

8:30 AM	Moderator: William L. Grosshandler, NIST *Discussion II: What are the right test fixtures?*
9:15 AM	Moderator: William Pitts, NIST *Discussion III: What do we want to measure?*
10:00 AM	Break
10:15 AM	Moderator: Herman Krier, University of Illinois *Discussion IV: The need for modeling?*
11:00 AM	Moderator: Jiann C. Yang, NIST *Discussion V: Other research needs?*
11:45 AM	William L. Grosshandler, NIST *Concluding Remarks*
12:00 Noon	Adjourn

APPENDIX E

WORKSHOP PRESENTATIONS

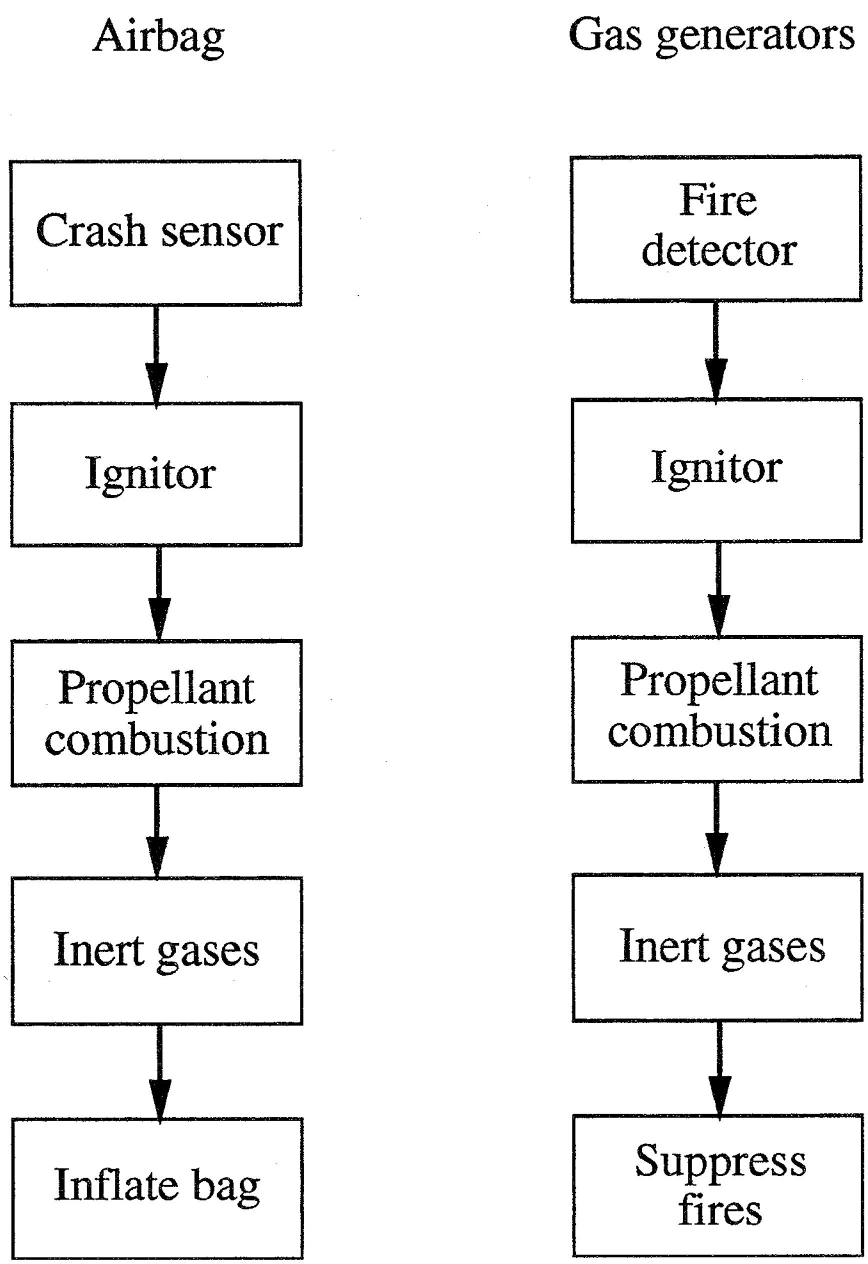
INTRODUCTORY REMARKS

Jiann C. Yang

Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, Maryland 20899

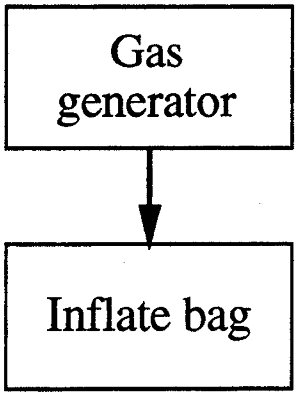
Objectives of the Workshop:

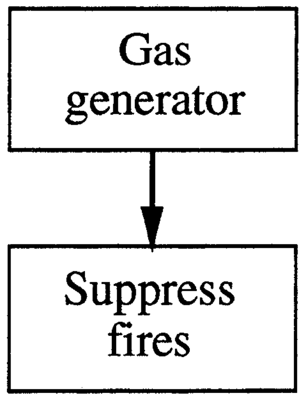
- To identify what we know and don't know in gas generator technology for fire suppression
- To identify future research areas in gas generator technology for fire suppression
- To identify potential users and address their needs and concerns


Airbag
Gas generators
Crash sensor
Ignitor
Propellant combustion
Inert gases
Inflate bag
Fire detector
Ignitor
Propellant combustion
Inert gases
Suppress fires

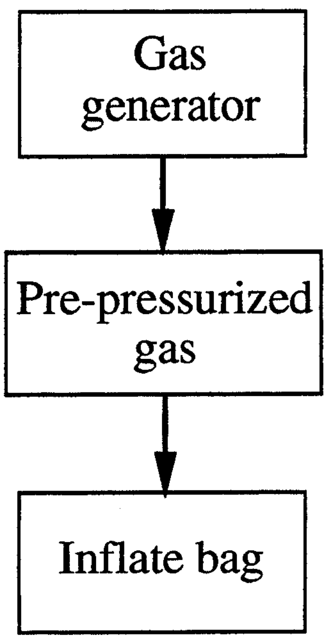
Classifications

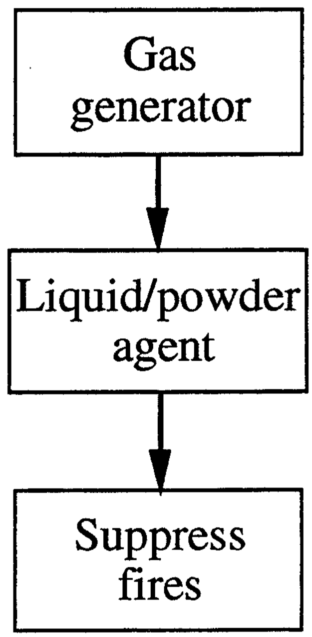
Conventional





Hybrid





Review of Airbag Technologies

- More than 10,000 patents internationally

  R & D Areas:

  - Propellant Research
  - Filter Systems
  - Airbag materials
  - Overall System Designs
  - Computer Simulation and Modeling of Airbag Deployment

Solid Propellant Gas Generators

- Search for new propellants
  - Non-azide based
  - Thermochemistry and stoichiometry
  - Ignitability and burning rate
  - Toxicity
  - Storage stability
- Understand how they suppress fires
  - Dilution, chemical, thermal, or physical
- Modeling
- Hardware optimization
  - Filter, cooling, dispersion of combustion gases

Advantages of Gas Generators for Fire Suppression

- No Ozone-Depletion Potential
- Minimum / No Global-Warming Potential
- Stability
- Long Service and Storage Life
- Physically Compact

Applications of Gas Generators for Fire Suppression

Current: Engine Nacelle Fires
Dry Bay Fires

Potential: Industrial Explosion Prevention
Warehouse Fire Protection
Race Cars
Shipboard Engines
....
....
....

FUNDAMENTALS OF SOLID PROPELLANT COMBUSTION

Kenneth K. Kuo

Department of Mechanical Engineering
The Pennsylvania State University
University Park, PA 16802

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presented at

"Solid Propellant Gas Generator Workshop"

NIST
Gaithersburg, MD 02899

June 28-29, 1995

ACKNOWLEDGEMENTS

- I would like to express my deep appreciation for various solid propellant research projects supported by many U.S. Government organizations (such as ARO, ONR, AFOSR, NWC, BRL, AFPL) as well as many other research projects supported by various industrial companies (such as TC, Aerojet, Olin, RRC, Wyle Lab, ARC). Through these projects and many related works, I have gained useful knowledge and experience in solid-propellant combustion and ignition processes.

- I would and like to thank Professor Martin Summerfield, series editor-in-chief, for the opportunity for me to serve as co-editor of <u>Fundamentals of Solid-Propellant Combustion</u>, printed as Vol. 90 of AIAA Progress Series, November 1984.

- I would also like to thank many of my co-workers and graduate students at The Pennsylvania State University. Through their collaboration and dedication many interesting and important research results were obtained.

- Thanks to Dr. John C. Yang and Dr. William L. Grosshandler of NIST for their invitation for my participation in this workshop.

COMMENTS ON WORKSHOP TOPIC

- It is very exciting to see that solid propellants are bring considered for gas generator application in fire extinguishment.
- Great Engineering Challenge!!

GENERAL BACKGROUND OF SOLID PROPELLANTS

(1) SOLID STATE SUBSTANCES WHICH CONTAIN BOTH OXIDIZERS AND FUEL INGREDIENTS

(2) ABLE TO BURN IN ABSENCE OF AMBIENT AIR OR OXIDIZERS

(3) NORMALLY USED TO GENERATE HIGH-TEMPERATURE COMBUSTION PRODUCTS FOR PROPULSION PURPOSES

(4) CLASSIFIED INTO TWO DIFFERENT TYPES (HOMOGENEOUS AND HETEROGENEOUS) BASED ON DIFFERENCES IN THEIR PHYSICAL STRUCTURE

CLASSES OF PROPELLANTS

- Homogeneous

    - Uniform physical structure.
    - Fuel and oxidizer are chemically bonded together.
    - Major constituents are nitrocellulose (NC) and nitroglycerine (NG).
    - Also referred to as double-base propellants.

- Heterogeneous

    - Non-uniform physical structure.
    - Polymeric fuel binder and crystalline oxidizers.
    - Also referred to as composite propellants.

FUNDAMENTALS OF SOLID-PROPELLANT COMBUSTION

Edited by
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Martin Summerfield
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Volume 90
Progress in
Astronautics and Aeronautics

Martin Summerfield, Series Editor-in-Chief
Princeton Combustion Research Laboratories, Inc.
Monmouth Junction, New Jersey

Published by the American Institute of Aeronautics and Astronautics, Inc.
1633 Broadway, New York, N.Y. 10019

Table of Contents

It provides an excellent tutorial introduction of the performance of solid-propellant rocket motors and a gener[illegible] survey of solid-propellant combustion characteristics.

presents the basic chemistry of ignition and combustion of AP-based propellants as well as the roles of oxidizers, binders, catalysts, and ambient conditions in ignition and combustion.

consists of pertinent information on the thermal behavior of RDX and HMX and a clear delineation of the sublimation, pyrolysis, ignition, and self-deflagration of these nitramine ingredients

describes detailed kinetics of NC, HMX, and RDX decomposition, catalysis of nitramine propellants, as well as flame-zone chemistry

Covers detailed description of various types of ignition experiments and theories, ignition phenomena and criteria.

presents detailed discussions on flame spreading over the surface of solid propellant and into the defects of propellant grains.

presents useful information on the flame structure and combustion mechanisms of homogeneous propellants, mechanism of super rates and Plateau or Mesa effect.

gives detailed treatment of various models developed for heterogeneous propellants

offers extensive descriptions and interpretations of the combustion phenomena of metalized propellants

covers various theoretical models which are grouped into different categories based upon the method of approach. Presents erosive burning data, observed phenomena, and basic mechanisms.

provides basic mechanisms, theoretical models, experimental observations, and effects of physicochemical parameters on transient burning rates

Presents extinction theories and experiments. Covers dynamic extinction of fast depressurization, deradiation, and various quenching techniques.

discusses experimentally observed combustion instabilities in rocket motors. Covers techniques for the measurement of combustion response functions, various modes of instabilities, effect of propellant characteristics on combustion instabilities

deals with theoretical analysis of combustion instability including linear analysis of wave motion, acoustic amplification and damping, non-acoustic instability, nonlinear analysis, and predictive capabilities of various theories.

contains detailed discussions of the chemical origins of smoke secondary smoke formation and its modeling, homogeneous and heterogeneous nucleation of smoke, and various methods of reducing smoke of propellant products.

Nonsteady Burning and Combustion Stability of Solid Propellants

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Volume 143
PROGRESS IN ASTRONAUTICS AND AERONAUTICS

A. Richard Seebass, Editor-in-Chief
University of Colorado at Boulder
Boulder, Colorado

Published by the American Institute of Aeronautics and Astronautics, Inc.,
370 L'Enfant Promenade, SW, Washington, DC, 20024-2518

Table 1 List of ingredients used for double-base and composite propellants

<u>Double-base propellant</u>
plasticizer (fuel and oxidizer)
NG: nitroglycerin
TMETN: trimethylolethane trinitrate
TEGDN: triethylene glycol dinitrate
DEGDN: diethylene glycol dinitrate
plasticizer (fuel)
DEP: diethylphtalate
TA: triacetine
PU: polyurethane
binder (fuel and oxidizer)
NC: nitrocellulose
stabilizer
EC: ethyl centralite
2NDPA: 2-nitrodiphenilamine
burning rate catalyst
PbSa: lead salicylate
PbSt: lead stearate
Pb2EH: lead 2-ethylhexoate
CuSa: copper salicylate
CuSt: copper stearate
LiF: lithium fluoride
high energy additive
RDX: cyclotrimethylene trinitramine
HMX: cyclotetramethylene tetranitramine
NGD: nitroguanidine
coolant
OXM: oxamide
opecifier
C: carbon black
flame suppressant
KNO_3: potassium nitrate
K_2SO_4: potassium sulfate
metal fuel
Al: aluminum
combustion instability suppressant
Al: aluminum
Zr: zirconium
ZrC: zirconium carbide

(Table 1 continued on next page.)

Table 1 (cont.) List of ingredients used for double-base and composite propellants

Composite propellant	
oxidizer	
AP:	ammonium perchlorate
AN:	ammonium nitrate
NP:	nitronium perchlorate
KP:	potassium perchlorate
RDX:	cyclotrimethylene trinitramine
HMX:	cyclotetramethylene tetranitramine
binder	
PS:	polysulfide
PVC:	polyvinyl chloride
PU:	polyurethane
CTPB:	carboxyl terminated polybutadiene
HTPB:	hydroxyl terminated polybutadiene
curing and/or crosslinking agents	
PQD:	paraquinone dioxime
TDI:	toluene-2,4-diisocyanate
MAPO:	tris{1-(2-methyl) aziridinyl} phosphine oxide
ERLA-0510:	N,N,O-tri (1,2-epoxy propyl)-4-aminophenol
IPDI:	isophorone diisocyanate
bonding agent	
MAPO:	tris{1-(2-methyl) aziridinyl} phosphine oxide
TEA:	triethanolamine
MT-4:	adduct of 2.0 moles MAPO, 0.7 mole azipic acid, and 0.3 mole tararic acid
plasticizer	
DOA:	dioctyl adipate
IDP:	isodecyl pelargonete
DOP:	dioctyl phthalate
burning rate catalyst	
Fe_2O_3:	ferric oxide
FeO(OH):	hydrated-ferric oxide
nBF:	n-butyl ferrocene
DnBF:	di-n-butyl ferrocene
LiF:	lithium fluoride
metal fuel	
Al:	aluminum
Mg:	magnesium
Be:	beryllium
B:	boron
combustion instability suppressant	
Al:	aluminum
Zr:	zirconium
ZrC:	zirconium carbide

APPLICATIONS OF SOLID PROPELLANTS

SOLID PROPELLANTS HAVE BEEN USED FOR BOTH MILITARY ANE COMMERCIAL PURPOSES.

- MILITARY APPLICATIONS
  - MISSILES
  - GUNS
  - AIR-BREATHING PROPULSION SYSTEMS, ETC.

- COMMERICIAL APPLICATIONS
  - ROCKETS FOR LAUNCHING EARTH SATELLITES
  - RAPID FILLING OF AIR BAGS
  - CONNECTION OF ELECTRICAL CABLES
  - EMERGENCY AIRPLANE CREW ESCAPE SYSTEMS
  - MINING
  - CONSTRUCTION, ETC.

Table 1 (cont.) List of ingredients used for double-base and composite propellants

Composite propellant

oxidizer
- AP: ammonium perchlorate
- AN: ammonium nitrate
- NP: nitronium perchlorate
- KP: potassium perchlorate
- RDX: cyclotrimethylene trinitramine
- HMX: cyclotetramethylene tetranitramine

binder
- PS: polysulfide
- PVC: polyvinyl chloride
- PU: polyurethane
- CTPB: carboxyl terminated polybutadiene
- HTPB: hydroxyl terminated polybutadiene

curing and/or crosslinking agents
- PQD: paraquinone dioxime
- TDI: toluene-2,4-diisocyanate
- MAPO: tris{1-(2-methyl) aziridinyl} phosphine oxide
- ERLA-0510: N,N,O-tri (1,2-epoxy propyl)-4-aminophenol
- IPDI: isophorone diisocyanate

bonding agent
- MAPO: tris{1-(2-methyl) aziridinyl} phosphine oxide
- TEA: triethanolamine
- MT-4: adduct of 2.0 moles MAPO, 0.7 mole azipic acid, and 0.3 mole tararic acid

plasticizer
- DOA: dioctyl adipate
- IDP: isodecyl pelargonete
- DOP: dioctyl phthalate

burning rate catalyst
- Fe_2O_3: ferric oxide
- FeO(OH): hydrated-ferric oxide
- nBF: n-butyl ferrocene
- DnBF: di-n-butyl ferrocene
- LiF: lithium fluoride

metal fuel
- Al: aluminum
- Mg: magnesium
- Be: beryllium
- B: boron

combustion instability suppressant
- Al: aluminum
- Zr: zirconium
- ZrC: zirconium carbide

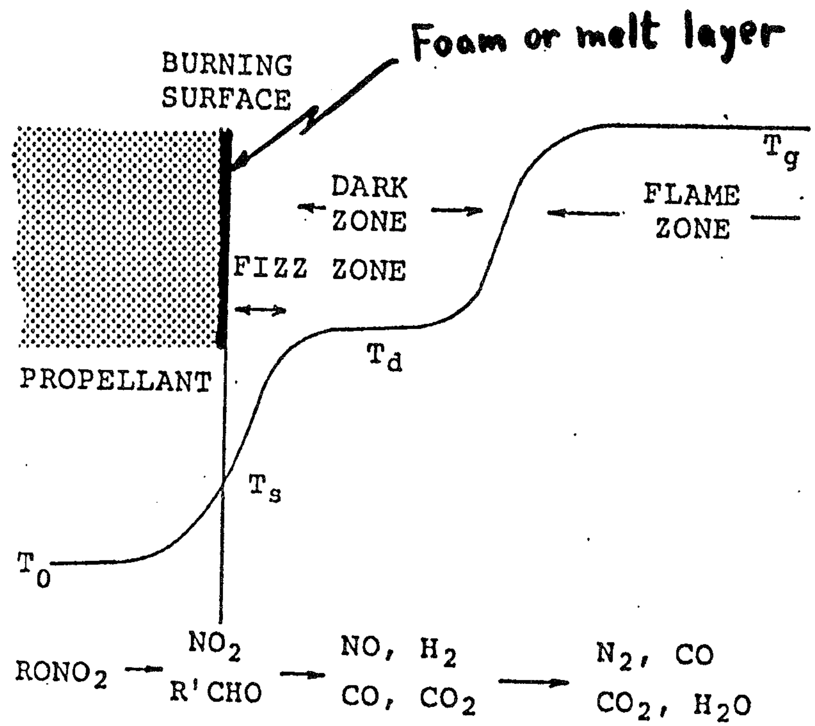
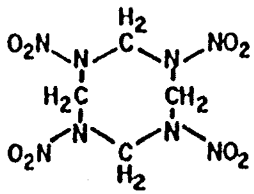


Fig. 16 Schematic description of the flame (combustion wave) structure of a double-base propellant.

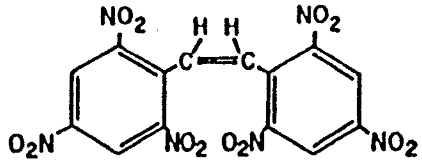
Several Commonly Used Solid Explosives

HMX



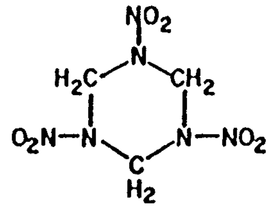
Cyclotetramethylene
tetranitramine

HNS



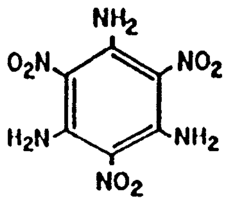
Hexanitrostilbene

RDX



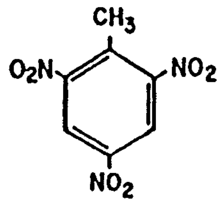
Cyclotrimethylene
trinitramine

TATB



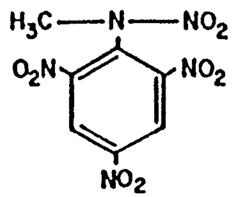
Triaminotrinitrobenzene

TNT



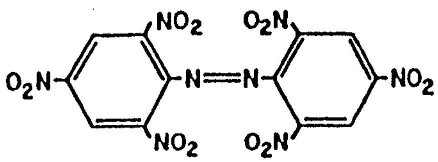
Trinitrotoluene

Tetryl



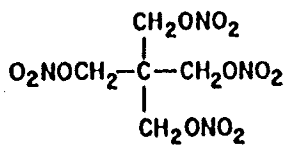
Trinitrophenyl
methylnitramine

HNAB



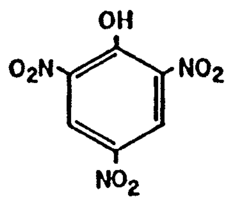
Hexanitroazobenzene

PETN



Pentaerythritoltetranitrate

Picric acid



Trinitrophenol

APPLICATIONS OF SOLID PROPELLANTS

SOLID PROPELLANTS HAVE BEEN USED FOR BOTH MILITARY ANE COMMERCIAL PURPOSES.

- MILITARY APPLICATIONS
  - MISSILES
  - GUNS
  - AIR-BREATHING PROPULSION SYSTEMS, ETC.

- COMMERICIAL APPLICATIONS
  - ROCKETS FOR LAUNCHING EARTH SATELLITES
  - RAPID FILLING OF AIR BAGS
  - CONNECTION OF ELECTRICAL CABLES
  - EMERGENCY AIRPLANE CREW ESCAPE SYSTEMS
  - MINING
  - CONSTRUCTION, ETC.

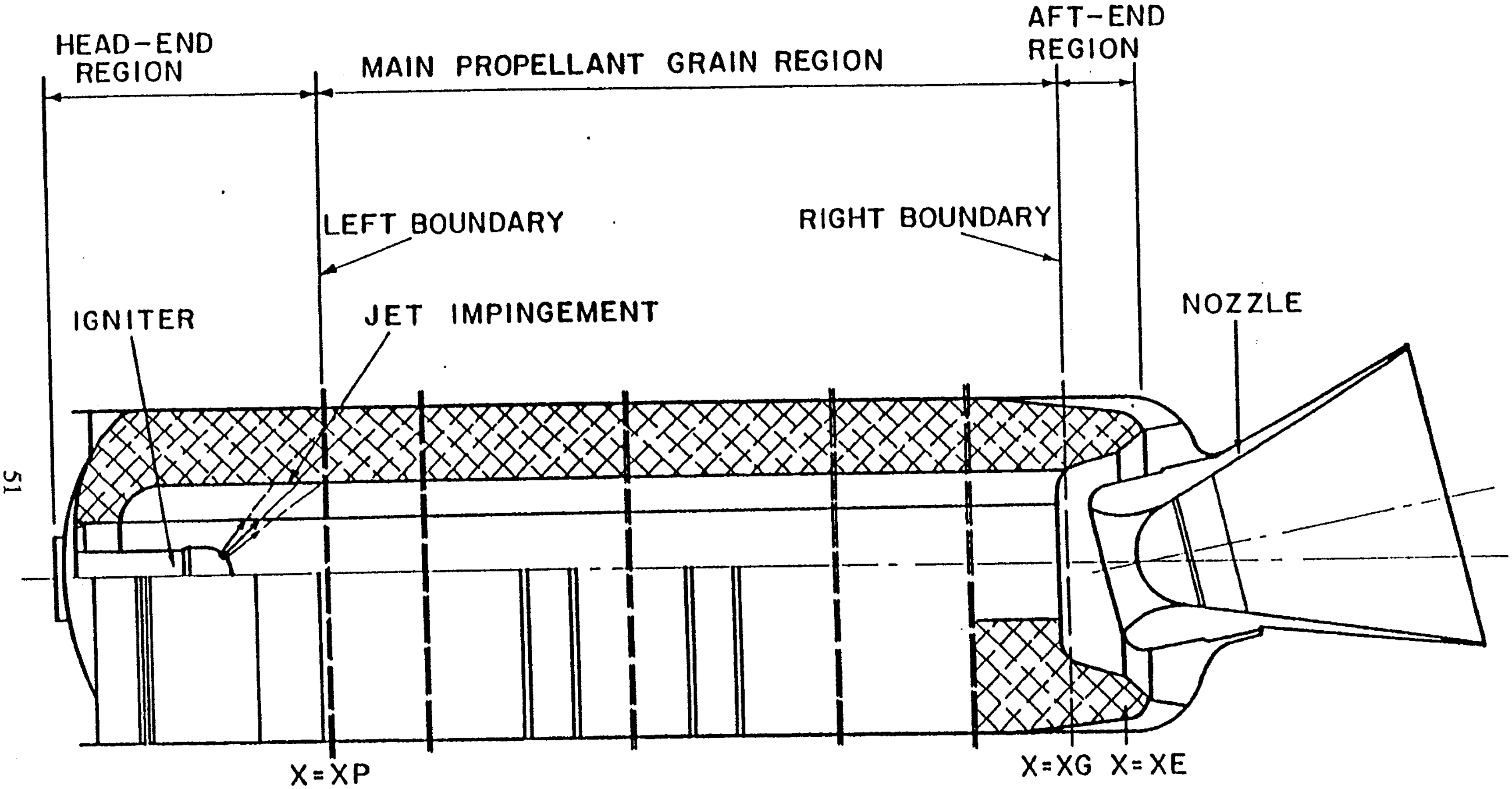
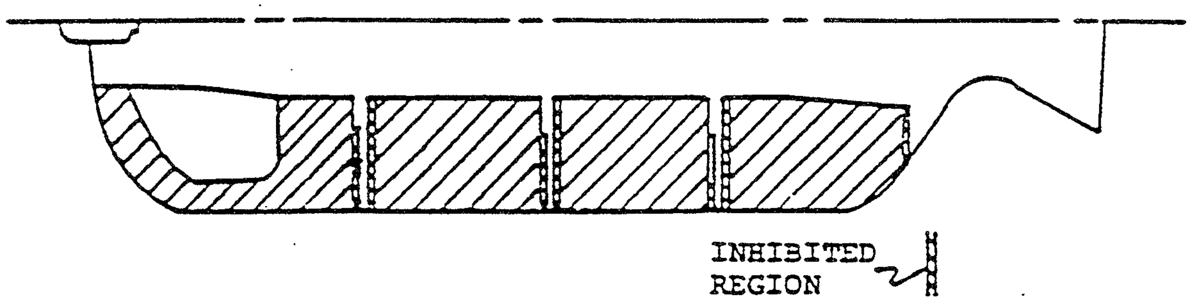
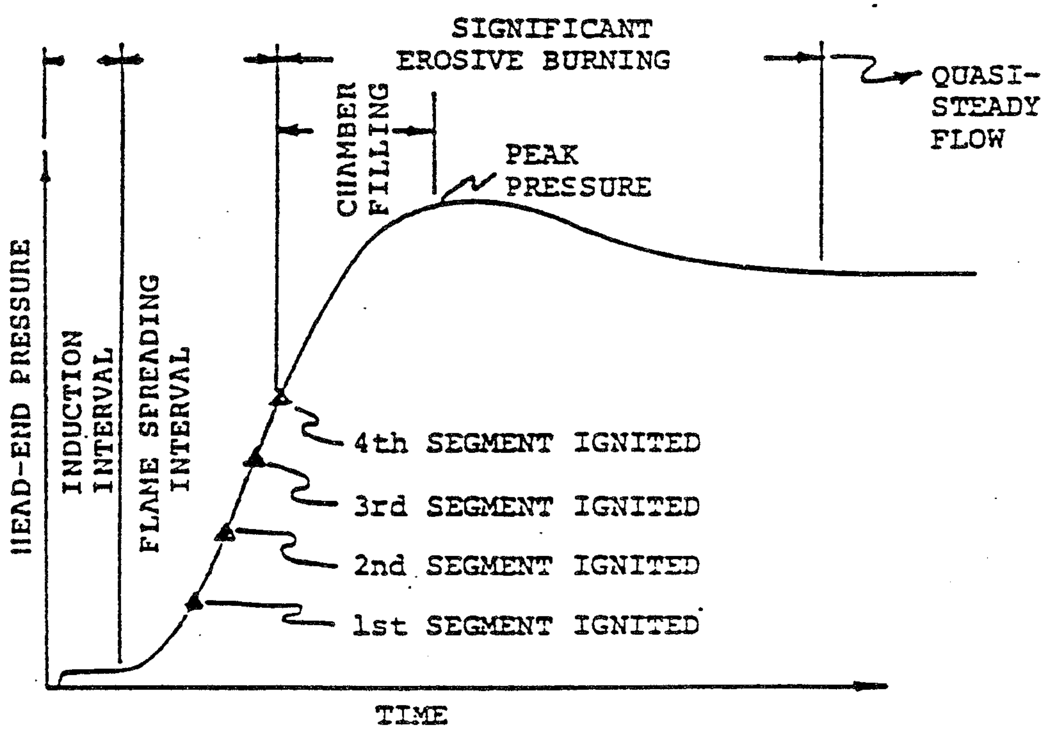


Fig. 2.1. Schematic Diagram of Analytical Model

I7712B Interim Report to Thiokol, Y.C. Lu & K.K. Kuo



(a) Segmented rocket motor configuration



(b) Significant ignition intervals.

Fig. 2.5. Type of Segmented Rocket Motor and Time Intervals During Ignition Transient

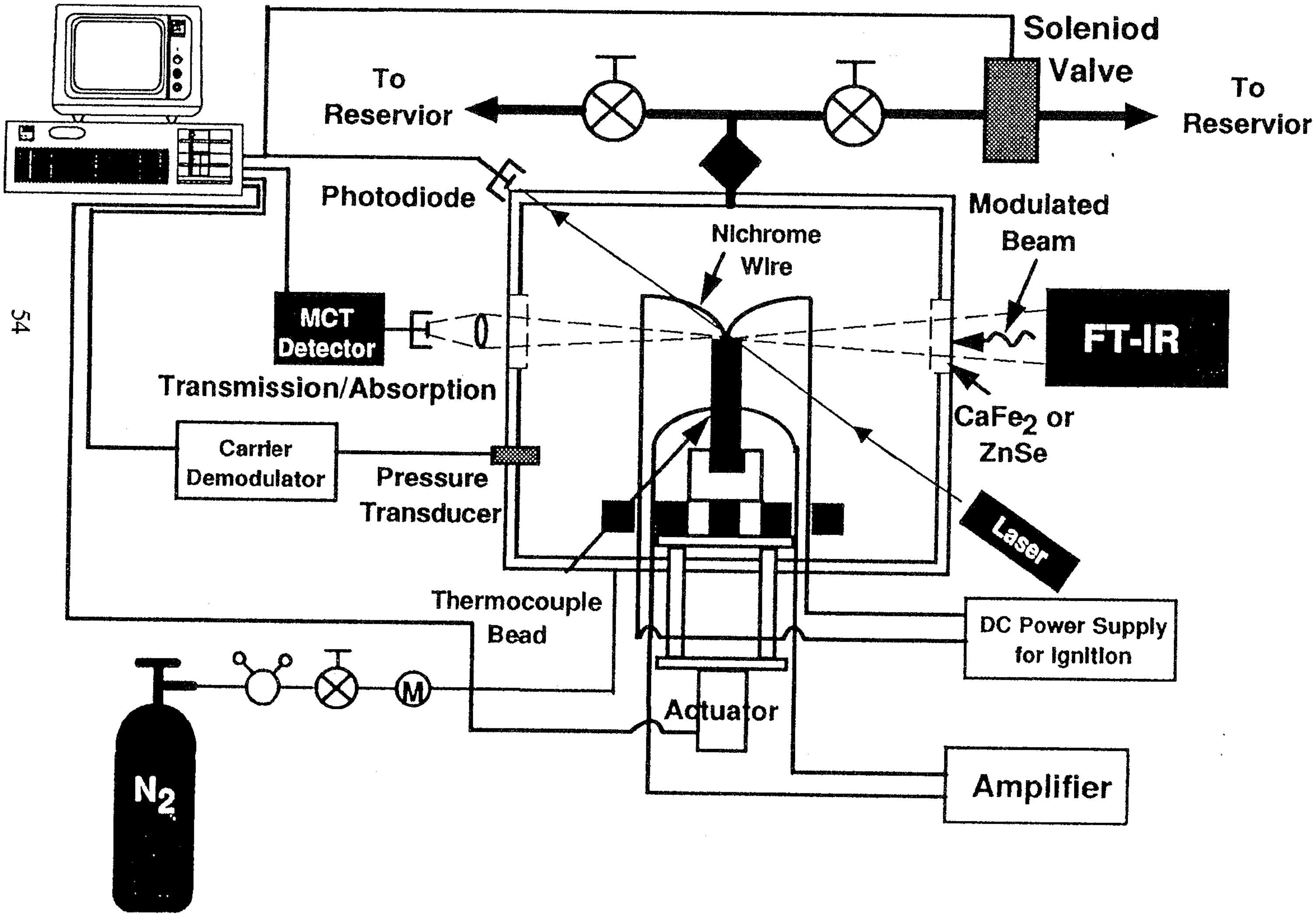
Different Modes of Combustion

- Transient Burning
  - Thermal Pyrolysis and slow cookoff
  - Ignition
  - Flame Spreading
  - Oscillatory Burning
  - Burning under large magnitude pressure excursion
  - Deflagration-to-Detonation Transition (DDT, SDT, XDT)
  - Explosion (Thermal vs. Chain-Branched)
  - Extinction
- Steady-State Burning
  - Deflagration
  - Detonation

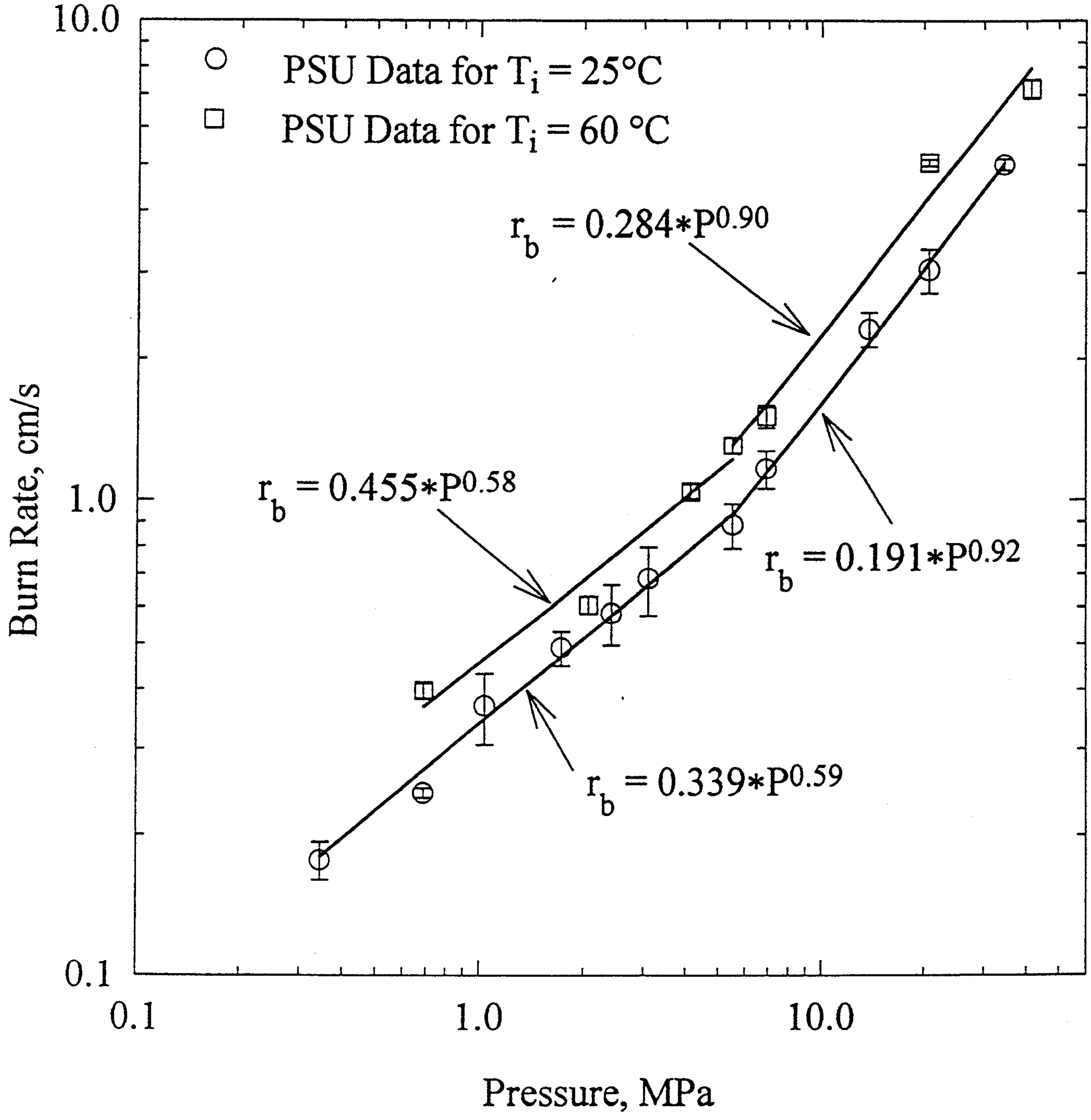
Propellant Studies in High Pressure Chamber Using FT-IR

Pennsylvania State University

High Pressure Combustion Laboratory



JA2 Strand Burning Rates



APPLICABLE EQUATIONS

A one-dimensional steady-state energy balance equation can be written:

$$\frac{d}{dx}(k\frac{dT}{dx}) - \rho_p \cdot r_b \cdot C_c \frac{dT}{dx} + \rho_p \cdot \dot{q}_{sub} = 0 \qquad (1)$$

If the thermal properties are assumed to be constant, the energy balance equation can be integrated with the following boundary conditions:

$$\begin{array}{ll} x = 0 & T = T_s \\ x = -\infty & T = T_o \end{array} \qquad (2)$$

to yield the following equation:

$$\frac{T - T_o}{T_s - T_o} = \exp(\frac{r_b \cdot \rho_p \cdot C_c \cdot x}{k}) \qquad (3)$$

where $-\infty < x \leq 0$.

EQUATIONS (cont)

The definition of the thermal diffusivity of the propellant:

$$\alpha_P = \frac{k}{\rho_p \cdot C_c} \tag{4}$$

can be used to determine k, if Cc is assumed to be constant.

Definition of the thermal wave depth:

$$\delta_{th} = -\frac{\alpha_p}{r_b} \cdot \ln(\frac{T - T_o}{T_s - T_o}) \tag{5}$$

δth is usually defined to be where the temperature ratio is equal to 0.01. Therefore, the equation for the thermal wave depth:

$$\delta_{th} = \frac{\alpha_p}{r_b} \cdot \ln(10^2) \tag{6}$$

The definition of the characteristic time of the propellant:

$$\tau = \frac{\alpha_p}{r_b^2} \tag{7}$$

EQUATIONS (cont)

The sensitivity of JA2 propellant to changes in initial temperature can be deduced from the equation:

$$\sigma_p = \frac{1}{r_b}\left[\frac{\partial \cdot r_b}{\partial \cdot T_{\cancel{ref}\, i}}\right]_p = \left[\frac{\ln(r_b) - \ln(r_{b,ref})}{T_i - T_{ref}}\right]_p \qquad (8)$$

The pyrolysis law may be expressed in the form of a mass-burning rate:

$$m_b = \rho_p \cdot r_b = \rho_p \cdot A \cdot \exp\left(\frac{-E_a}{2 \cdot R_u \cdot T_s}\right) \qquad (9)$$

when Ts becomes large, m will approach a maximum value:

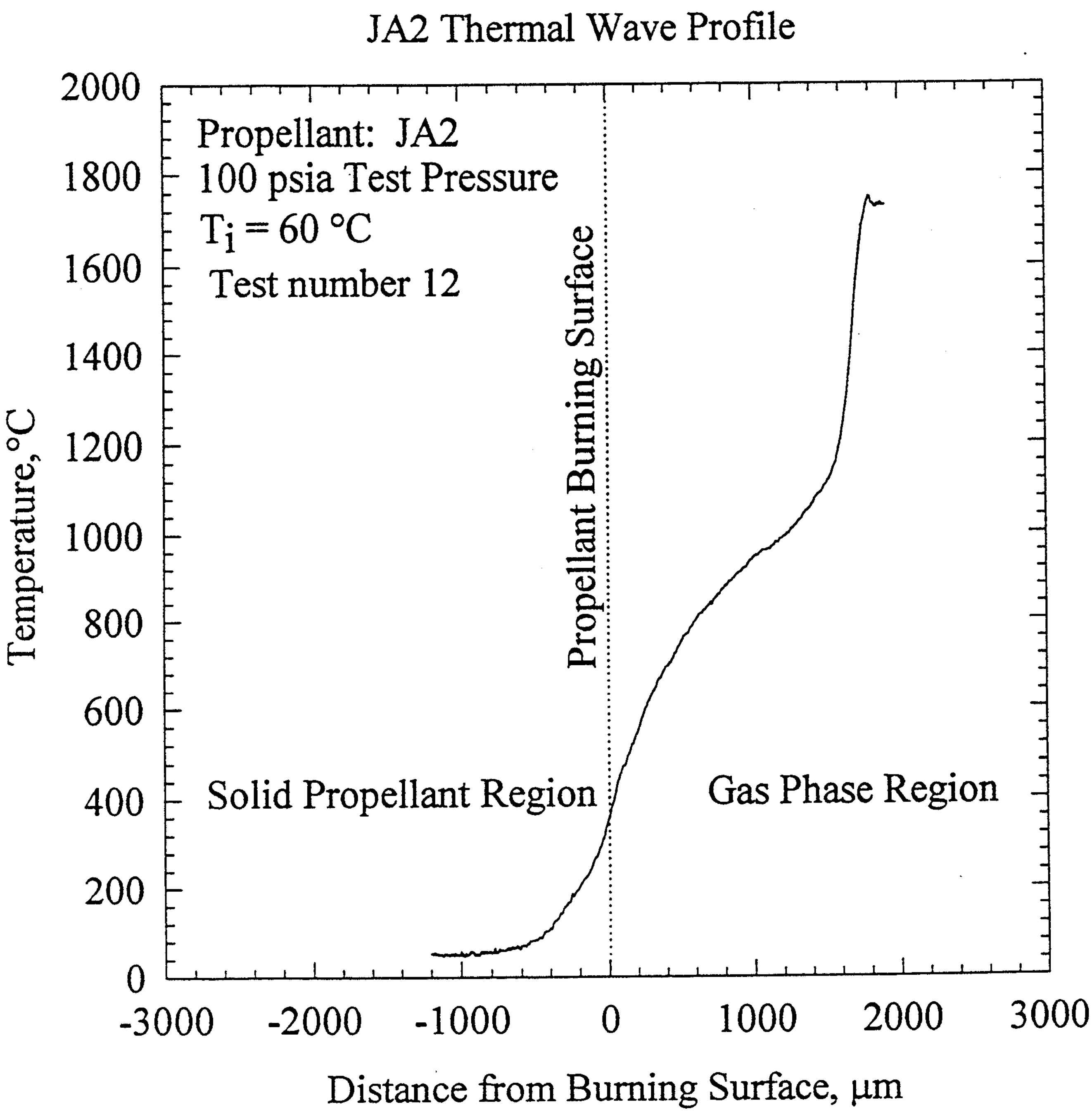
$$m_{b,max} = 1.8 \cdot 10^3 \ {}^{gm}\!/_{cm^2 \cdot sec} \qquad (10)$$

Using the following ratio, the burning surface temperature can be estimated:

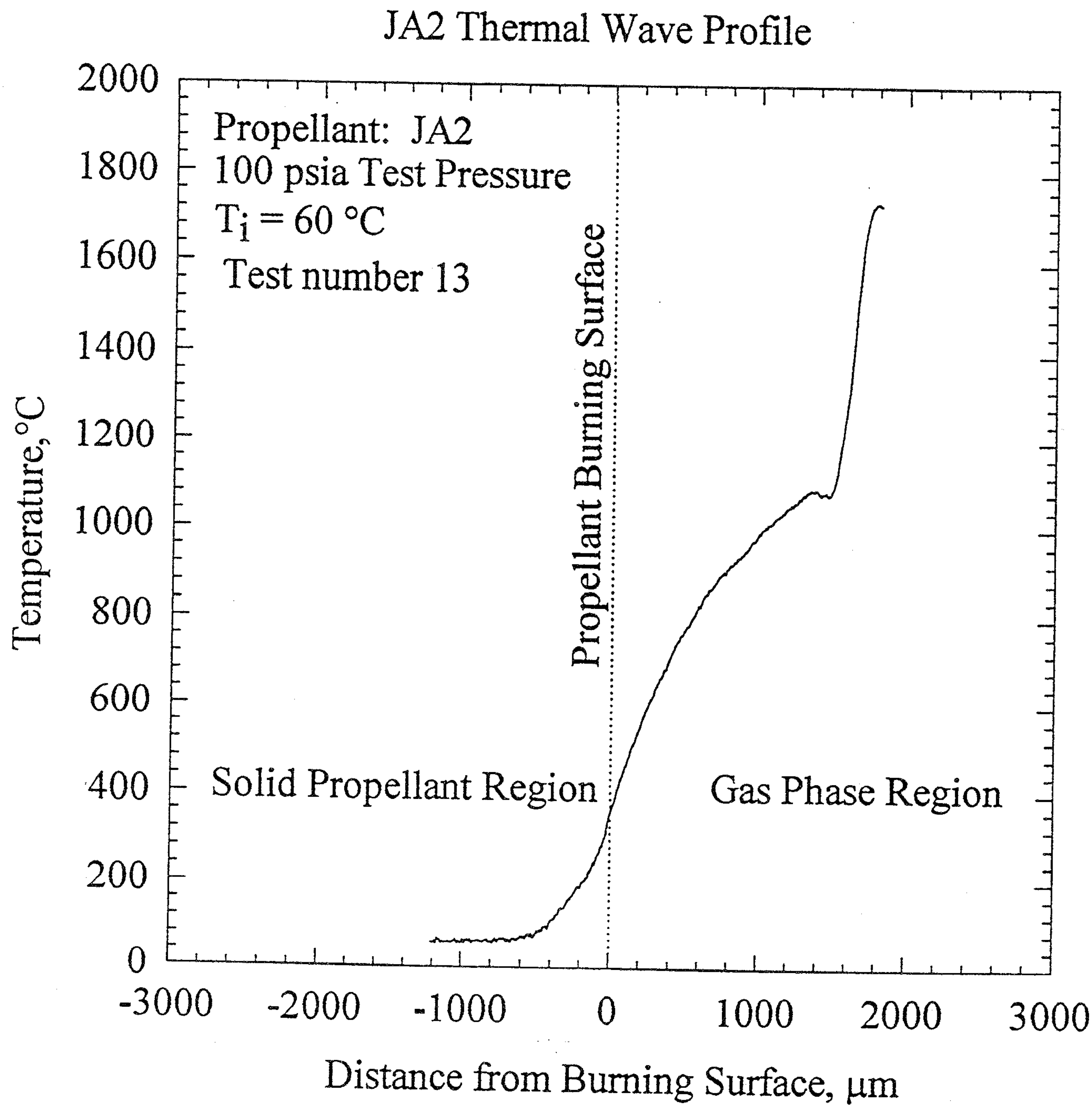
$$\frac{m_b}{m_{b.max}} = \exp\left(\frac{-E_a}{2 \cdot R_u \cdot T_s}\right) \qquad (11)$$

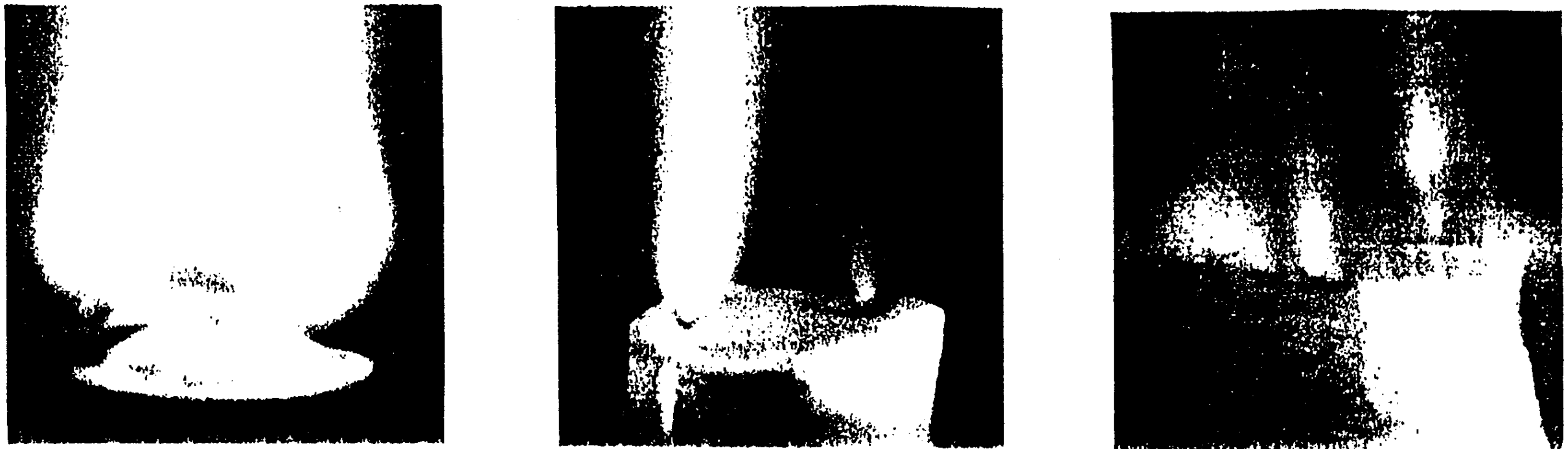
St. Robert's Law of combustion:

$$r_b = a \cdot p^n \qquad (12)$$



JA2 Thermal Wave Profile
Propellant: JA2
100 psia Test Pressure
$T_i = 60\ °C$
Test number 12
Propellant Burning Surface
Solid Propellant Region
Gas Phase Region
Temperature, °C
Distance from Burning Surface, µm
2000
1800
1600
1400
1200
1000
800
600
400
200
0
-3000
-2000
-1000
0
1000
2000
3000


JA2 Thermal Wave Profile
Propellant: JA2
100 psia Test Pressure
$T_i = 60$ °C
Test number 13
Propellant Burning Surface
Solid Propellant Region
Gas Phase Region
Temperature, °C
2000
1800
1600
1400
1200
1000
800
600
400
200
0
-3000
-2000
-1000
0
1000
2000
3000
Distance from Burning Surface, μm



(a) thick foam layer at 0.17 MPa (10 psig)

(b) attached flames to carbonaceous patches at 0.51 MPa (60 psig)

(c) multiple attached flames at 2.23 MPa (310 psig)

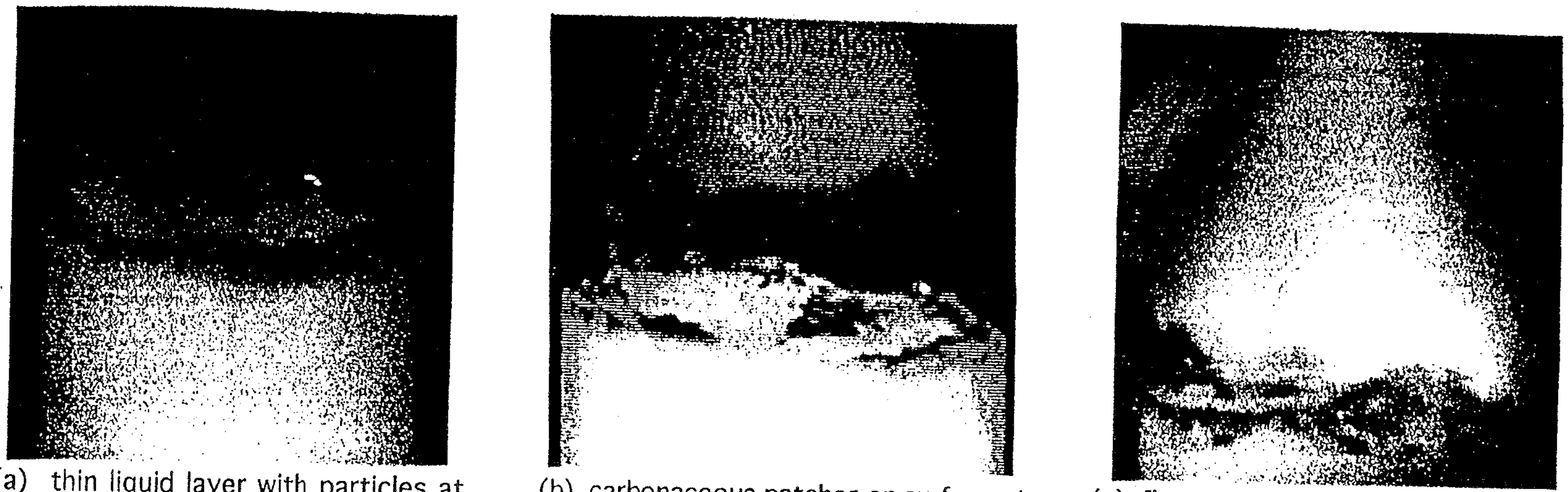
Fig. 2. Burning surface of RDX samples of 0.25 in. diameter

(a) particles in surface liquid layer at 0.65 MPa (80 psig)

(b) flame attached to agglomerates at 1.23 MPa (165 psig)

(c) many points of attachment at 2.16 MPa (300 psig)

Fig. 3. Burning surface of M43 samples of 0.25 in. diameter



(a) thin liquid layer with particles at 1.13 MPa (150 psig)

(b) carbonaceous patches on surface at 2.44 MPa (340 psig)

(c) flame attachment to surface at 3.55 MPa (500 psig)

Fig. 4. Burning surface of XM39 samples of 0.25 in. diameter

(a) glowing flakes with no visible flame at 0.38 MPa (40 psig)

(b) flame attached to flakes at 1.48 MPa (200 psig)

(c) nearly uniform flame attachment at 3.55 MPa (500 psig)

Fig. 5. Burning surface of JA-2 samples of 0.25 in. diameter

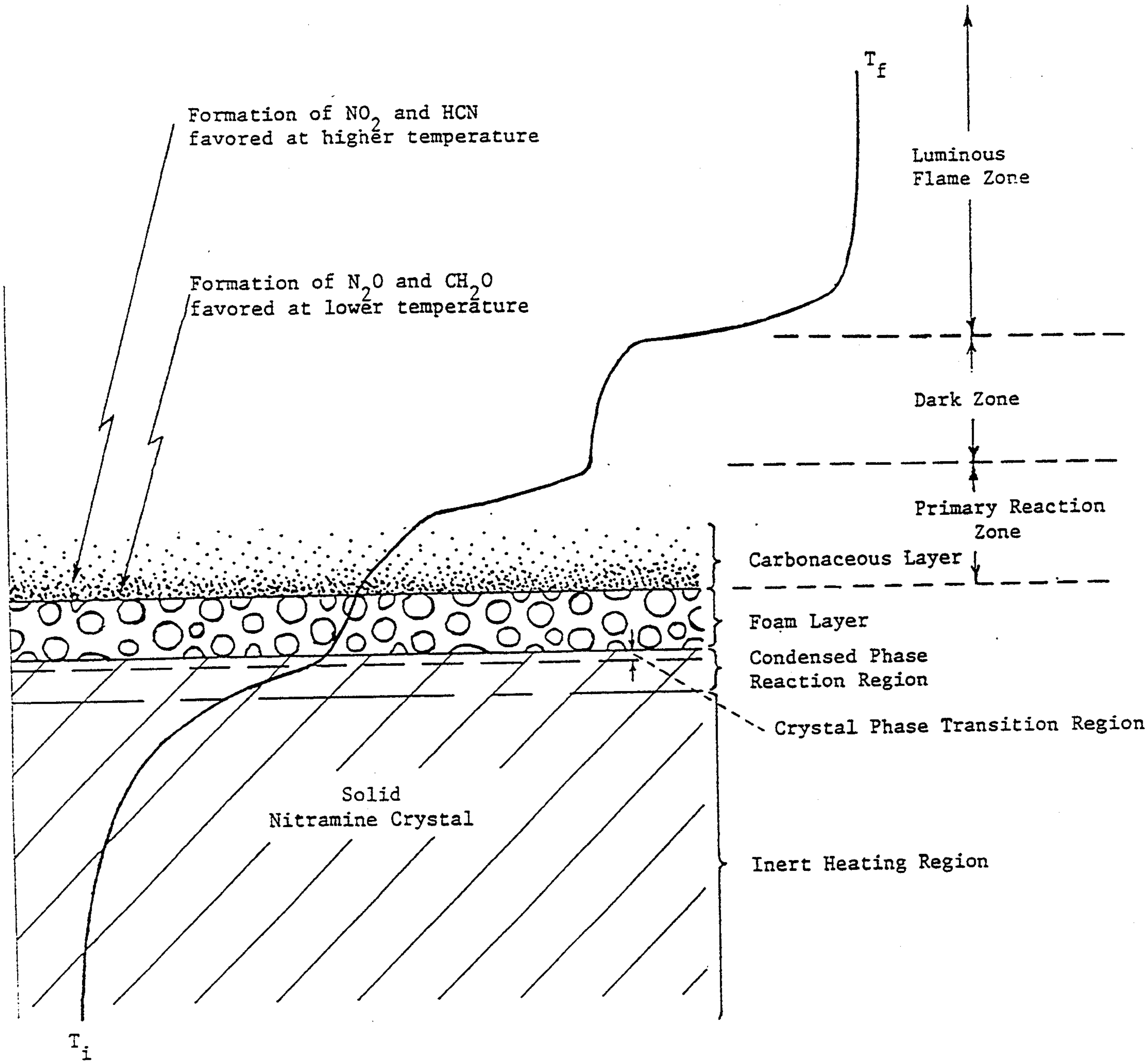
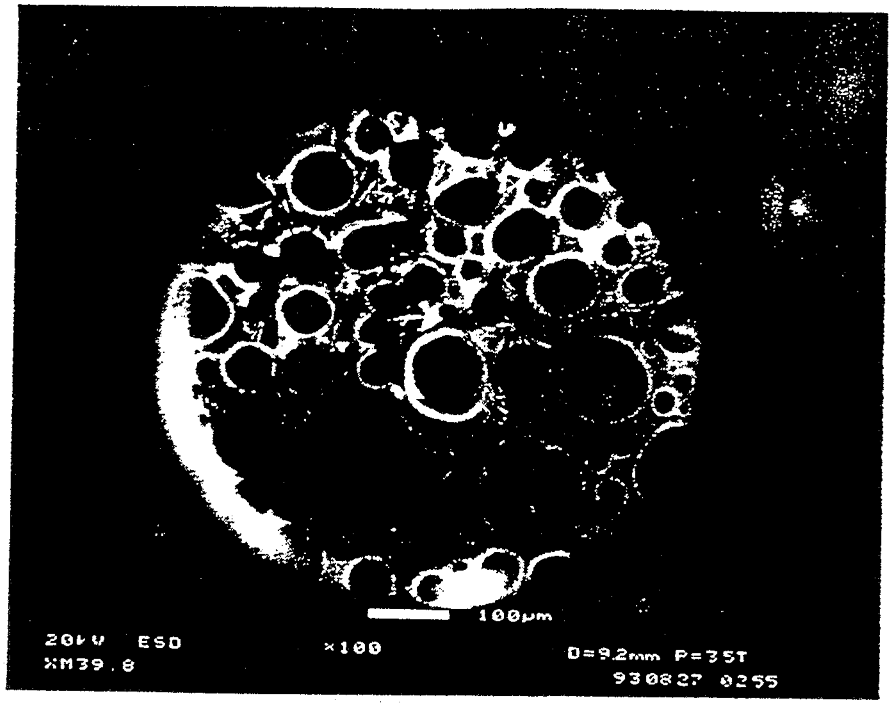
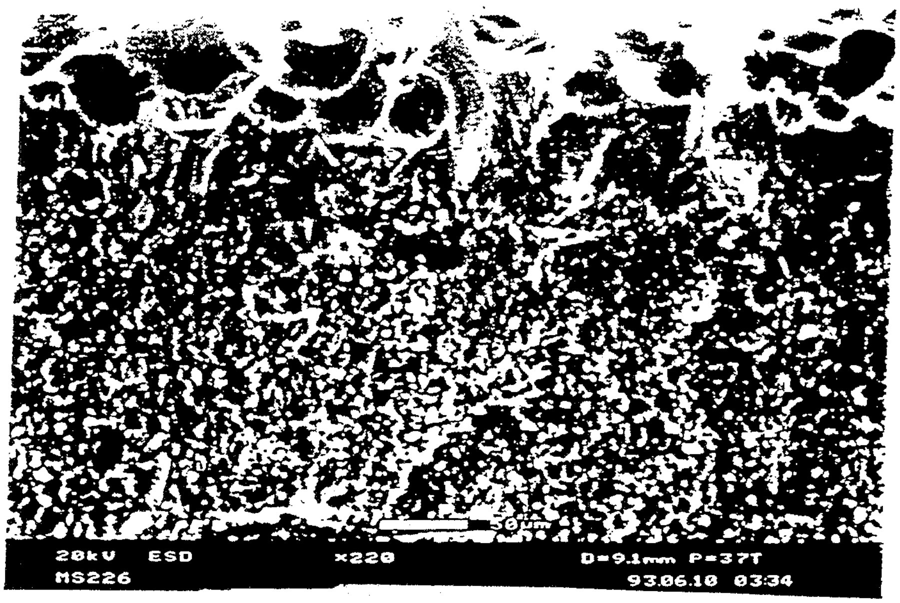


Fig. 1 A Schematic Diagram Showing Various Flame Zones and Condensed Phase Reaction Regions as well as a Typical Temperature Profile.



a



b

Figure 1: Typical micrographs for a) surface bubble analysis (XM39 at 1 atm and 300 W/cm^2) and b) melt layer thickness determination (XM39 at 3 atm and 100 W/cm^2).

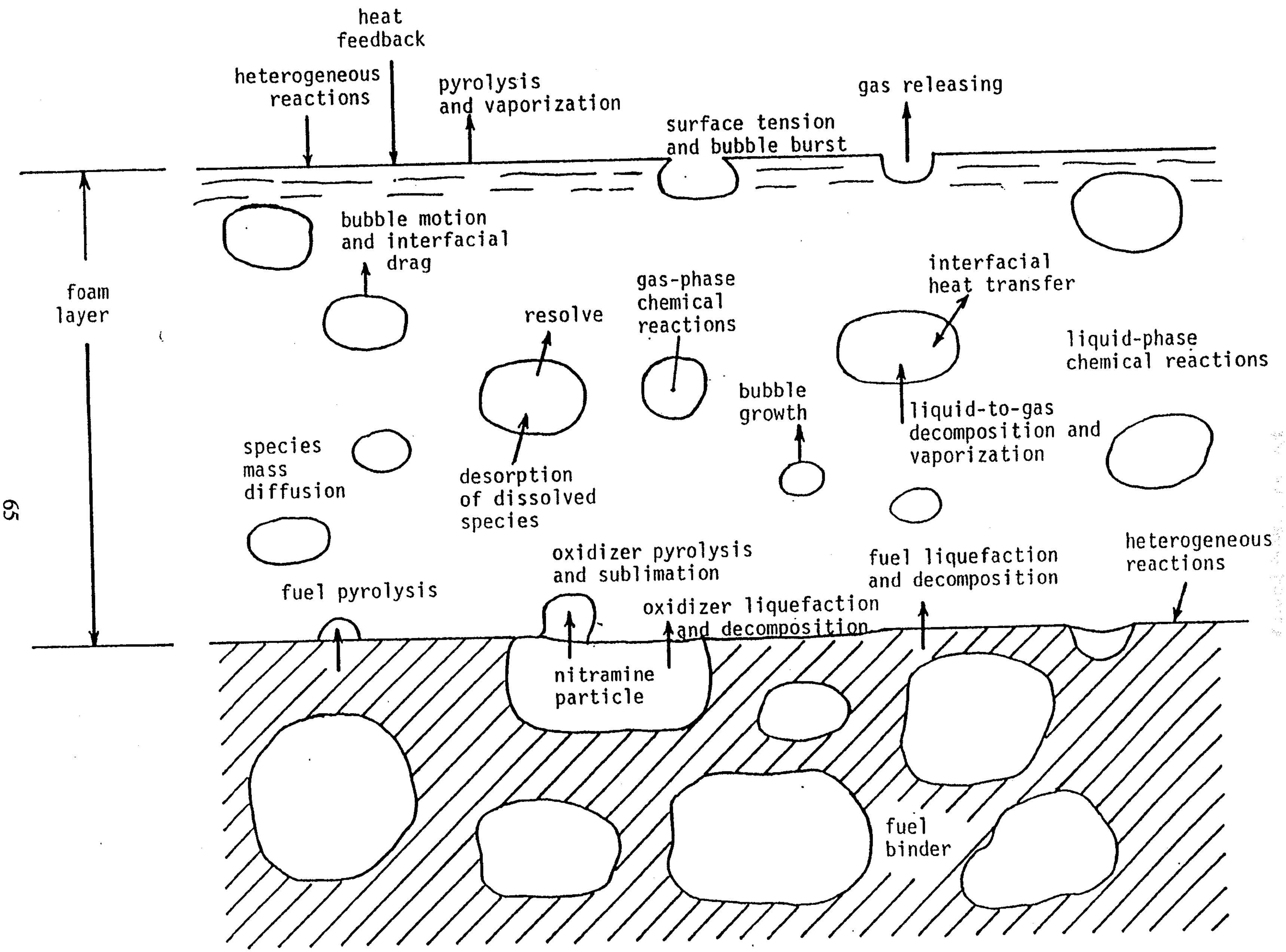
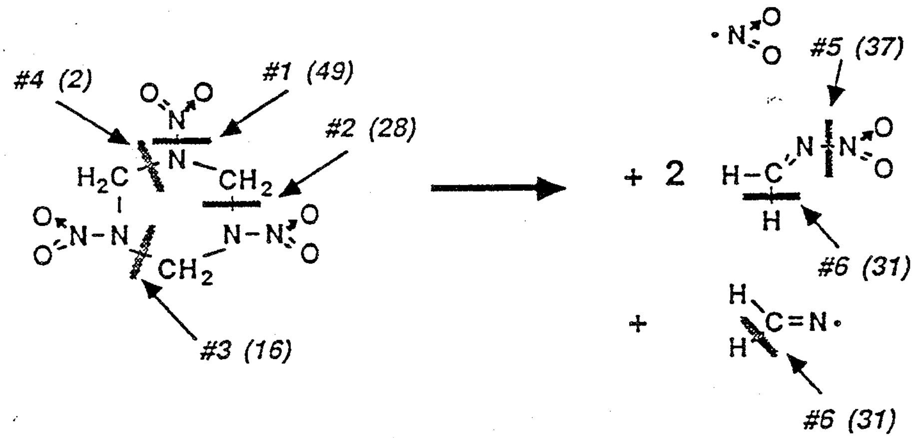


Fig. 2 A Schematic Diagram Showing the Physicochemical Processes in the Foam Layer of a Nitramine-Based Solid Propellant.

Decomposition of RDX (C.Melius,1990)

At Fast Heating Rates



#n (ΔE) : Position, Order, and Energy of Chain Bond Breaking (Energy in kcal/mole)

Figure 10. Decomposition mechanism for RDX under rapid heating rates. The number indicates the order in which the bonds are broken. The bond breaking energies (in kcal-mol^{-1}) are given in parentheses. The final products are HCN, NO_2, and H.

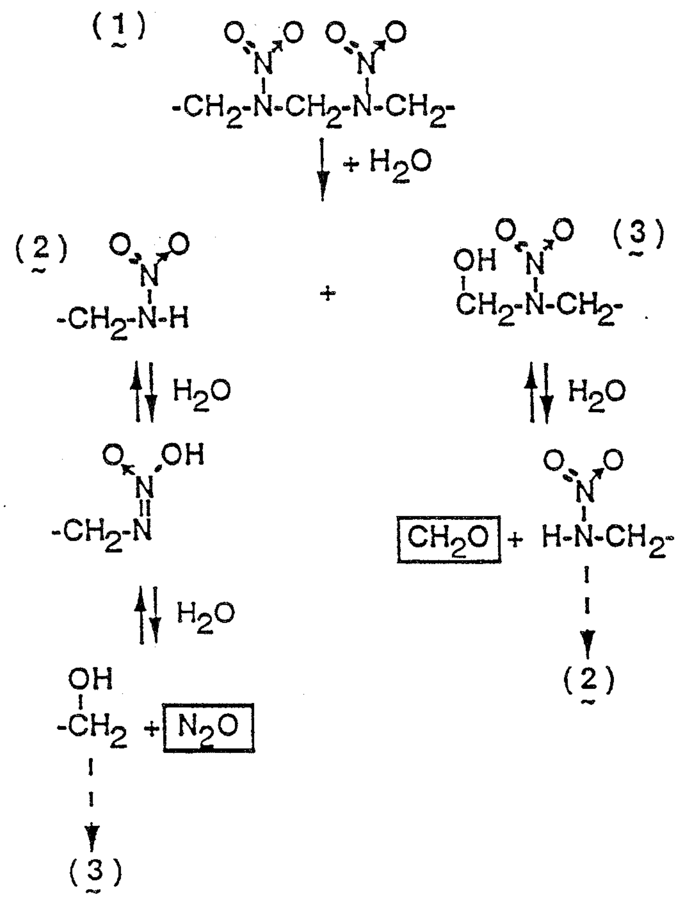


Figure 11. The water-catalyzed decomposition pathway for nitramines containing the -(-$CH_2N(NO_2)$-)- subgroup. The initial step is the hydrolysis of the C-N bond in (1) to form the primary nitramine (2) and the hydroxymethyl species (3). The primary nitramine undergoes further decomposition to form N_2O and the hydroxymethyl species (3), which undergoes further decomposition to form CH_2O and the primary nitramine (2)

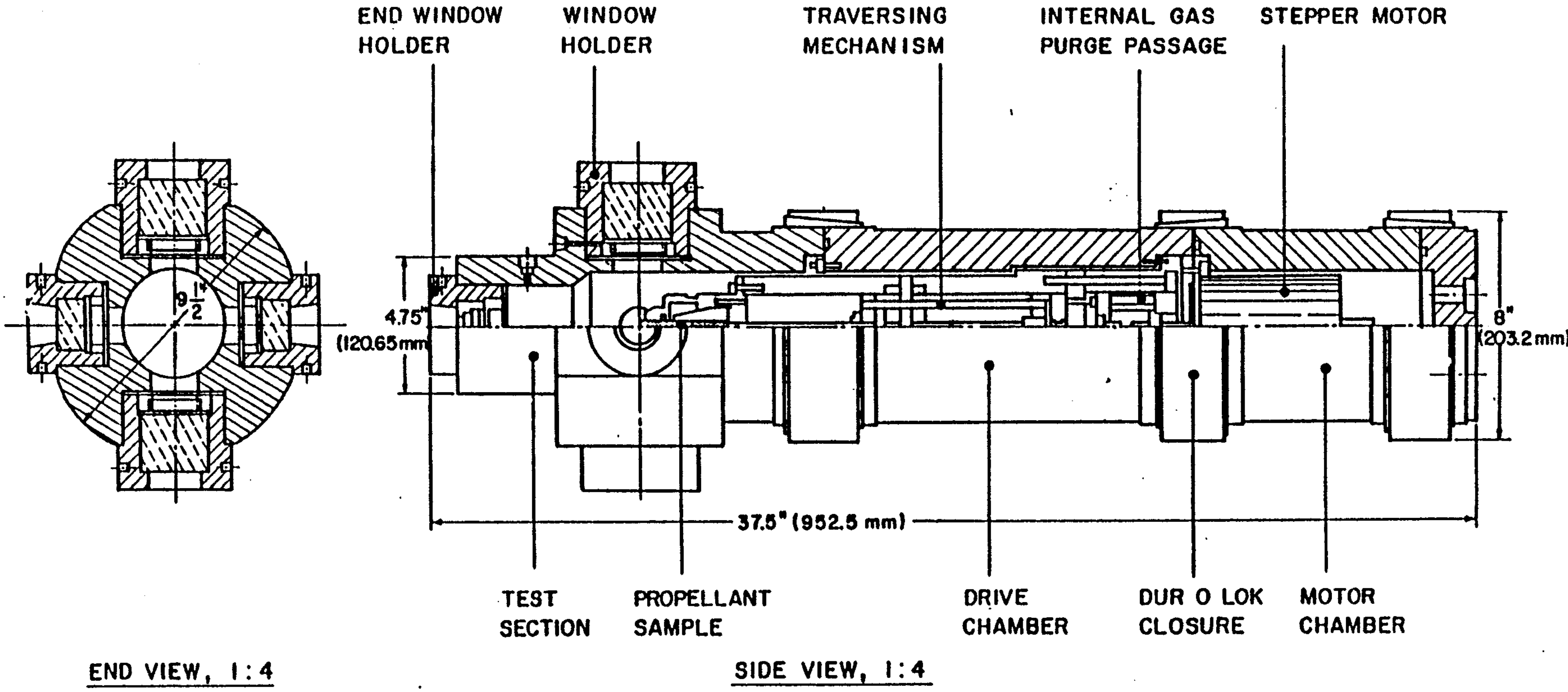


Fig. 1 Schematic Diagram of Single-ended Windowed Strand Burner

Desirable Features of Energetic Materials

- Deliver high specific impulse and high impetus
- Generate low molecular weight combustion product gases
- Being environmental compatible
  - Reduced emission levels of NO_x, SO_x, CO and other undesirable gases
  - Reduced particulates
- Have long term storage capability
- Possess low vulnerability characteristic
  - Thermally stable
  - Reduced ESD hazards
  - Reduced impact sensitivity

Desirable Features of Energetic Materials (cont'd)

- High Reproducibility in Burning Characteristics
- Good Mechanical Properties
  - High dewetting stress
  - High fracture toughness
  - Low glass transition temperature
- Easy for Processing and Manufacturing
- Low Cost

Scientific Challenges in Combustion of Solid Propellant (SP)

- **Extremely thin reaction zones [~O(100 μm)]**

- **Regression rate depends upon the rate of heat release in the thin surface reaction zone and the heat feedback from adjacent gaseous flame(s).**

- **Surface reaction zone can not be characterized easily due to the complicated condensed phase structure:**
  - **Foam layer with numerous physical and chemical processes**
  - **Heterogeneous surface conditions**
  - **Deposition and expulsion of carbonaceous residues**
  - **Intermittent flame attachment to burning surface**
  - **Uncertainty in nucleation rate and initial bubble size distribution**

- **Liquefaction process at the liquid/solid interface is a strong function of propellant formulation.**

- **Thermal and transport properties of propellant ingredients and their intermediate products are difficult to characterize.**

Scientific Challenges in Combustion of Solid Propellant (SP) (cont'd)

- **Transient burning rate (r_b) of SP could differ significantly from steady-state r_b. Usually the parameters** (e.g., σ_p, $\partial T_s/\partial T_i|_p$) **required to determine the transient r_b are not easily obtainable.**

- **Harsh environments for combustion diagnostics**
  - **High temperature and pressure**
  - **Multi-phase behavior of the reaction zone**
  - **Condensed phase decomposition and reaction**

- **Multiple reaction pathways**

- **Multiple ignition mechanisms (laser induced, conductive, shock wave induced, ESD, impact, friction, etc)**

- **Go/No Go ignition boundary of SP can vary significantly with the operating condition (such as degree of confinement).**

- **Complicated interactions between mechanical deformation and combustion processes**

Various Non-Intrusive Combustion Diagnostics Techniques

- Laser-Induced Flourescence (LIF and PLIF) Techniques
- Coherent and Spontaneous Raman Spectroscopies
  - CARS
  - Degenerate Four-Wave Mixing (DFWM)
- Absorption and Emission Spectroscopies
  - FT-IR Spectroscopies
  - UV/Visible Spectroscopies
- Holographic and Microwave Interferometries
- Particle Diagnostics (PDPA, Laser Sheet Illumination, etc.)
- X-Ray Diagnostics and Image Analyses
- Flow Field Measurements and Visualization
  - LDV
  - Particle Image Displacement Velocimetry
  - Michelson Spectrometer
- Regression Rate Measurement Techniques

Suggested Approach for State-Of-The-Art Advancements

- Utilization of Advanced Diagnostic Techniques for Detailed Measurements
- Application of High-Speed Computational Facility for Simulation of Various Combustion Processes
- Encouragement of Interdisciplinary Approach and Strong Interactions Between Constituent Disciplines, Including:

- Chemistry	- Material Sciences
- Physics	- Instrumentation
- Thermodynamics	- Mathematics
- Fluid Mechanics	- Numerical Methods
- Heat and Mass Transfer	- Mechanical Design
- Turbulence	- Ballistics

Necessary Elements for Progress

No Advancements Can Be Achieved Without

- Research Funding $??
- Long-Term Strategic Planning and Programs
- Continued Support of Specialized Personnel in this Area
- Cultivation of New Generation of Engineers and Scientists with Continued Stimulation

Fire Extinguishing Pyrotechnics

Jim Hoover, Russ Reed
Combustion/Detonation Research Section

Vicki Brady, John Hitner
Airframe, Ordnance and Propulsion Division

Leo Budd, Mike Gray, Marty Krammer, Hardy Tyson
Weapons Survivability Laboratory

Naval Air Warfare Center Weapons Division
China Lake

Unclassified

NAVAL AVIATION SYSTEMS TEAM

Goal and Objective

NAWC Weapons Division NAVAL AIR WARFARE CENTER

- Goal from the Next Generation Plan (NGP):

> " The program goal is to develop and demonstrate, by 2004, environmentally-friendly, user-safe processes, techniques and fluids that meet the operational requirements currently satisfied by halon 1301 systems in aircraft, ships, land combat vehicles, and critical command and control facilities."

- Objective for China Lake Gas Generator Efforts:

> Develop and demonstrate active, chemical and chemical precursor flame suppressing gas generators (FSGG) that comply with the NGP goal.

NAVAL AVIATION SYSTEMS TEAM

Fire Science &Technology Panel FY95 Participants

NAWC Weapons Division NAVAL AIR WARFARE CENTER

Joe Benavides, NAWCWPNS Albuquerque	A28N103
Prof. Matt Kelleher, Naval Postgraduate School	Me/KK
Leo Budd and Hardy Tyson	418300D
Wayne Doucette and Gill Cornell	473A00D
Dr. Warren Jaul, Brenda Allen and Rodney Harris	473110D
Vicki Brady	473410D
Dr. Kelvin Higa, Dr. Rich Hollins and Dr. Curt Johnson	474220D
Thom Boggs	474300D
Dr. Jim Hoover and Dr. Russ Reed	474310D
Les Bowman and Dr. M.J. Lee	474320D
Dr. Jo Covino, Dr. Ilzoo Lee and Ross Heimdahl	474330D
Jay McClellan	528400D
Ross Davidson, Dick Rivers and Wil Simoneau	824220D

NAVAL AVIATION SYSTEMS TEAM

Fire Science &Technology Panel FY95 Accomplishments

NAWC Weapons Division NAVAL AIR WARFARE CENTER

- Coordinated local review of DDR&E proposal drafts "Next Generation Fire Suppression Technology" ($48M/8 years)
- Conducted China Lake Fire S&T Workshop and established working group to promote Fire S&T work within NAWCWPNS
- Sponsored Fire S&T marketing brochure and electronic media describing China Lake RDT&E capabilities and expertise
- Conducted Navy-wide Fire S&T Workshop (14 &15 Mar 95 at NASNI) attended by NAVAIR, NAVSEA, ONR, NRL, NAWCAD (Lakehurst and Warminster), NAWCWPNS, NPG and Federal Fire Dept.
- Obtained NAVSEA sponsorship for Shipboard Magazine Fire Protection Program ($2.5M over 5 years) and JTCG sponsorship for Pyrotechnic Fire Extinguisher R&D.
- Developed networked teams (Industrial/Academic/Gov't labs) for pursuing major outside sponsorship (i.e., SERDP) and in-house discretionary projects
- Participated in international Fire S&T meeting and NIST Workshop

NAVAL AVIATION SYSTEMS TEAM

Gas Generator Formulation Work History at China Lake

NAWC Weapons Division NAVAL AIR WARFARE CENTER

1979 High Nitrogen Binder (GAP) Work (Funded by ARC)

Goal: No Ammonium Nitrate (AN)

Significance: High nitrogen binders attractive for gas generators

1980s High Nitrogen Binder Work (Funded by ONR/ONT)

79 Collaboration with Thiokol (Dr. Manser), later with Aerojet

Goal: Alternative high nitrogen compounds - no AN

Approach: demonstrate azidooxetanes as good as PEG E-4500 (Dow), tetrazoles and GAP

1979-1982 NAVAIR Gas Generator Technology

Amoco MK-6 (N-28 comp.), AN/PE binder, 2000-2200°F, 0.06"/s

Goal: 1500°F, 1"/s, noncorrosive, no particulates

Approach: High nitrogen compounds yield less H_2O, CO, CO_2; new deflagration mechanism for azides and tetrazoles, driving force is high ΔH_f

NAVAL AVIATION SYSTEMS TEAM

Gas Generator Formulation Work History at China Lake

NAWC Weapons Division NAVAL AIR WARFARE CENTER

1983-1985 NAVSEA Submarine Deballasting Gas Generators

Goal: High N_2 (inert), noncondensable gases, tailorable sustained higher burn rate than AN (>0.5″/s)

Approach: High nitrogen compounds with high nitrogen binders (i.e., hydroxyethyltetrazoles)

1987 Patent on Pyrotechnic Fire Extinguisher (PFE) Compositions

1992 Flame Suppressing Gas Generator (FSGG)

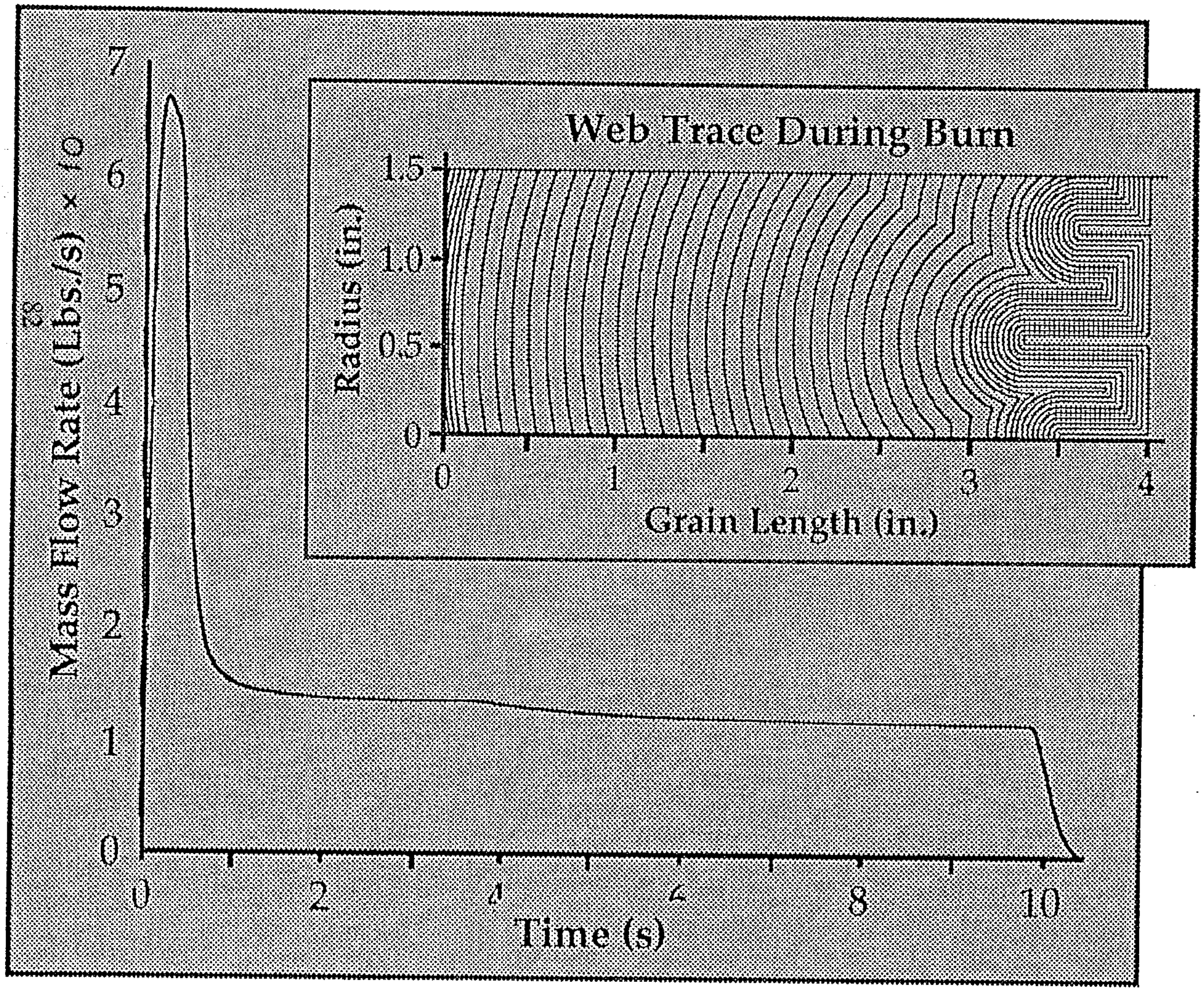
NAVAL AVIATION SYSTEMS TEAM

Gas Generator Comparison

NAWC Weapons Division NAVAL AIR WARFARE CENTER

	FSGG	Double Base	Am. Nit.	Olin
Composition	azides/prec.	NC/plast.	AN/rubber	propr.
Products	>N_2/chem.	$N_2/CO/CO_2$ H_2O/C	$N_2/CO/CO_2$ H_2O	N_2... (~50%)
Rel. Temp.	cool	hot	hot	hot
Deflagration	flameless	flame	flame	flame
Rel. Rate	fast	slow	slow	fast
Gas Quality	clean	dirty (C)	clean	filtered
Application		starter	SM/APU	Air Bags

FSGG-02 Propellant Concept and Calculated Burn Rate



Initial Concept

1.5 Lb_m propellant

Density:
0.0542 $Lb_m/in.^3$

CStar: 4000 ft./s

Burning Rate:
0.50 in./s @ 1000 psia

Slope: 0.50

NAVAL AVIATION SYSTEMS TEAM

Gas Generator T&E History at China Lake

NAWC Weapons Division NAVAL AIR WARFARE CENTER

Weapons Survivability Laboratory Facilities

Test Equipment / Instrumentation / Ballistic Threats
Test Sites / Fabrication Capabilities

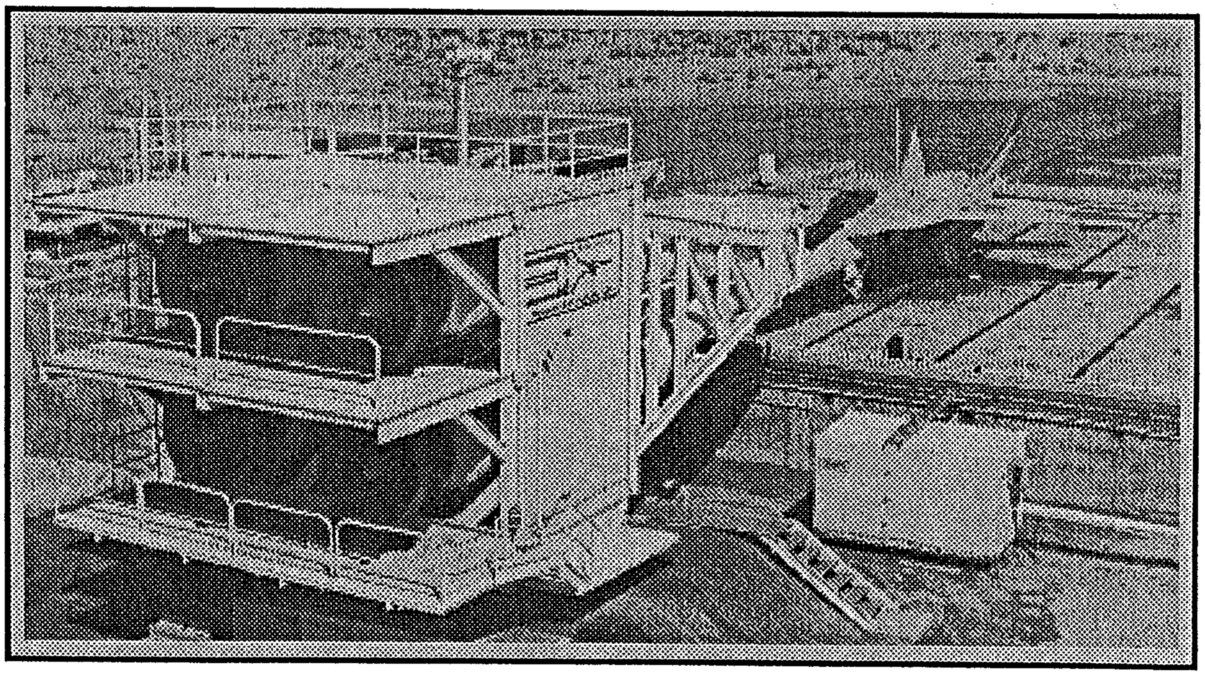
High Velocity Airflow System (HIVAS)

83

Airflow Source:
Bypass airflow ducted from 4 TF-33 P11 engines

Velocity Ranges:
160-550 knots over 18 ft.^{2}
100-300 knots over 35 ft.^{2}
40-120 knots over 110 ft.^{2}

Rotatability: 360° to cover 6 test pads



Gas Generator T&E History at China Lake

Testing Program:
F/A-18 Dry Bay Simulator

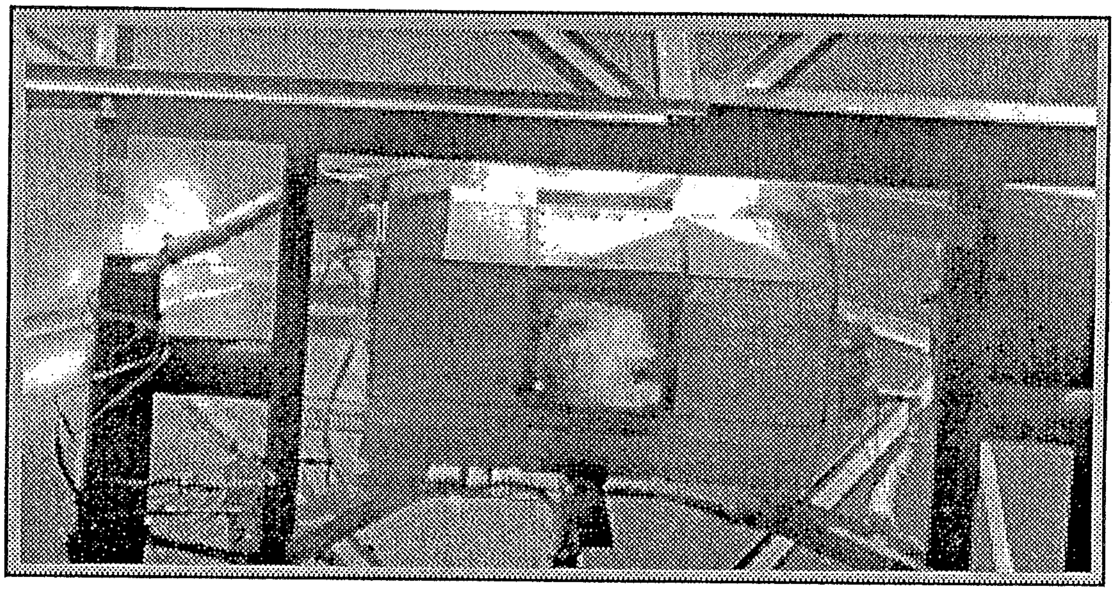
Dates: April - June 1993

Program Sponsor(s):
Navy, F/A-18

Technical Support:
Northrop,
McDonnell-Douglas,
Olin

Significance:
First demonstration of gas generator (Olin) effectiveness in real-scale scenario sim.

Test Conditions:
Real-scale F/A-18 dry bay simulator with fuel cell and clutter, HIVAS 450-500 knots,
Halon 1301 and FM-200 baselines,
Ballistic ignition (small arms, 12.7 - 30 mm),
Olin gas generator hardware



NAVAL AVIATION SYSTEMS TEAM

Gas Generator T&E History at China Lake

Testing Program:
V-22 Wing Dry Bay Simulator

Dates: Dec. - Jan. 1994

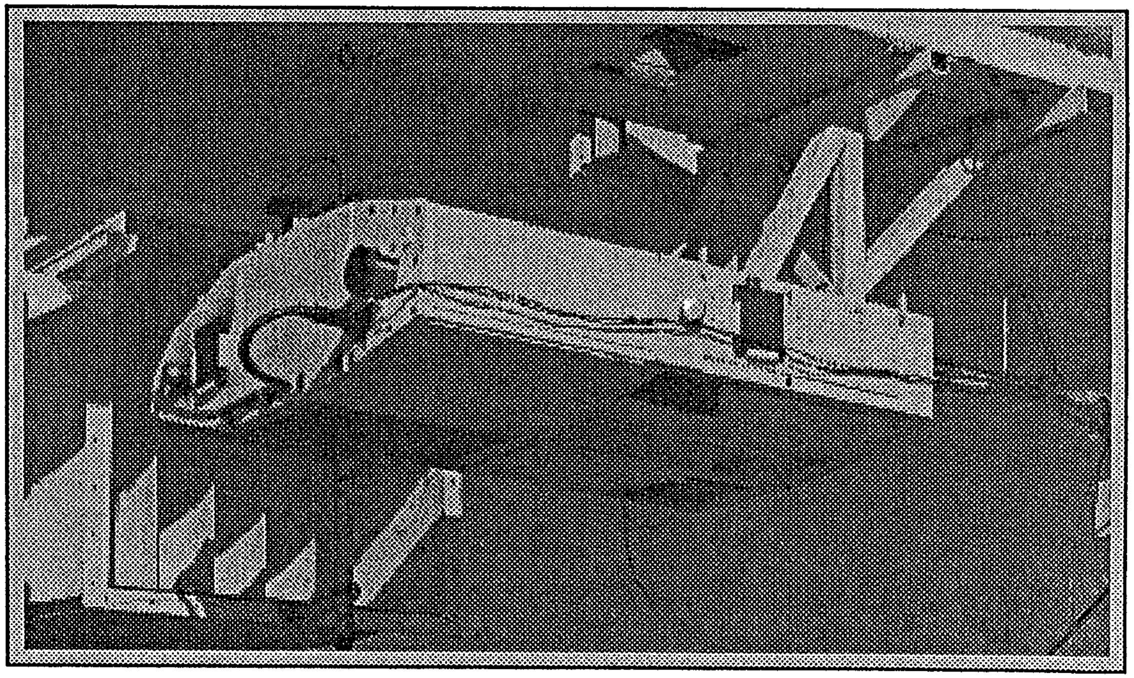
85

Program Sponsor(s):
Navy, V-22 (CDR Curtis)

Technical Support:
Bell-Boeing, Olin

Significance:
Active suppression needed and demonstration of gas generator (Olin) effectiveness in real-scale simul. scenario

Test Conditions:
Real-scale V-22 wing dry bay simulators (3) with fuel cell and clutter, HIVAS 250 knots, Halon 1301 and FM-200 (RFE) baselines, Ballistic ignition, Olin gas generator hardware



NAWC Weapons Division
NAVAL AIR WARFARE CENTER

Gas Generator T&E History at China Lake

NAVAL AVIATION SYSTEMS TEAM

NAWC Weapons Division NAVAL AIR WARFARE CENTER

Testing Program:
F/A-18 Engine Nacelle Simulator

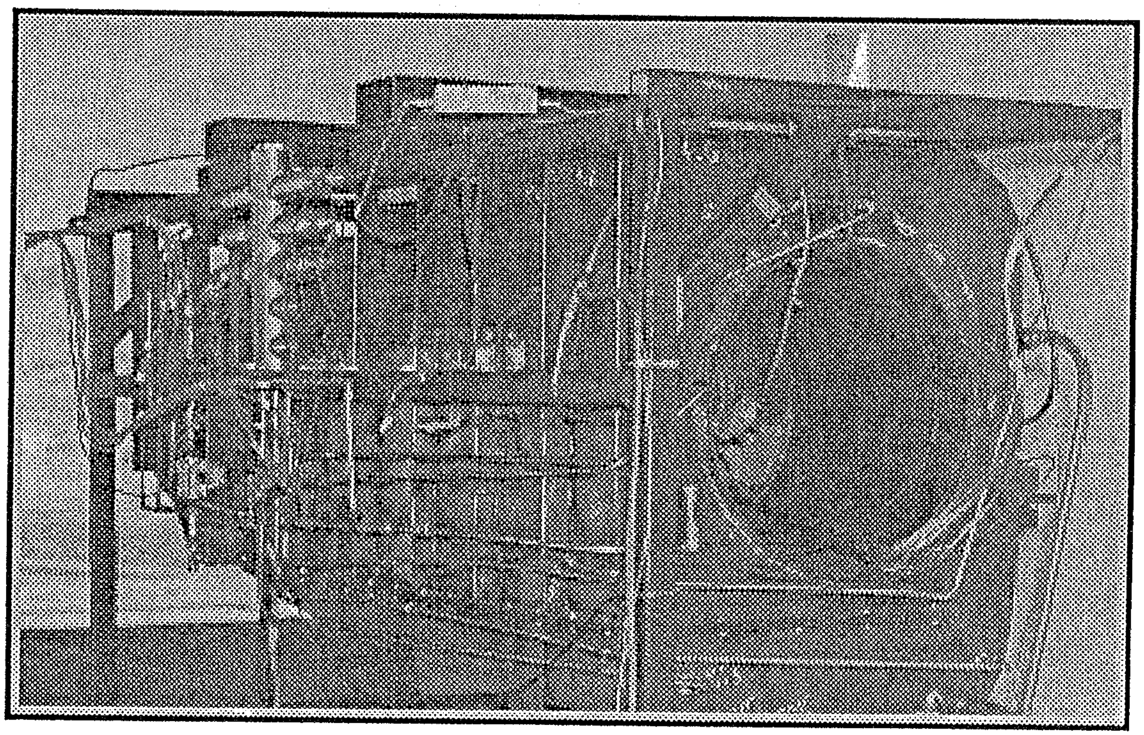
Dates: Aug. - Nov. 1994

Program Sponsor(s):
Navy, F/A-18
NAVAIR (Mr. Homan)

Technical Support:
Northrop, McDonnell-Douglas, Olin

Significance:
Demonstration of gas generator (Olin) effectiveness in real-scale scenario sim.

Test Conditions:
Real-scale F/A-18 engine nacelle simulator with clutter and air flow, Halon 1301 baseline, spark ignition and ballistic ignition wrap-up, Olin gas generator hardware (manifolded, unfiltered)



NAVAL AVIATION SYSTEMS TEAM

Future Gas Generator T&E at China Lake

NAWC Weapons Division NAVAL AIR WARFARE CENTER

- **F/A-18 E/F Fuselage Dry Bay Fire Suppression Test, FY95**
  Sponsor: Navy (CPT Dyer)
  Tech. Support: Northrop, McDonnell-Douglas, Olin
  - Real-scale E/F modified C/D model aircraft
  - Proof of concept for gas generators with ballistic ignition
  - Airflow (HIVAS) 450-500 knots

- **V-22 Midwing Gearbox Fire Suppression Test, FY96**
  Sponsor: Navy (CDR Curtis)
  Tech. Support: Bell-Boeing, Olin
  - Real-scale V-22 structure
  - Proof of concept for gas generators
  - Airflow (HIVAS) 250 knots

- **AV-8B Dry Bay and Aft Wheelwell Fire Suppression Test**

NAVAL AVIATION SYSTEMS TEAM

Fire Protection RDT&E
Future Efforts

NAWC Weapons Division NAVAL AIR WARFARE CENTER

Continue Support of NAVAIR and NAVSEA Programs through:

- Weapons Survivability Laboratory
- Fire Research Office (Les Bowman)
- Fire S&T Networks Panel (multi-competency)

Continue Team Building Efforts through S&T Networks to address:

- DDR&E's Next Generation Plan BAA (SERDP type proposal)
- Market ILIR discretionary support for "Superagents" research
- Market support for scale-up and loading of FSGG formulations
- Unclassified/unlimited dist. information services via Internet (WWW, etc.)

Rapid, Low-cost, Total Quality Response to DoD Needs

Modeling and Experimental Validation of Pyrotechnic Gas Generators

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NIST Gas Generator Workshop
Gaithersburg, MD

28 June, 1995

REFERENCES

Butler, P.B., Krier, H.K., Faigle, E.M., Semchema, J.H., and Thompson, R., "**Modeling Azide-Based Propellant Combustion in a Passenger-Side Automotive Airbag Inflator,**" The Combustion Institute Central States Meeting, April 26, 1992, Columbus, OH.

Butler, P.B., Kang, J., and Krier, H., "**Modeling Pyrotechnic Combustion in an Automotive Airbag Inflator,**" 5th International Congress of the Groupe de Travail de Pyrotechnie, June, 1993, France.

Butler, P.B., Kang, J., and Krier, H., "**Modeling and Numerical Simulation of the Internal Thermochemistry of an Automotive Airbag Inflator,**" Progress in Energy and Combustion Science, Vol. 19, 1993, pp. 365-382.

Butler, P.B., Kang, J., and Krier, H., "**Numerical Simulation of a Pre-Pressurized Pyrotechnic Automotive Airbag Inflator,**" 5th International Congress of the Groupe de Travail de Pyrotechnie, June, 1993, France.

Berger, J.M., and Butler, P.B., "**Equilibrium Analysis of of Three Classes of Automotive Airbag Inflator Propellants,**" Combustion Science and Technology, Vol. 104, No. 1-3, 1995, pp. 93-114.

Greenlee, C.L., and Butler, P.B., "**Influence of Product Species Selection on Thermochemical Equilibrium Calculations, Part I: Energetic Materials,**" submitted to Propellants, Explosives, and Pyrotechnics, 1995.

BACKGROUND

- CONSULTANTS TO AIRBAG INDUSTRY
- MODELING WORK
  - developed general-purpose gas generator models
  - validated performance of numerous inflators
  - used in design of new inflators
- EXPERIMENTAL WORK
  - cold-flow test apparatus
  - combustion test apparatus
  - ignition test apparatus
  - design of experiments (DOE)
- ADVANCED CONCEPTS
  - next-generation inflator designs

AIRBAG COMPONENTS

- CRASH SENSORS AND COMPUTER LOGIC

- INFLATOR UNIT (i.e., both hybrid and pyrotechnic gas generators)
  - ignitor
  - propellant grains
  - hardware items
  - particle filter

- BAG HOLDER AND EXTERIOR PADDING

- NYLON AIRBAG ASSEMBLY

ENGINEERING CHALLENGES

- IGNITOR RELIABILITY (output history, is it repeatable ?)

- TIMING OF EVENTS (pressure-time profiles)

- PRODUCT CHEMICAL COMPOSITION
  - tank gas
  - tank particulates
  - inflator slag (multi-phase mixture)

- AMBIENT OPERATING ENVIRONMENT
  - temperature
  - pressure

- AIRBAG DEPLOYMENT
  - dynamics of bag filling
  - thermal and mechanical response of bag as it opens

- PROPELLANT LIFE (>15 years)

- PROPELLANT DISPOSAL

GOALS AND OBJECTIVES

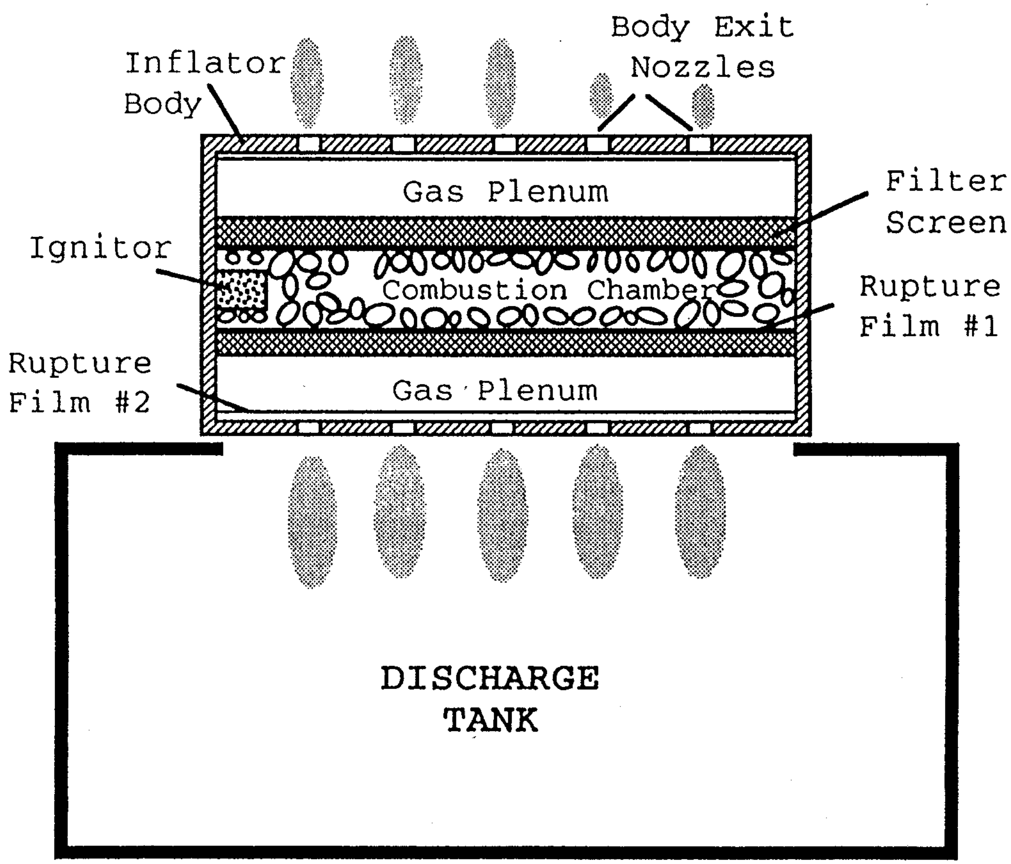
- DEVELOP A MODEL THAT DESCRIBES THE THERMOCHEMICAL EVENTS OCCURRING IN A GAS GENERATOR

- VALIDATE MODEL WITH EXPERIMENTS

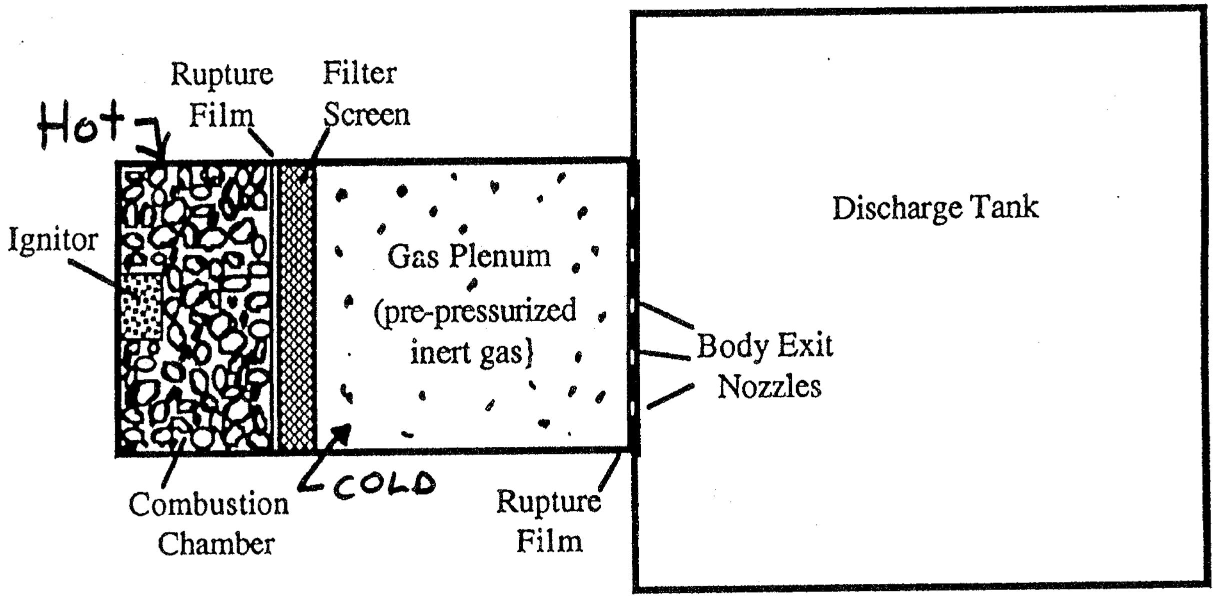
- STUDY THE INFLUENCE OF MATERIAL PROPERTIES AND DESIGN PARAMETERS ON PERFORMANCE OF GAS GENERATOR
    - maximum inflator pressure, temperature
    - maximum tank pressure, temperature
    - tank impulse
    - pressure-time profiles
    - temperature-time profiles
    - tank gas composition

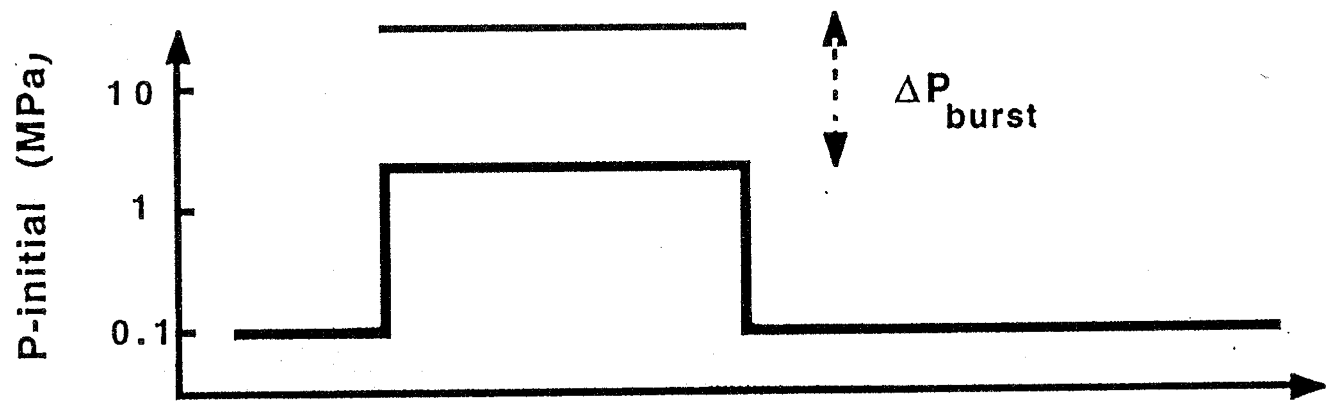
- COMPUTER PROGRAM FOR DESIGN OF NEW GAS GENERATORS

PHYSICAL MODEL
OF
GAS GENERATOR AND DISCHARGE TANK

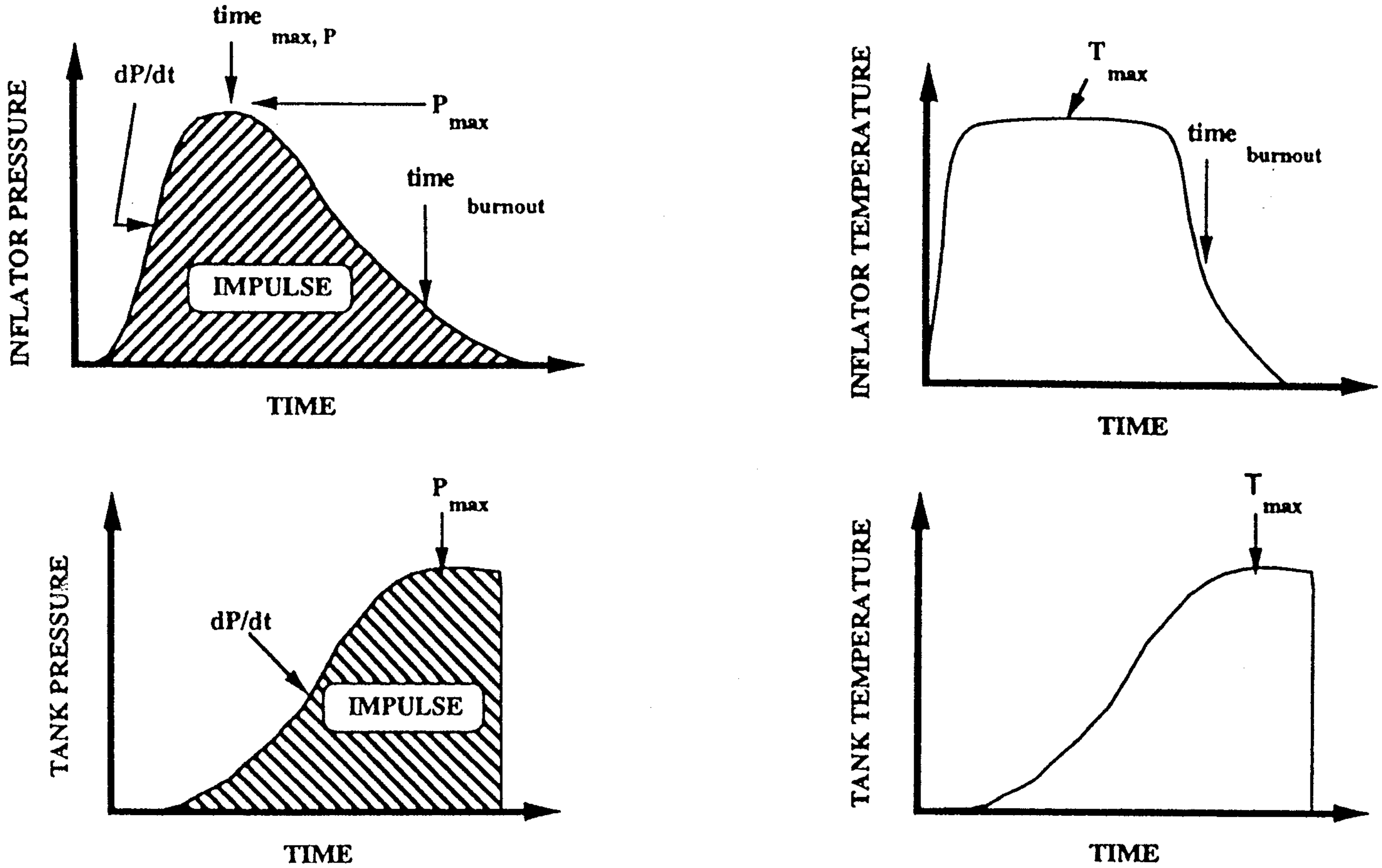


GAS-ASSISTED PYROTECHNIC INFLATOR





GAS GENERATOR
PERFORMANCE PARAMETERS



COMPUTER SIMULATION

- KEY FEATURES INCLUDED IN MODEL
  - ignition time delay (flame spreading)
  - tracks individual species with time (g, s, l)
  - grain geometry (form function)
  - nozzle discharge flow rates
  - filter collection process and gas flow restriction
- MODEL PREDICTING
  - $P_J(t)$, $T_J(t)$, $X_J(t)$
  - heat exchange rates
  - hardware temperatures
  - propellant properties per time
  - flow properties at exit nozzle
- EXPERIMENTAL VALIDATION DATA
  - ignition delay time
  - mass of collected particles in filter
  - $P_J(t)$, $T_J(t)$, $X_{JJ}(t = \infty)$, $P_{JJ}(t = \infty)$
- NUMERICAL PROCEDURE
  - large system of ODE's (dT_i/dt, dm_K/dt, etc.)
  - solved using DVODE
  - CPU time is 0.1 - 1 minute on HP-735

MODEL DESCRIPTION

- BASED ON FUNDAMANTAL CONSERVATION LAWS (MASS, ENERGY)
- TWO MAJOR SUBSYSTEMS CONSIDERED:
    - gas generator assembly
    - discharge tank
- GAS GENERATOR ASSEMBLY INCLUDES:
    - body (metal hardware)
    - propellant grains
    - ignitor assembly
    - filter screen
    - thin metal foil for environmental seal and burst strength
- DISCHARGE TANK INCLUDES:
    - tank walls (heat loss)
    - mass discharged from inflator
- DIFFERENT MODES OF HEAT TRANSFER ARE CONSIDERED

MODEL ASSUMPTIONS

- FILTER <u>DOES NOT</u> COLLECT GAS SPECIES

- FILTER <u>DOES</u> COLLECT SOLID AND LIQUID PRODUCTS OF COMBUSTION

    - collection efficiency depends on filter design (mass, fiber size, etc.)

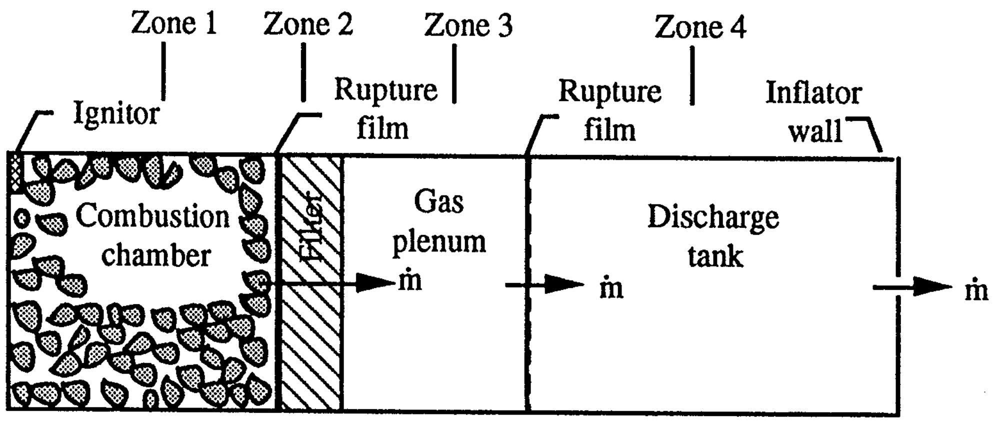
- GAS MIXTURE IS:

    - multiple species
    - $C_p(T)$
    - well-mixed, perfect gas
    - can be chemically reactive

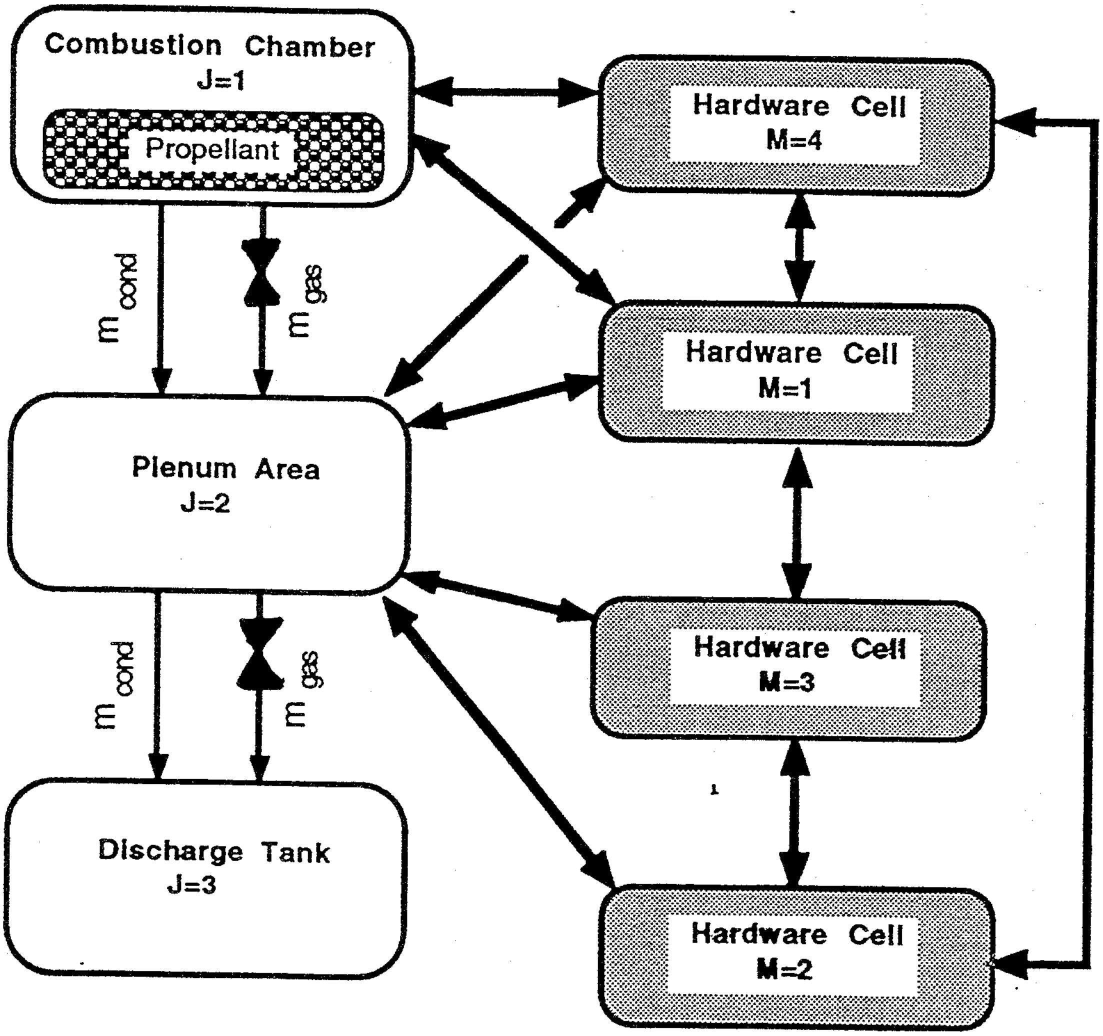
- CONDENSED SPECIES ARE:

    - multiple species
    - $C_p(T)$
    - not compressible

COMPUTATIONAL MODEL OF GAS GENERATOR AND DISCHARGE TANK



INFLATOR MODEL FLOW CHART

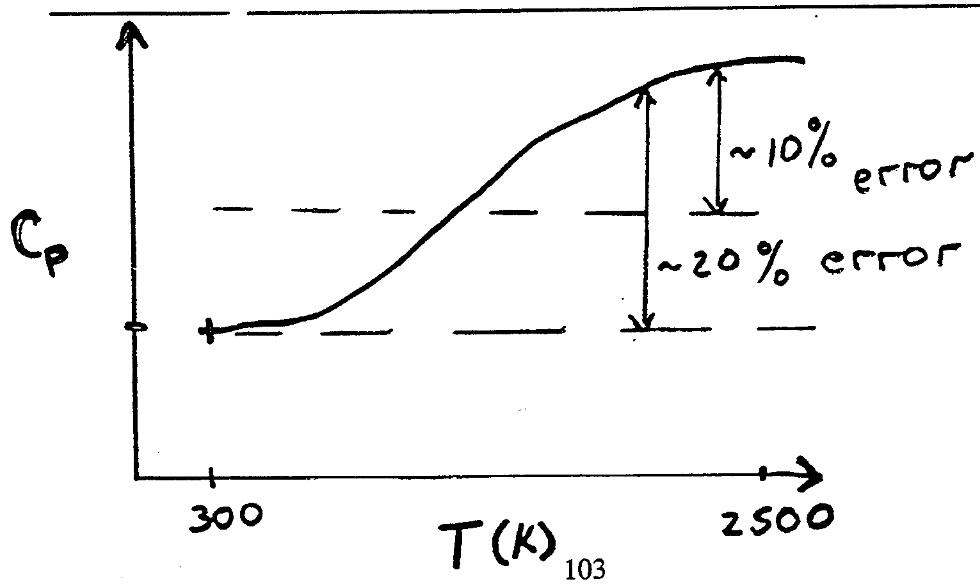


THERMODYNAMIC DATA BASE

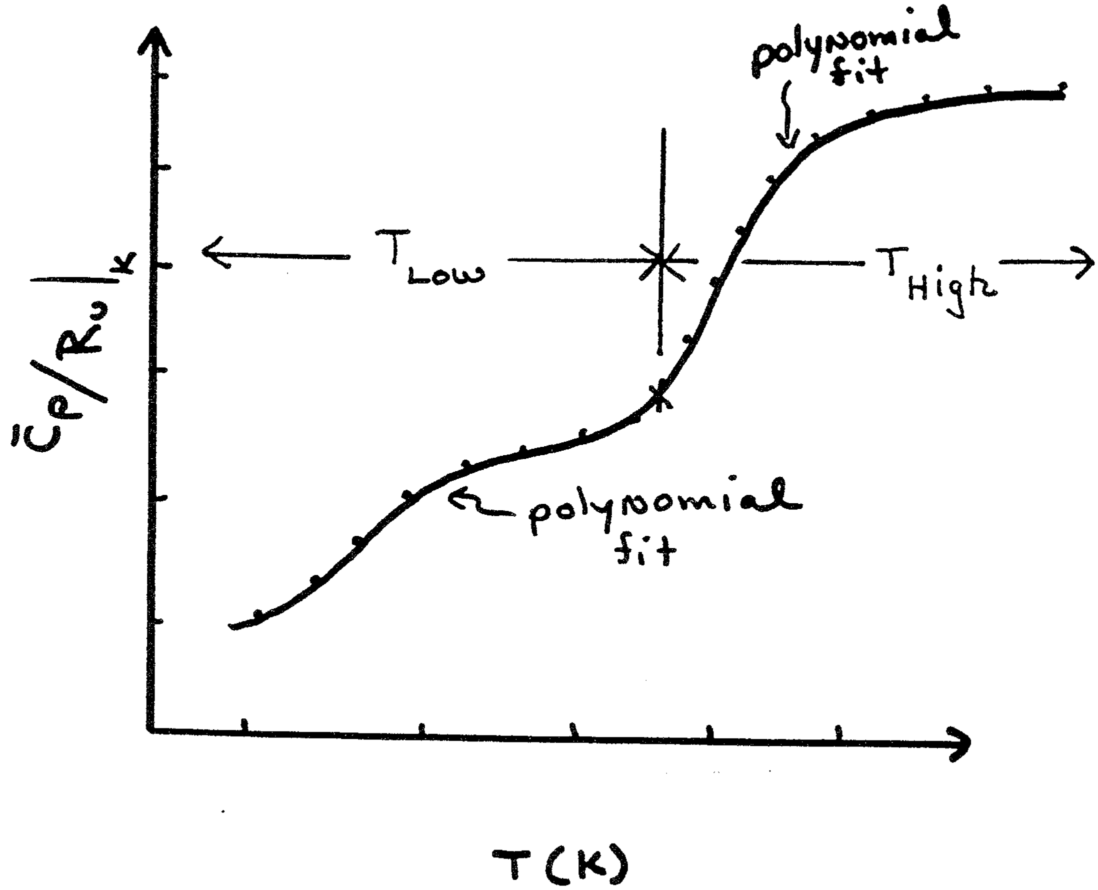
- Treats multiple chemical species in propellant grains and products of reaction
- Gaseous as well as condensed-phase species are possible
- Uses NASA/CHEMKIN thermodynamic data base for $C^o_{pk}(T)$

$$\boxed{\frac{C^o_{pk}(T)}{R} = a_{1k} + a_{2k}\,T + \ldots + a_{Nk}\,T^{(N-1)}}$$

- $C^o_{pk}(T)$ used to assemble enthalpy $H^o_k(T)$



SPECIFIC HEAT DATA



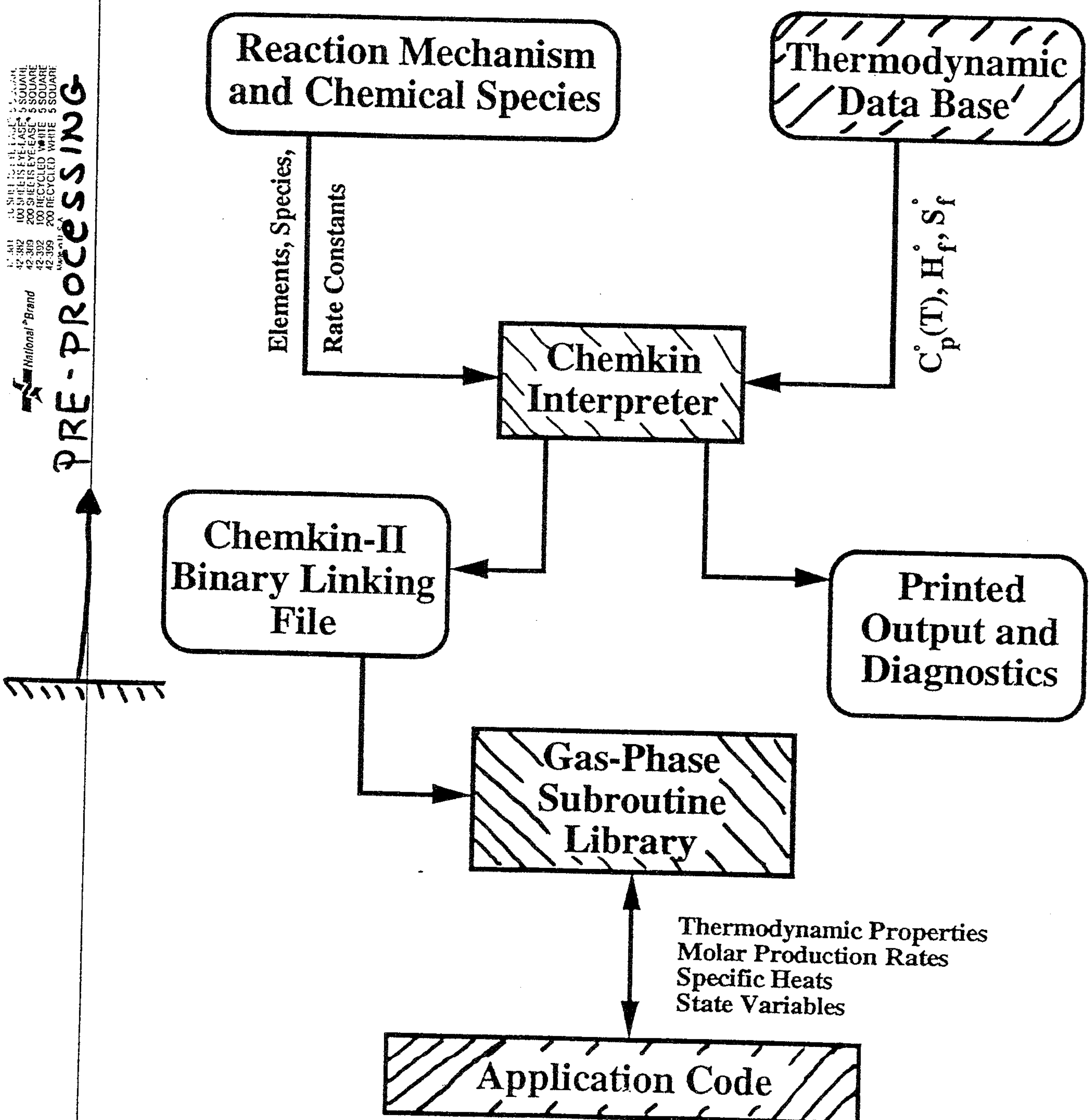
- gas (300 < T(K) < 5000)
- liquid (T_M < T(K) < T_v)
- solid (multiple phases) (T < T_M)
  - Debye temp.

GAS-PHASE CHEMISTRY

```
              <<<<<<<  GAS-PHASE REACTIONS  >>>>>>>

 Rxn number Symbolic representation
-----------------------------------------------------------------------
          1.    C+O2<=>CO+O
          2.    C+OH<=>CO+H
          3.    HCO+OH<=>H2O+CO
          4.    HCO+M<=>H+CO+M
          5.    HCO+H<=>CO+H2
          6.    HCO+O<=>CO+OH
          7.    HCO+O<=>CO2+H
          8.    HCO+O2<=>HO2+CO
          9.    CO+O+M<=>CO2+M
         10.    CO+OH<=>CO2+H
         11.    CO+O2<=>CO2+O
         12.    HO2+CO<=>CO2+OH
         13.    H2+O2<=>2OH
         14.    O+OH<=>O2+H
         15.    O+H2<=>OH+H
         16.    H+O2+M<=>HO2+M
```

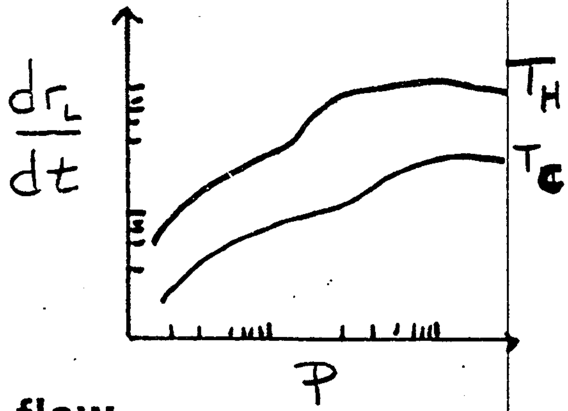
CHEMKIN-II: FLOW CHART



CONSTITUTIVE RELATIONS

- **Burn-rate**

$$\frac{dr_L}{dt} = b(T)\{a P^n\}$$

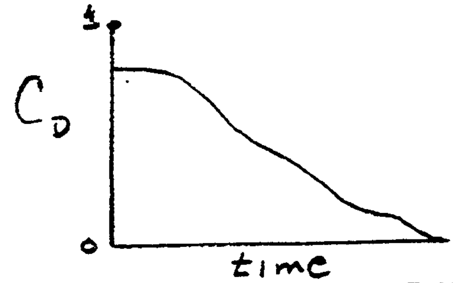


- **Flow at the exit ports is choked-flow**

$$\frac{dm_{ex}}{dt} = \frac{\Gamma A_{ex} P_i}{c_i} \times C_D \text{ (filter contamination)}$$

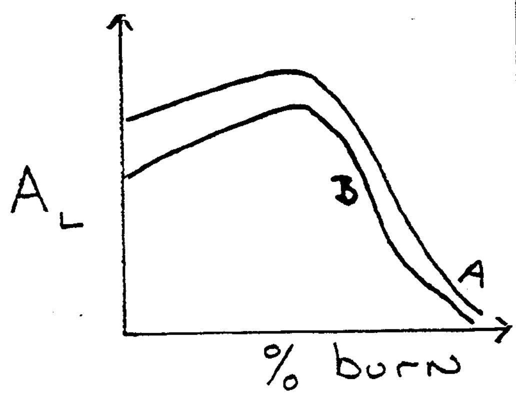
where Γ is a function of the specific heat ratio of the exit gas,

$$\Gamma = \gamma\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$$



- **Instantaneous surface area (form function)**

$A_L(t)$ = function of grain geometry



PARTICLE FILTER

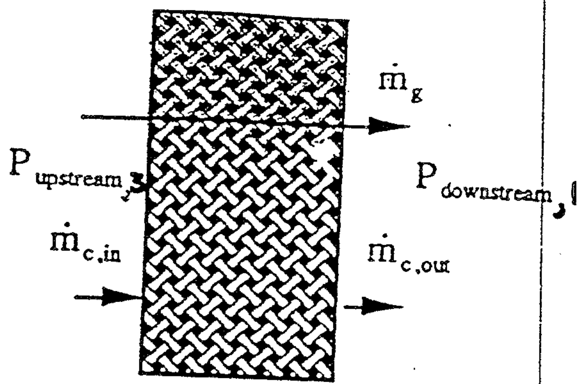
- **FILTER FLOW LOSS**

$$\dot{m}_{g,1,out} = \cancel{A}_{filter} c_{\mu,1} \{ \frac{2k}{k-1} P_1 \rho_1 [(\frac{P_3}{P_1})^{\frac{2}{k}} - (\frac{P_3}{P_1})^{\frac{k+1}{k}}] \}^{\frac{1}{2}}$$

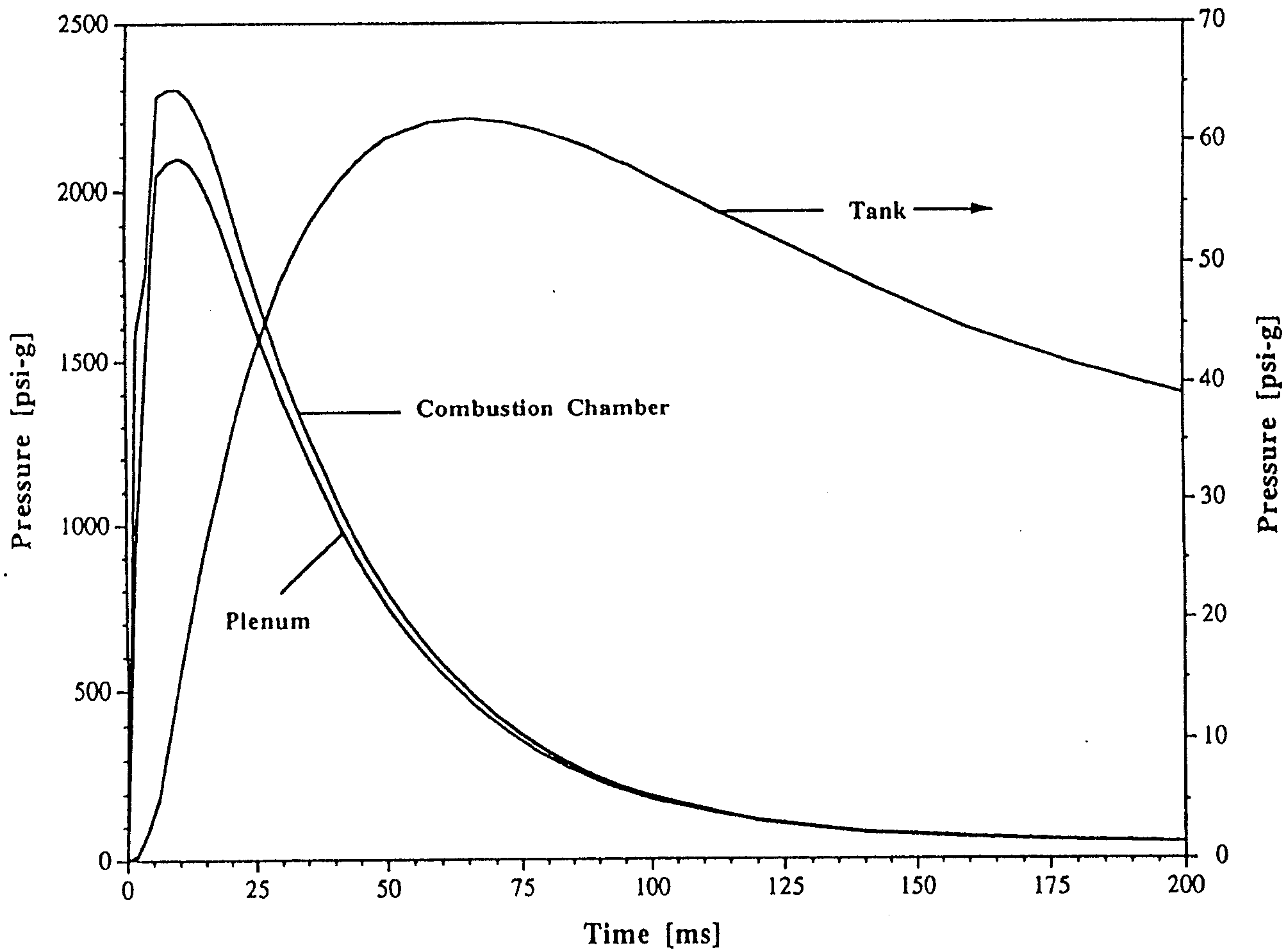
f(filter design)

- **FILTER COLLECTION EFFICIENCY**

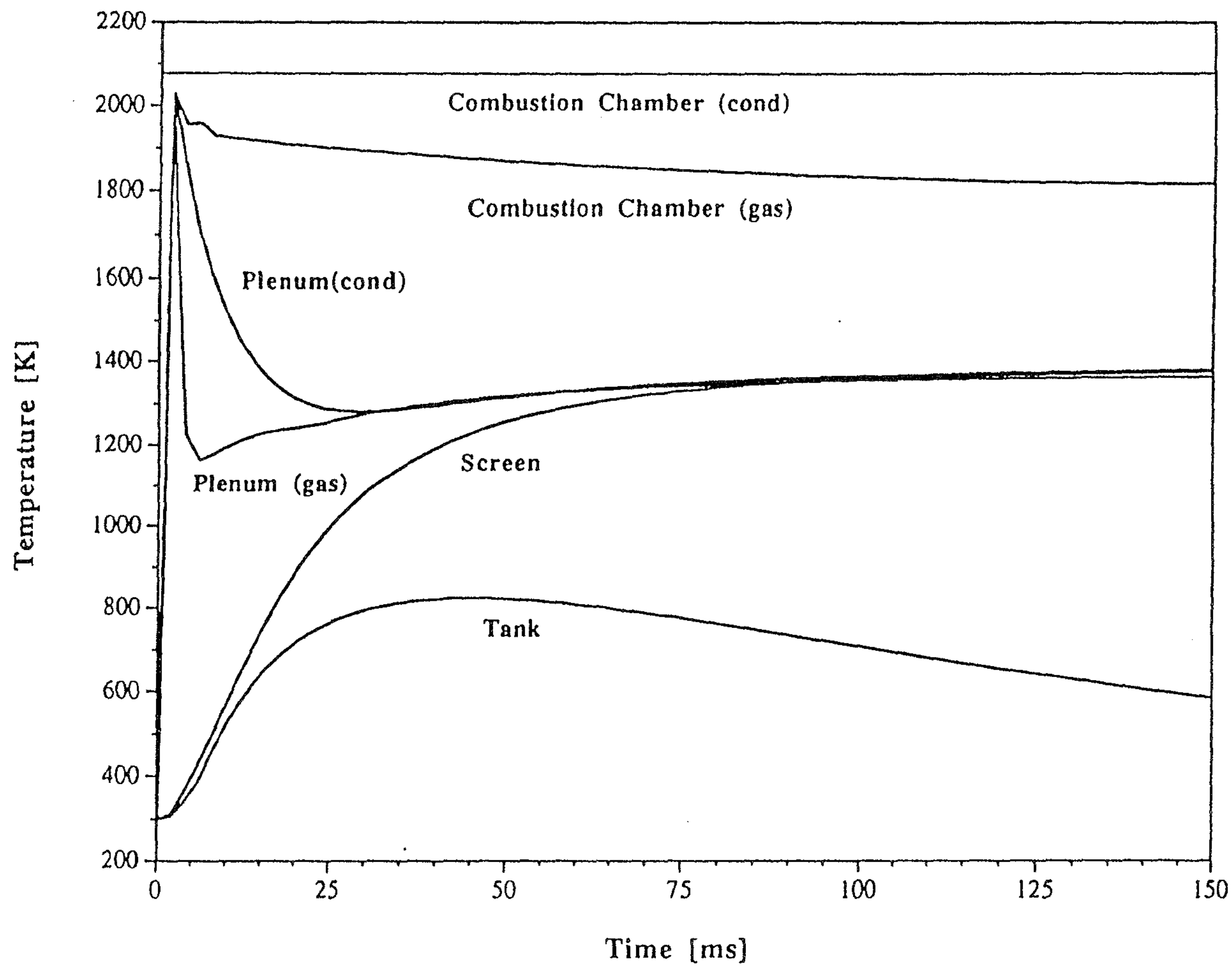
$$\dot{m}_{c,1,out} = \dot{m}_{g,1,out} \frac{m_{c,1}}{m_{g,1}}$$



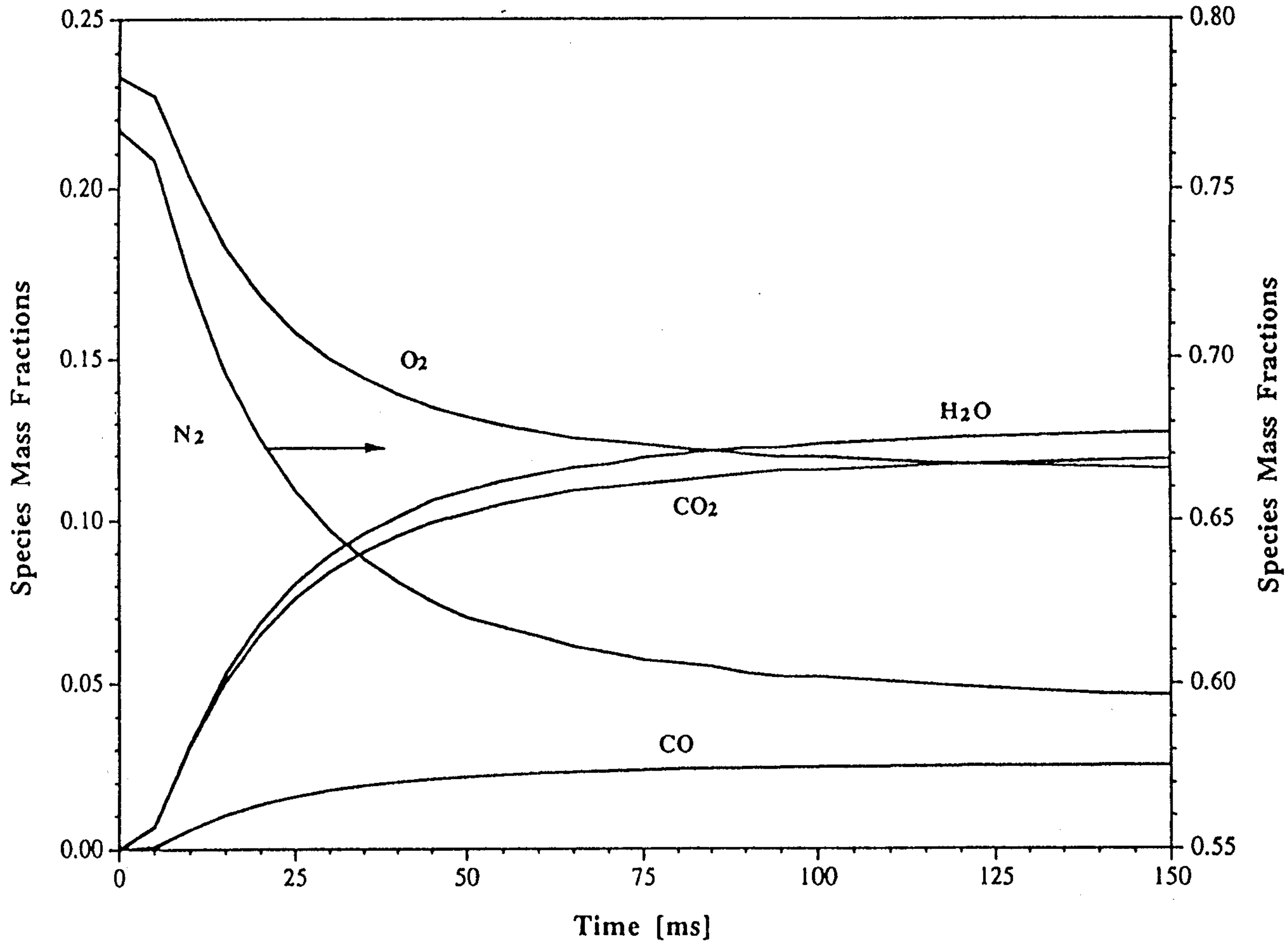
RESULTS - COMPUTER SIMULATION

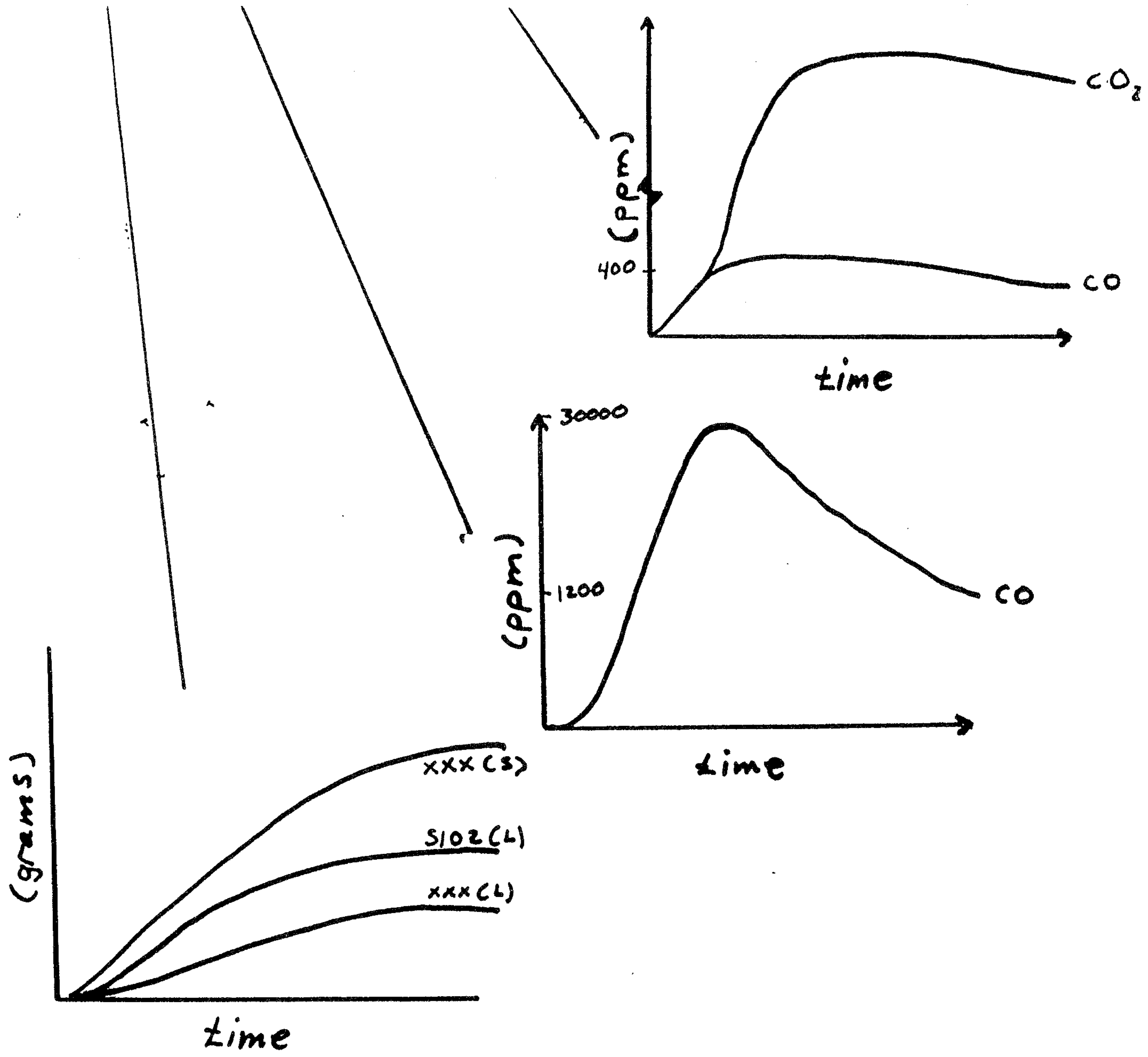


RESULTS - COMPUTER SIMULATION



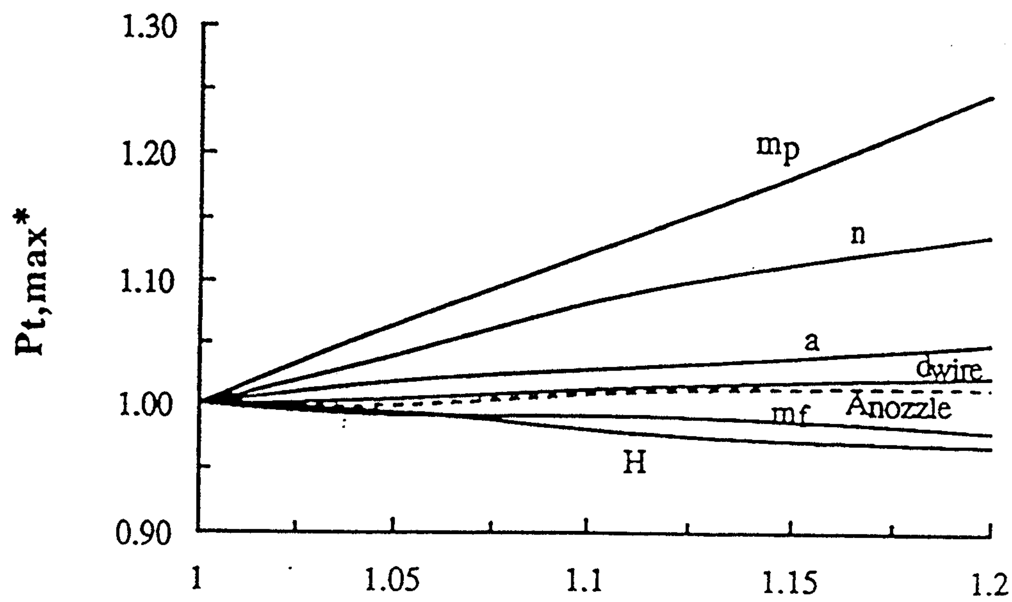
RESULTS - COMPUTER SIMULATION



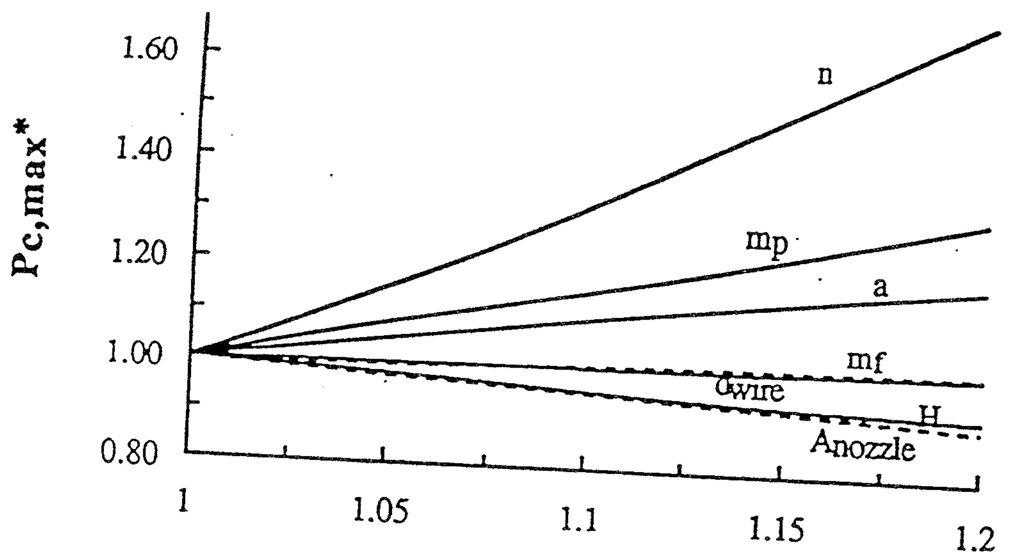


(ppm)
400
time
CO_2
CO
30000
1200
(ppm)
time
CO
(grams)
XXX (S)
SIO2 (L)
XXX (L)
time

RESULTS - SENSITIVITY STUDY



RESULTS - SENSITIVITY STUDY



NECESSARY FOR MEANINGFUL INFLATOR SIMULATION PROGRAM

- DESCRIPTION OF PROPELLANT AND PRODUCTS CHEMICAL COMPOSITION
- TEMPERATURE-DEPENDENT SPECIFIC HEAT FUNCTIONS FOR ALL POSSIBLE SPECIES
- PRECISE SOLID PHASE PROPERTIES (V, DENSITY)
- SURFACE REGRESSION RATE (= F(P,T))
- SURFACE/VOLUME RATIO OF PROPELLANT DURING BURN
- IGNITION SEQUENCE OF THE PROPELLANT (COATING, SQUIB SIZE, TEMPERATURE, ETC.)
- FRACTURE OF GRAINS DURING RAPID PRESSURIZATION
- SOLID-PHASE THERMAL PROPERTIES (MODEL SLAG FORMATION)
- NOZZLE OPENING PROCESS (INCLUDED MULTIPLE NOZZLE SIZES TO AVOID SADDLING EFFECT)
- HEAT LOSS TO SCREENS
- DYNAMIC MASS-FLOW DISCHARGE COEFFICIENTS
- DEVELOPMENT OF EXPERIMENTAL PLAN IN PARALLEL WITH MODEL DEVELOPMENT

EXPERIMENTAL REQUIREMENTS

- **DESCRIPTION OF PROPELLANT**
  - chemical composition
  - grain geometry
  - burn-rate function

- **ANALYSIS OF SPECIES REMAINING IN THE INFLATOR AFTER FIRING**

- **DYNAMIC PRESSURE MEASUREMENTS IN:**
  - inflator body
  - discharge tank

- **AFTER-FIRING INSPECTION OF HARDWARE FOR CONDENSED PARTICLES**

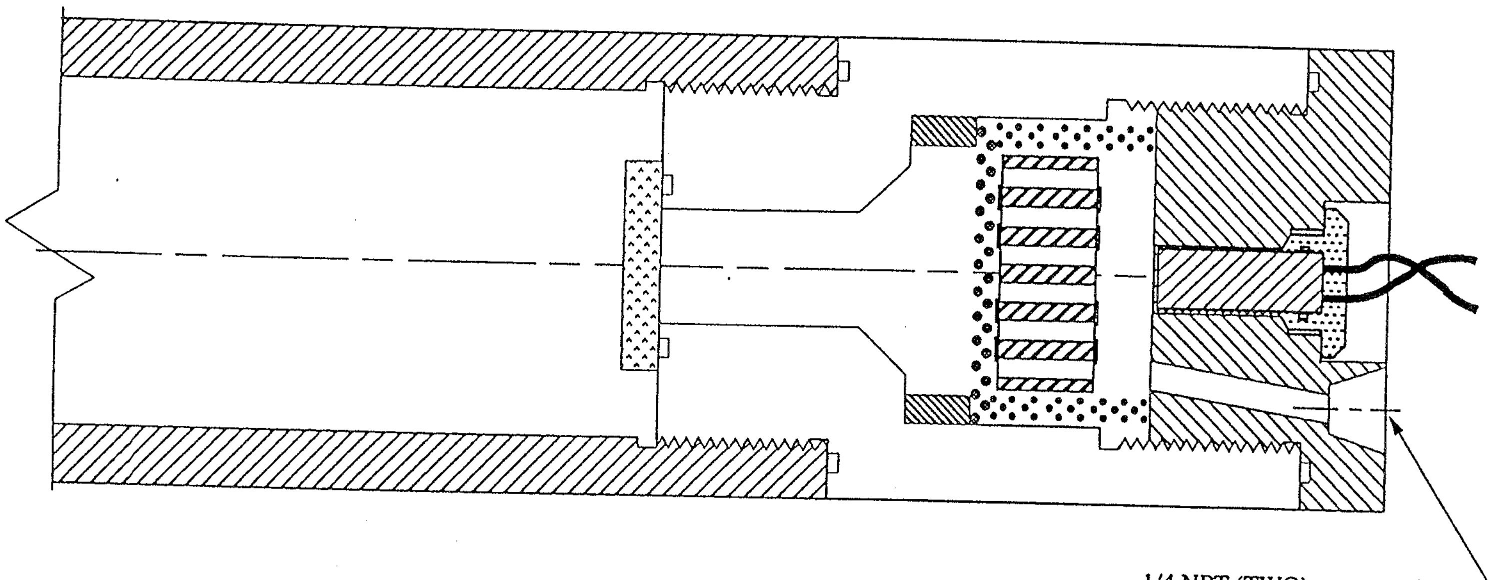
- **INDEPENDENT STUDIES OF THE FILTER COLLECTION EFFICIENCY**

- **INDEPENDENT STUDIES OF THE PROPELLANT IGNITION SEQUENCE**

PROPELLANT CONCERNS

- PRODUCT CHEMICAL COMPOSITION
  - tank gas
  - tank particulates
  - inflator slag (multi-phase mixture)
- LIFE (>15 years)
- DISPOSAL
- PROPELLANT OUTPUT
  - hot vs. cold firing
  - squib can fracture propellant grains
- LABORATORY COMBUSTION STUDIES SHOULD REPLICATE ACTUAL GAS GENERATOR OPERATING ENVIRONMENT
  - high confinement (solids loading)
  - pressure variations (14.7 - 4,000 psi)
  - possible slag build-up
  - flame spreading

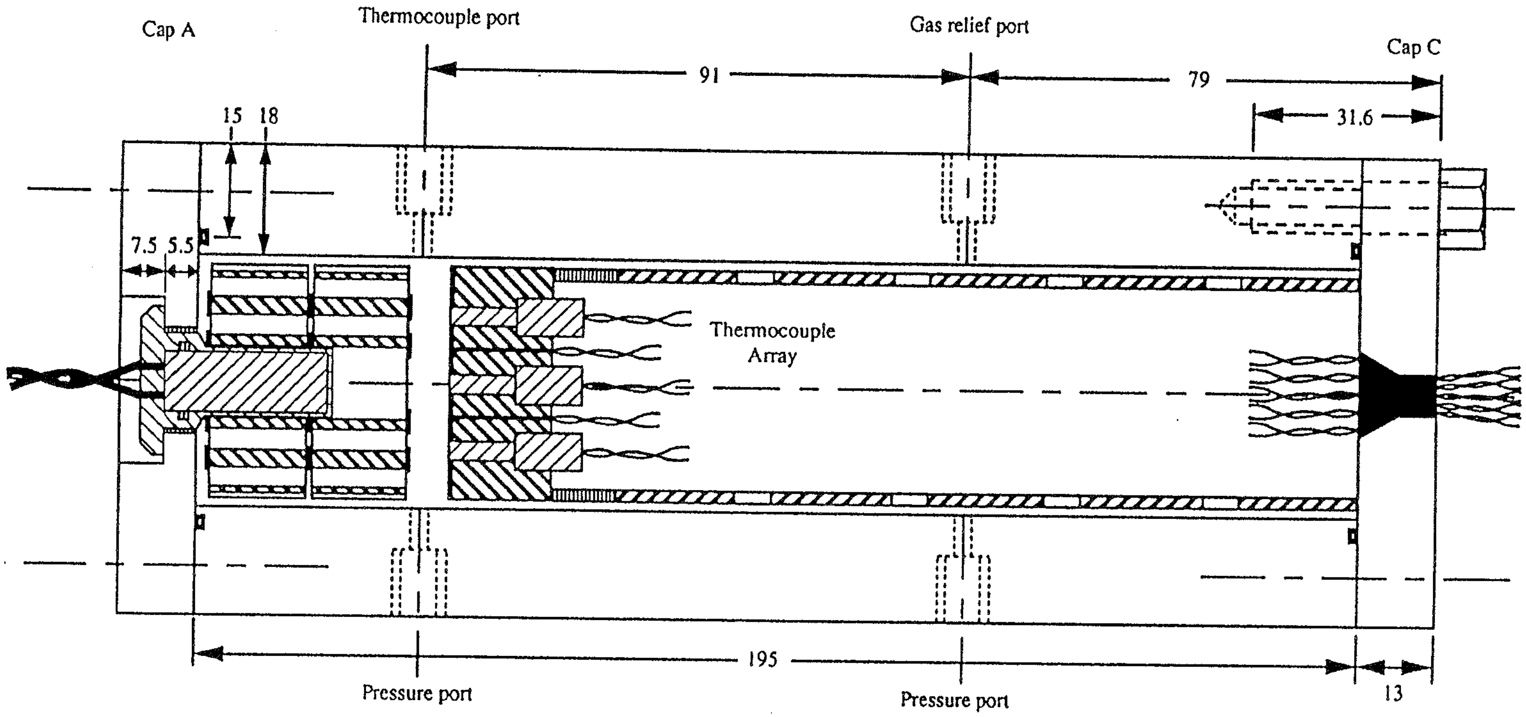
COMBUSTION TEST APPARATUS



IGNITION CONCERNS

- ACTION TIME
  - hot vs. cold firing
  - uniform performance of "similar" squibs
  - some "good" gas-generating propellants require accelerant coatings
- IGNITOR OUTPUT
  - hot vs. cold firing
  - uniformity in performance of "similar" squibs
  - can fracture propellant grains
- IGNITOR LIFE
  - uniform performance after storage
- INDEPENDENT STUDIES OF IGNITOR AND PROPELLANT IGNITION SEQUENCE ARE NECESSARY UNDER ALL OPERATING CONDITIONS

IGNITION TEST APPARATUS



CONCLUSIONS

- COMPREHENSIVE GAS GENERATOR MODEL WAS DEVELOPED

- MODEL HAS BEEN APPLIED TO

  - conventional pyrotechnic inflators
  - hybrid inflators

- AGREEMENT WITH DATA IS EXCELLENT

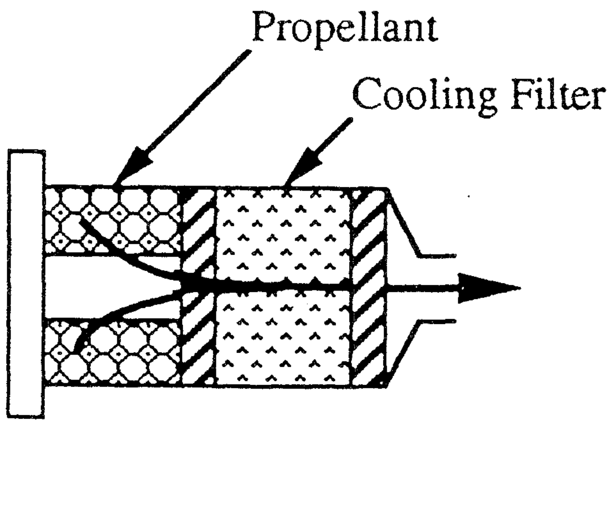
- MODEL IS A USEFUL TOOL FOR DESIGN AND DEVELOPMENT OF:

  - new inflators (material properties, size, etc.)
  - new pyrotechnic compositions
  - propellant grain modifications
  - ignitors
  - new filter designs

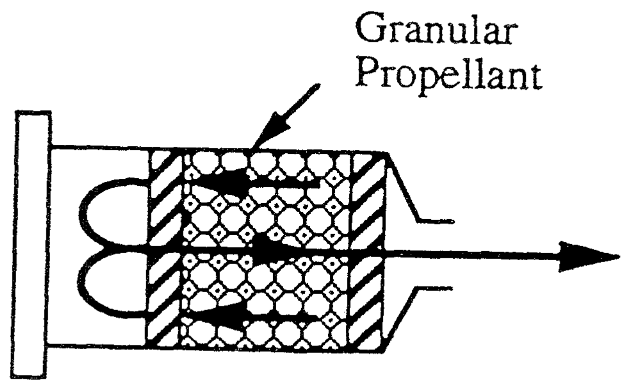
- EXPERIENCE SHOWS THAT A RELIABLE EXPERIMENTAL DATABASE IS ESSENTIAL

- WE RECOMMEND THAT SOLID PROPELLANT FIRE EXTINGUISHMENT PROGRAM FOLLOW SAME METHODOLOGY

ALTERNATIVE DESIGNS



a.) Standard Scheme



b.) Self-cooling Scheme

ASPECTS OF FLAME SUPPRESSION

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OBJECTIVE

Give guidance on the performance of fire suppression systems in engine nacelles.

Compare Effectiveness of 3 Key Agents

Formula	Designation	IUPAC Name
CF_3I	–	iodotrifluoromethane
C_2HF_5	HFC-125	pentafluoroethane
C_3HF_7	HFC-227ea	heptafluoropropane

Testing Solid Propellant Gas Generators

1. What are key parameters controlling flame extinction?

   Flow Velocity

   Air Temperature

   Pressure

   baffle height

   Agent

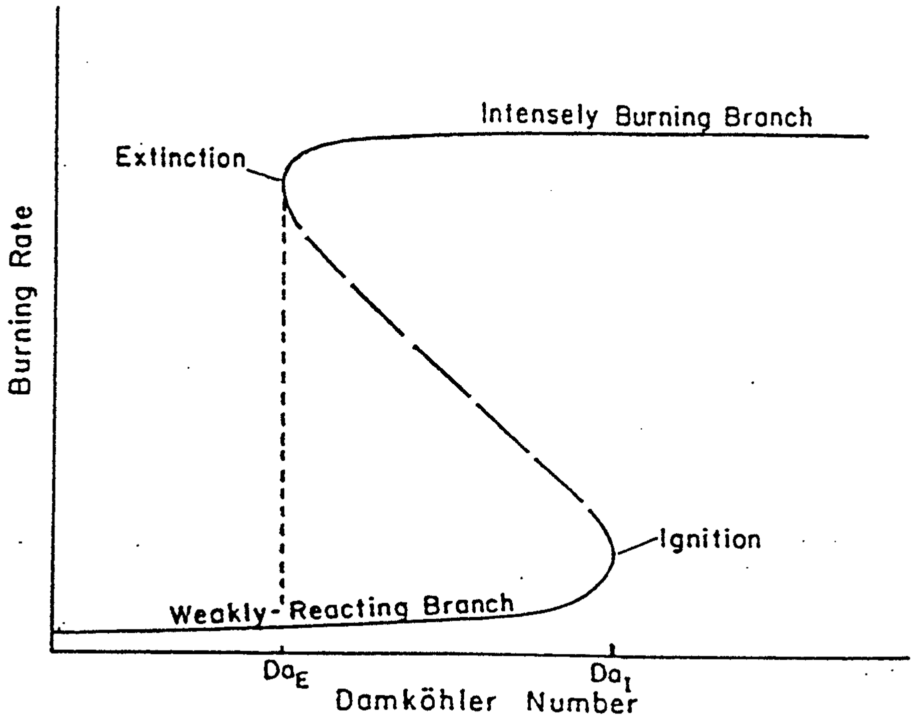
   Fuel

2. What is an appropriate test apparatus?

ASPECTS OF FLAME SUPPRESSION

Suppression Tests

Experiment	Flow Configuration	Type of Combustion	Flow Field
cup burner	coflow	non-premixed	quasi-laminar
opposed flow diffusion flame	counterflow	non-premixed	laminar
baffle stabilized spray flame	obstacle in middle of field	recirculation zone	turbulent
baffle stabilized pool fire	obstacle against wall	recirculation zone	turbulent

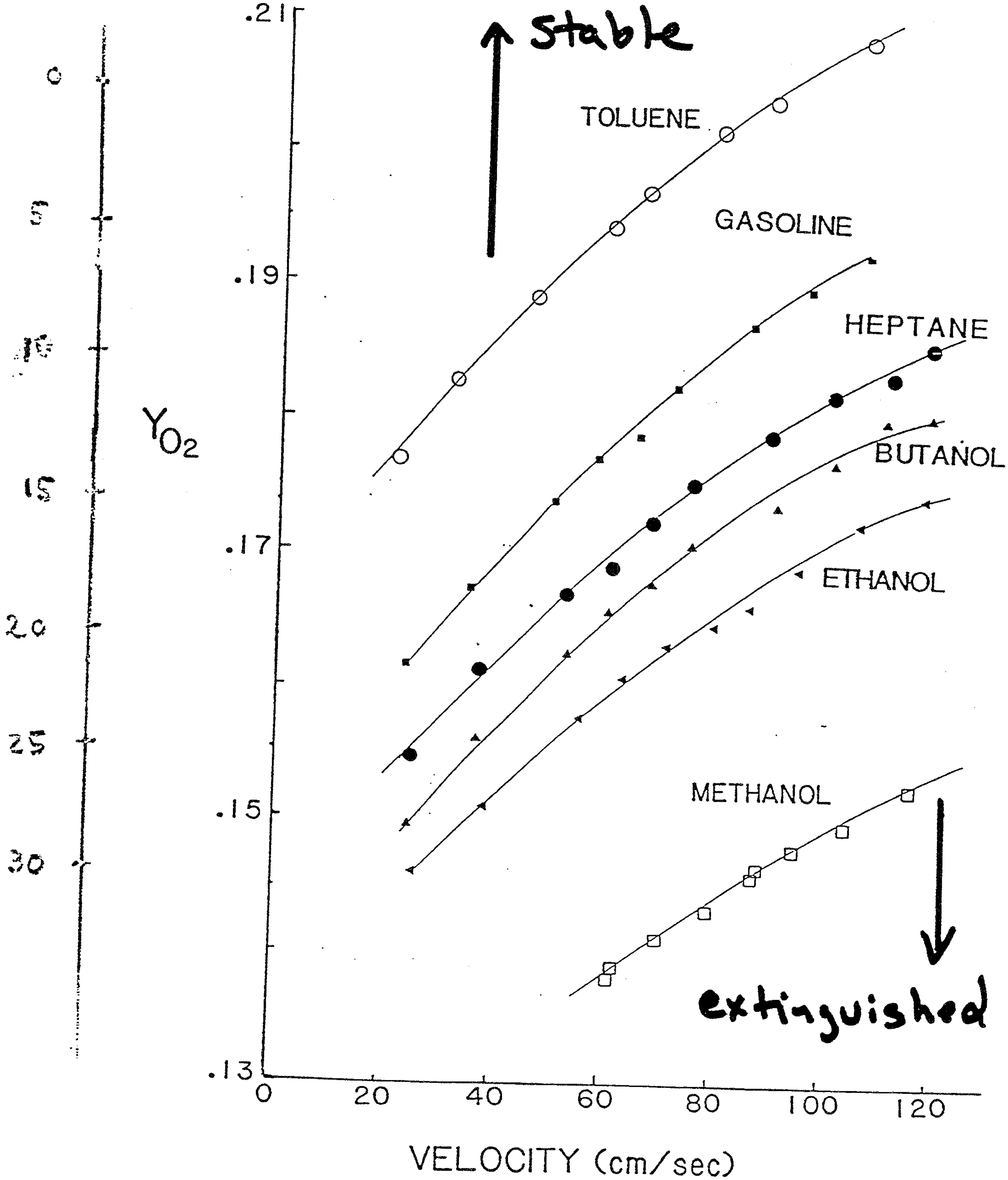


$$Da = \tau_F / \tau_{CR} = \text{Flow Time / Chemical Reaction Time}$$

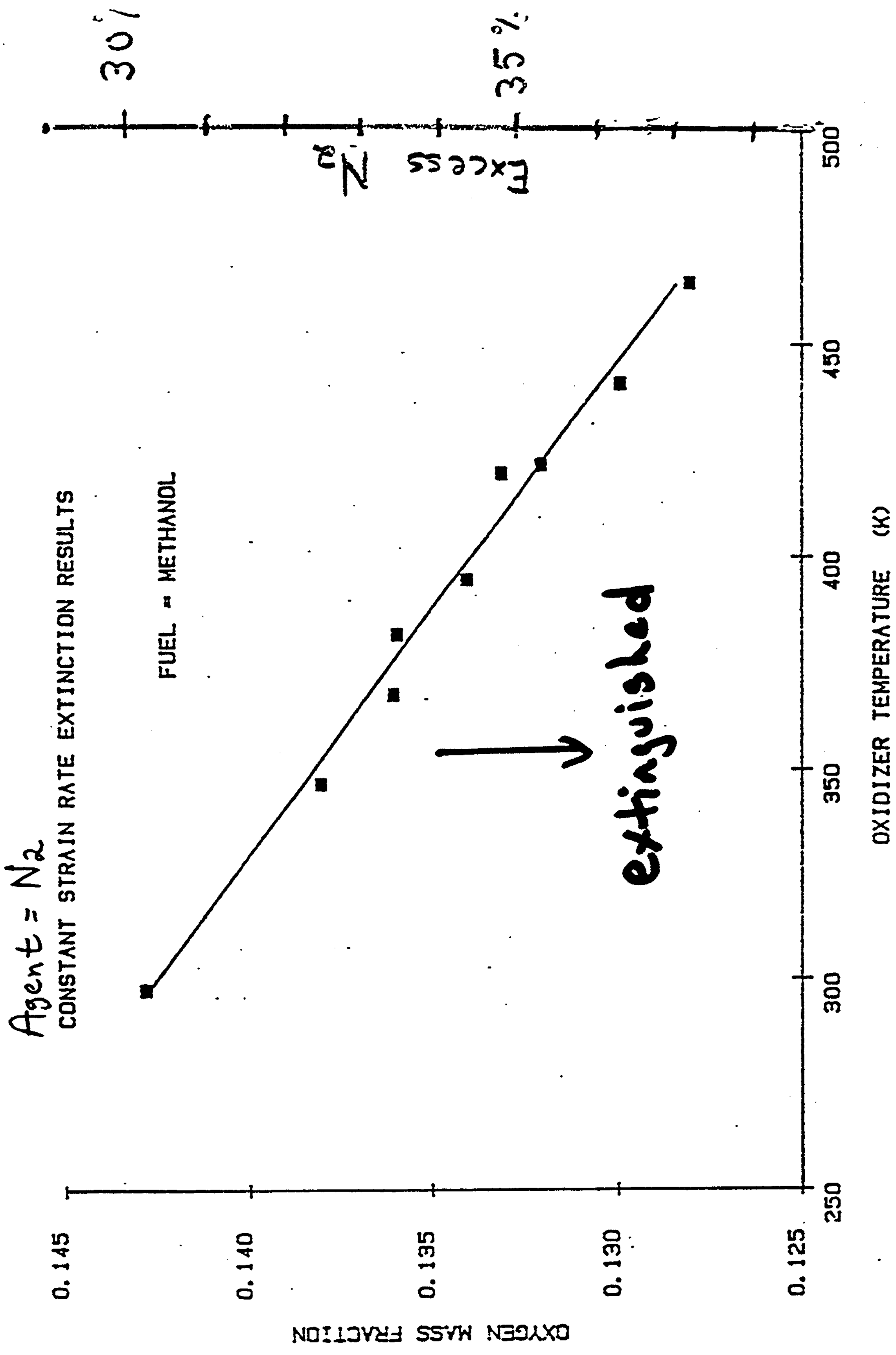
$$\tau_F \propto 1/(\text{Velocity Gradient}) = 1/(U/L)$$

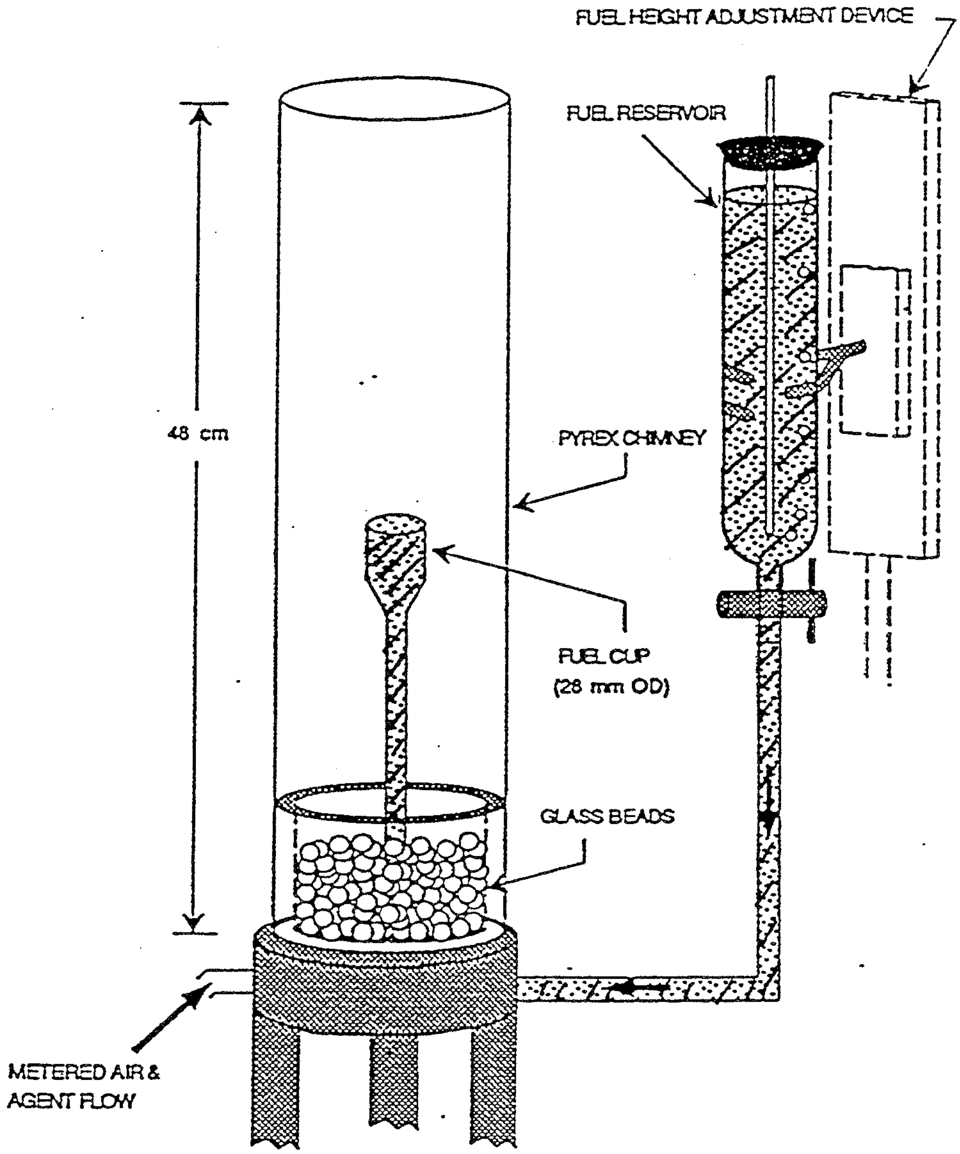
$$\tau_{CR} \propto 1/(\text{Rate Constant}) = 1/(B \cdot \exp[-E/RT])$$

Excess N_2



0
5
10
15
20
25
30
Y_{O_2}
.21
.19
.17
.15
.13
Stable
TOLUENE
GASOLINE
HEPTANE
BUTANOL
ETHANOL
METHANOL
extinguished
0
20
40
60
80
100
120
VELOCITY (cm/sec)

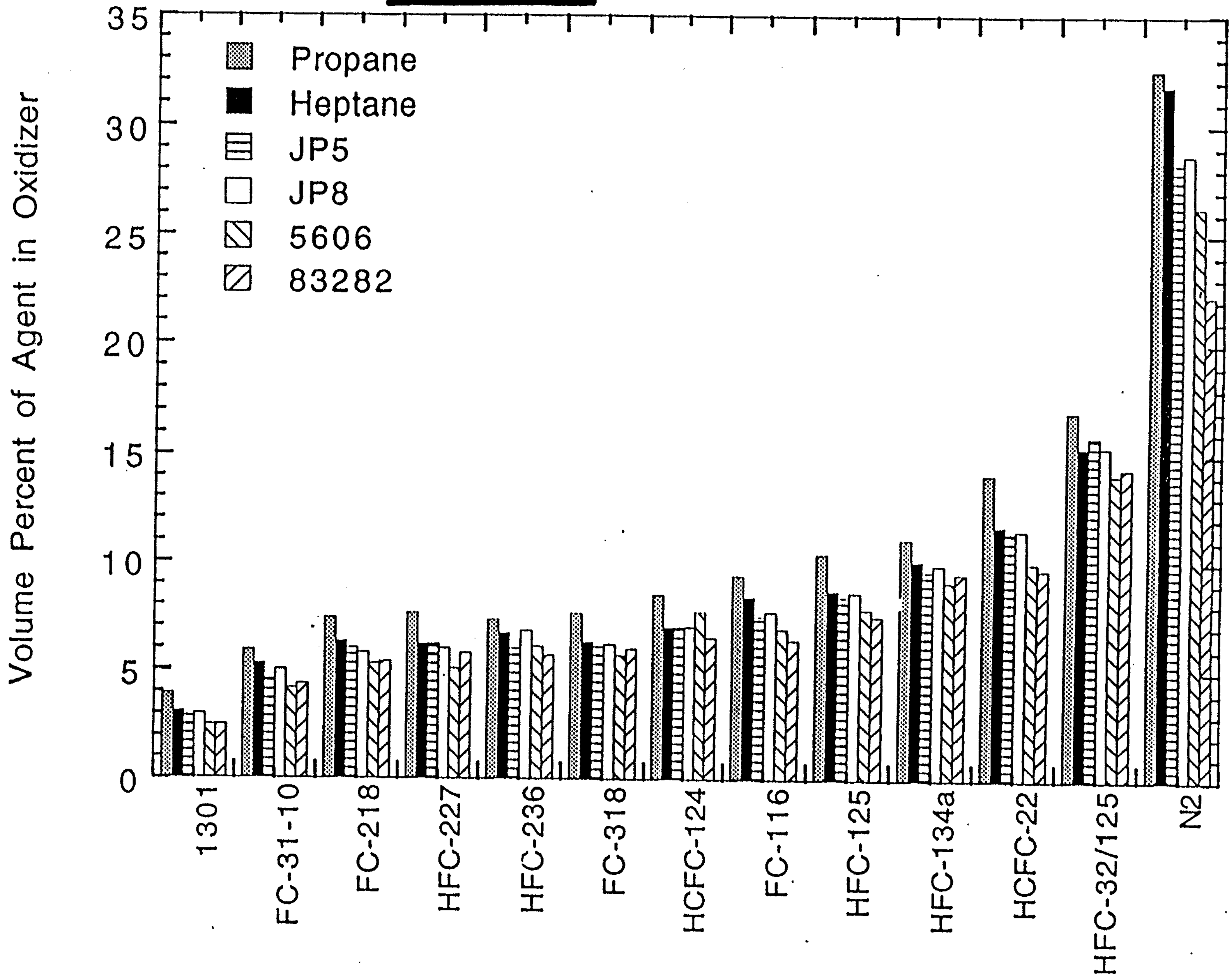

Agent = N_2
CONSTANT STRAIN RATE EXTINCTION RESULTS
FUEL = METHANOL
extinguished
Excess N_2
30%
35%
OXYGEN MASS FRACTION
0.145
0.140
0.135
0.130
0.125
OXIDIZER TEMPERATURE (K)
250
300
350
400
450
500



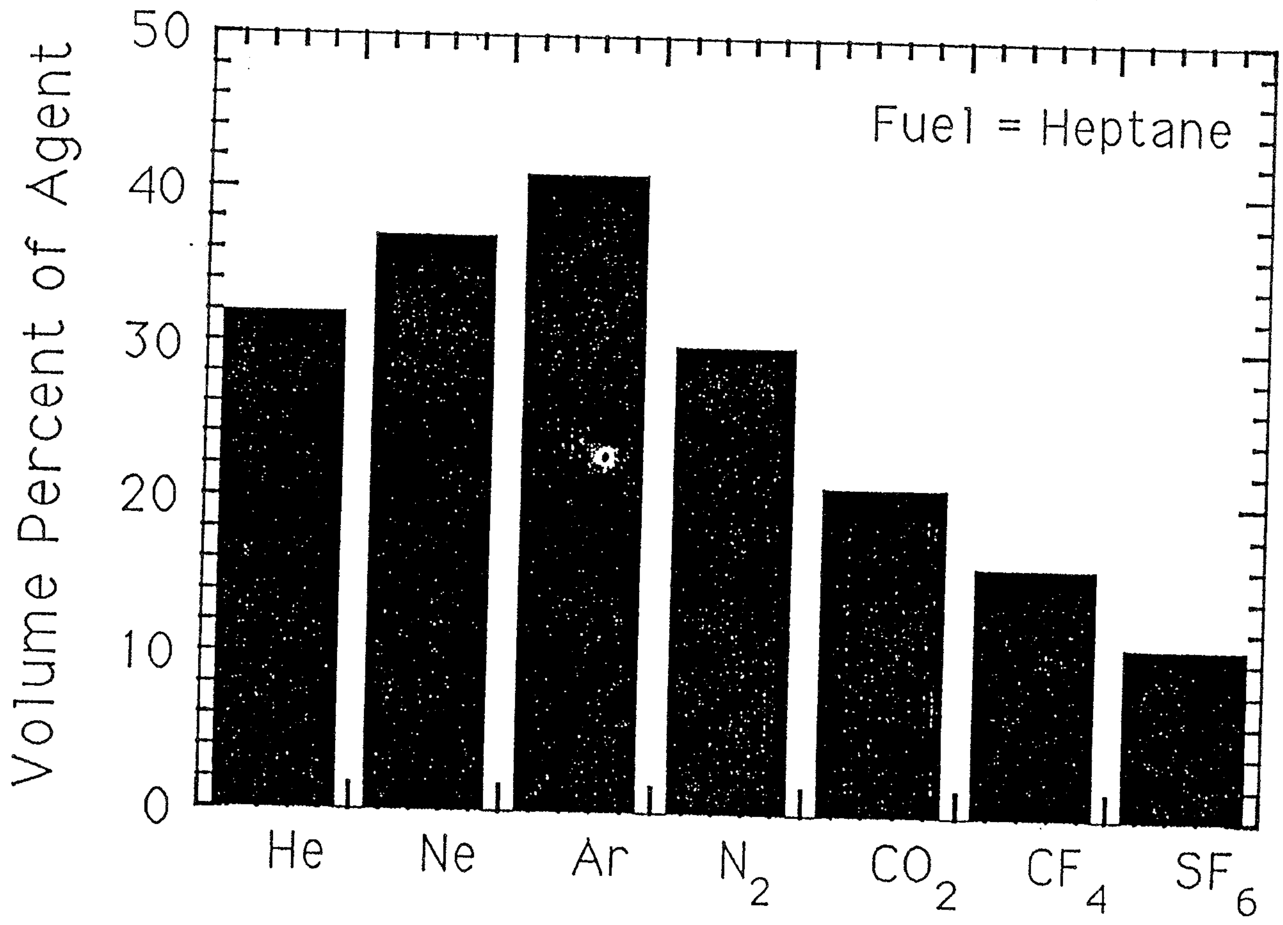
FUEL HEIGHT ADJUSTMENT DEVICE
FUEL RESERVOIR
48 cm
PYREX CHIMNEY
FUEL CUP
(28 mm OD)
GLASS BEADS
METERED AIR &
AGENT FLOW

CUP BURNER

Cup Burner Extinction Results

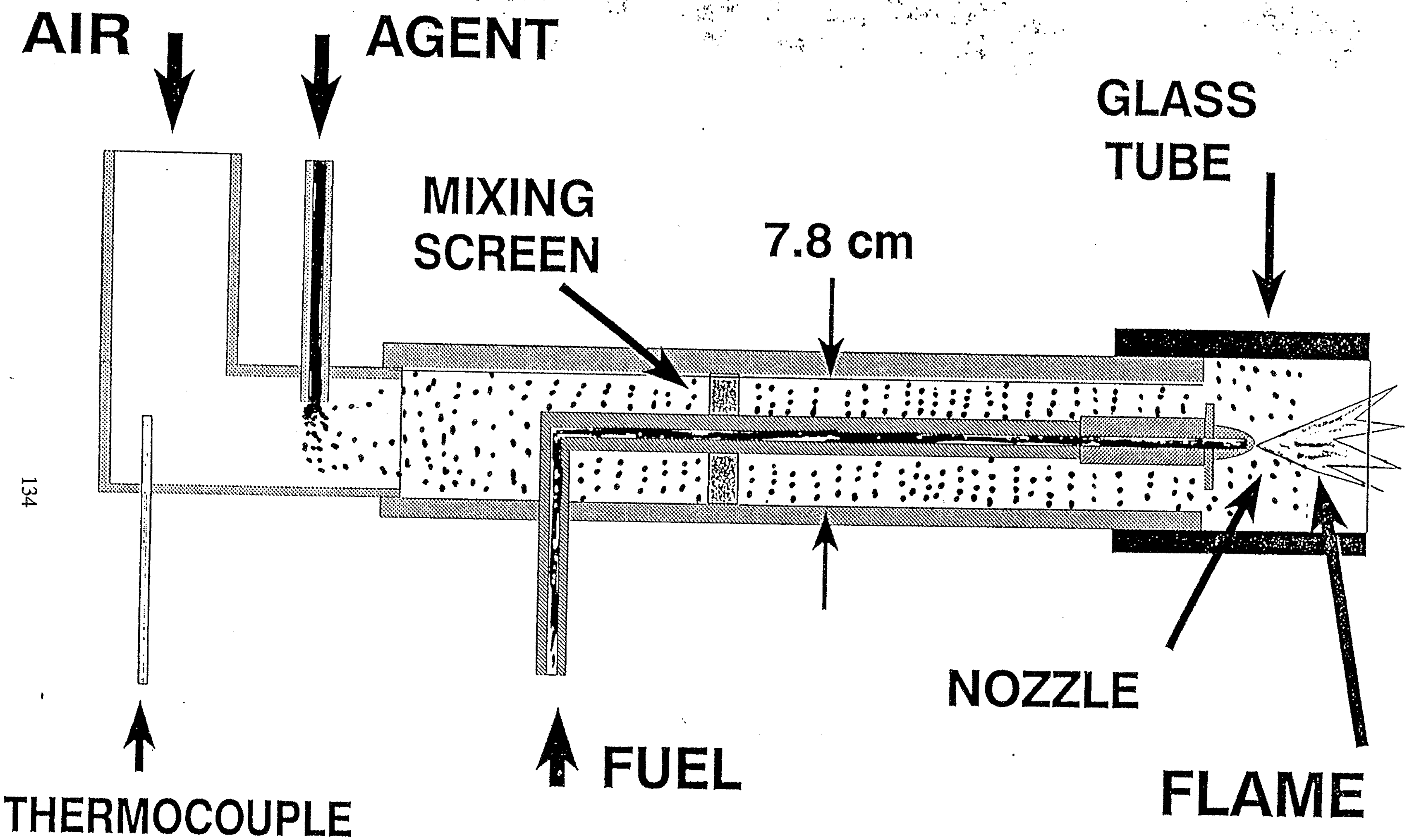


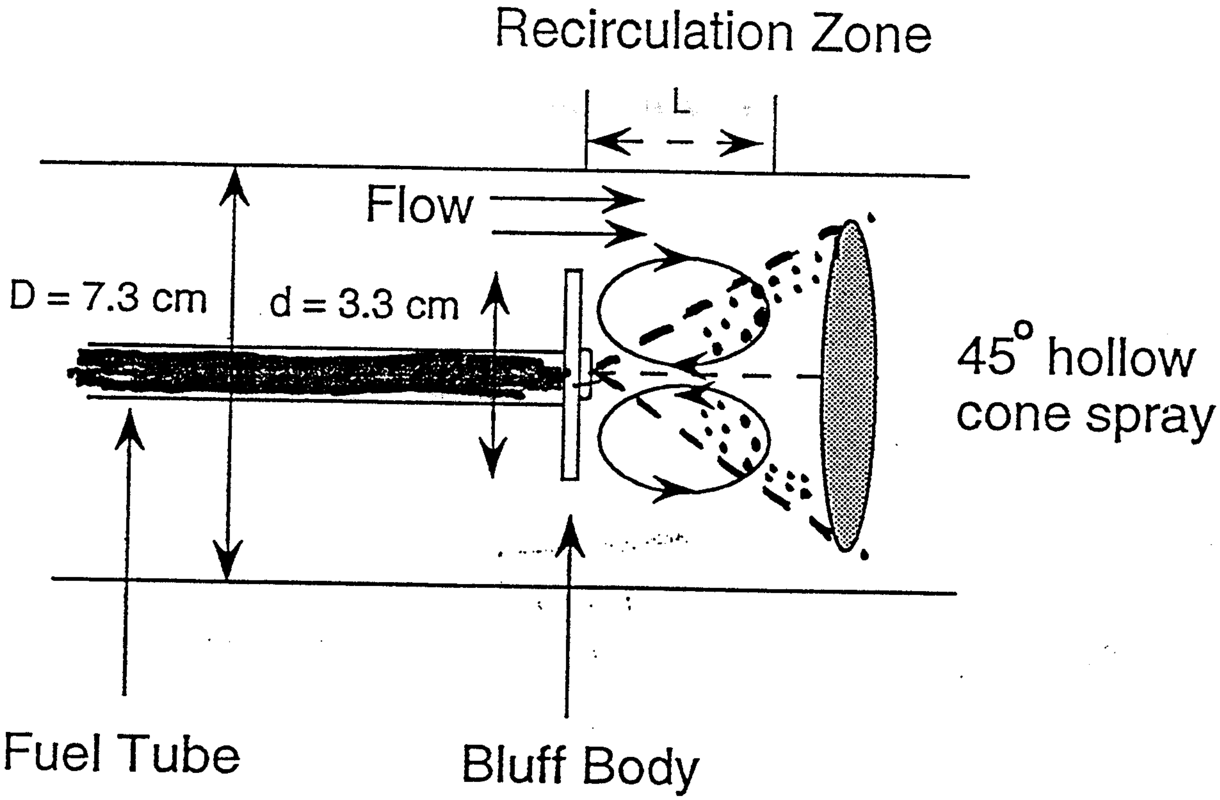
2. FLAME STABILIZATION BEHIND AN OBSTACLE

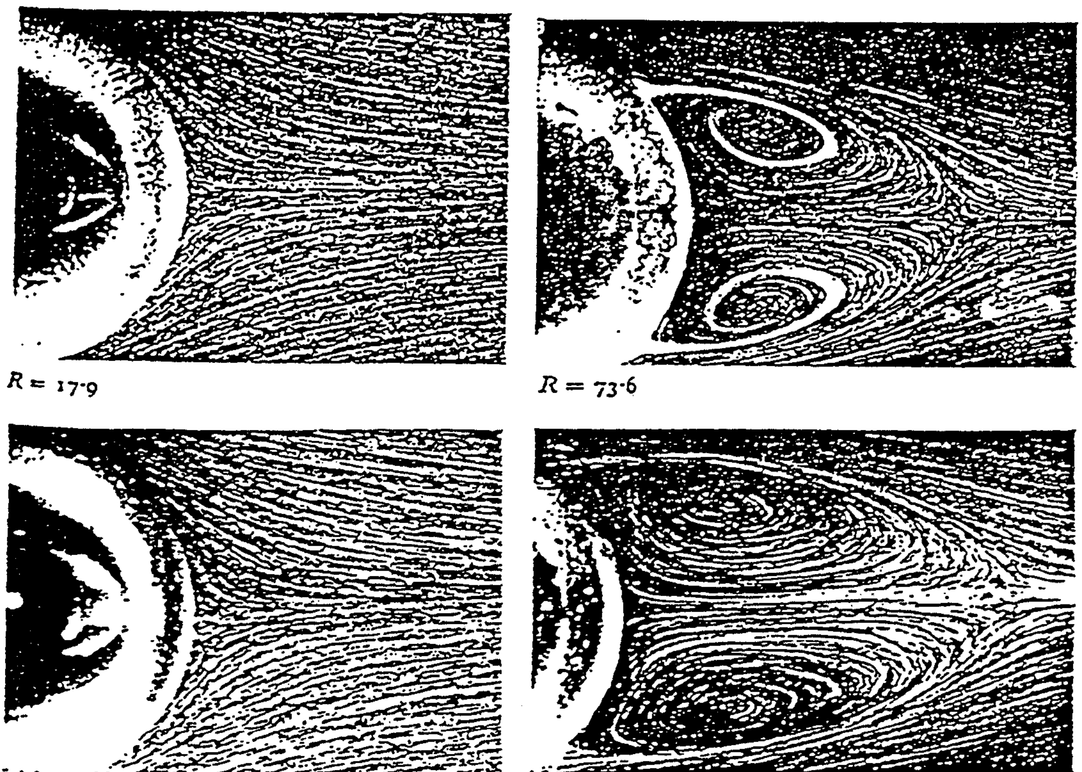


Flame Stability in a Recirculation Zone

Parameter	increased Stability
velocity	decreased
temperature	increased
pressure	increased
turbulence	decreased
equivalence ratio	flammability peak
flame-holder size	increased
flame-holder drag coefficent	increased
geometric blockage	increased
fuel volatility	increased
atomization	finer


AIR
AGENT
MIXING SCREEN
7.8 cm
GLASS TUBE
NOZZLE
FLAME
THERMOCOUPLE
FUEL



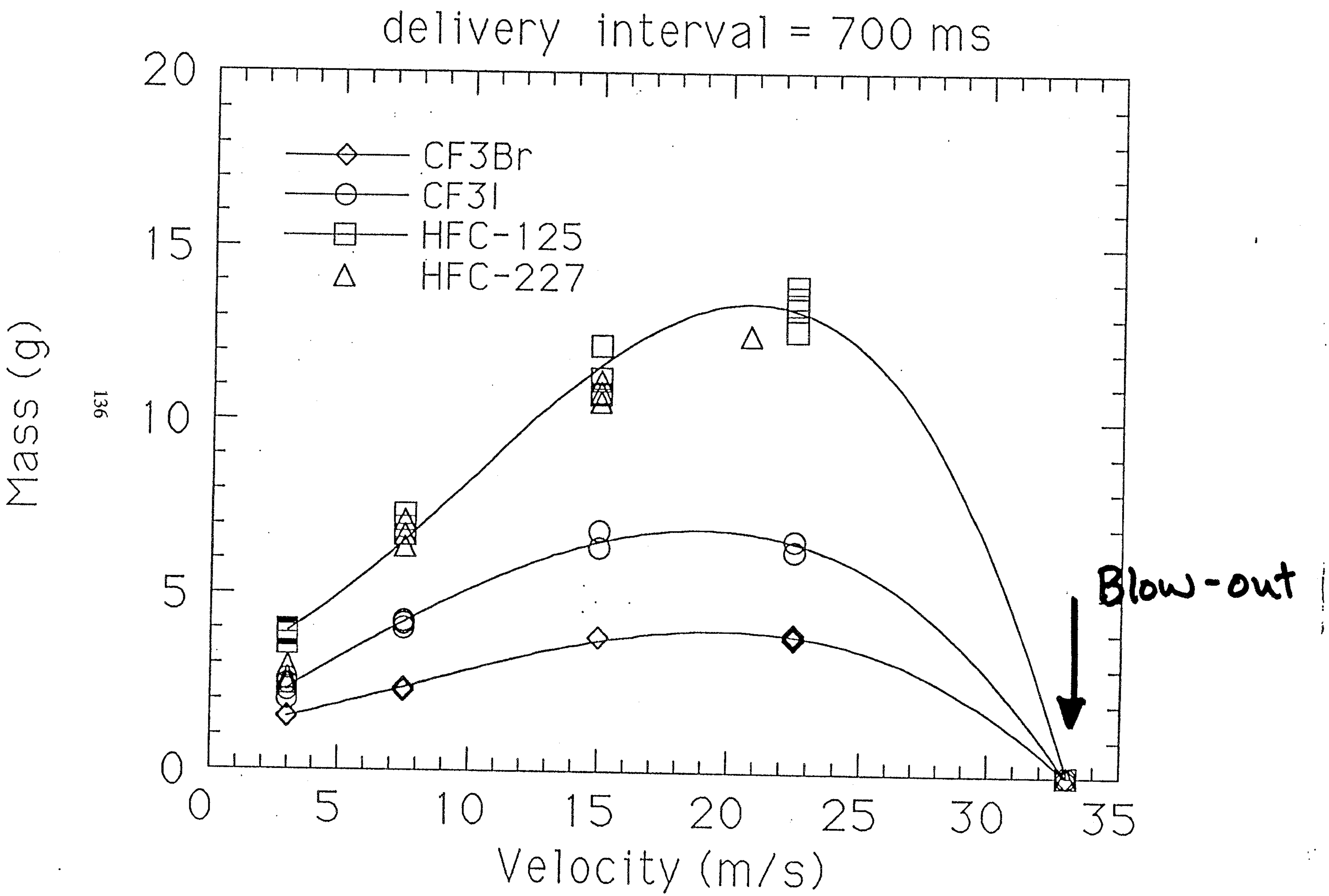


R = 17·9

R = 73·6

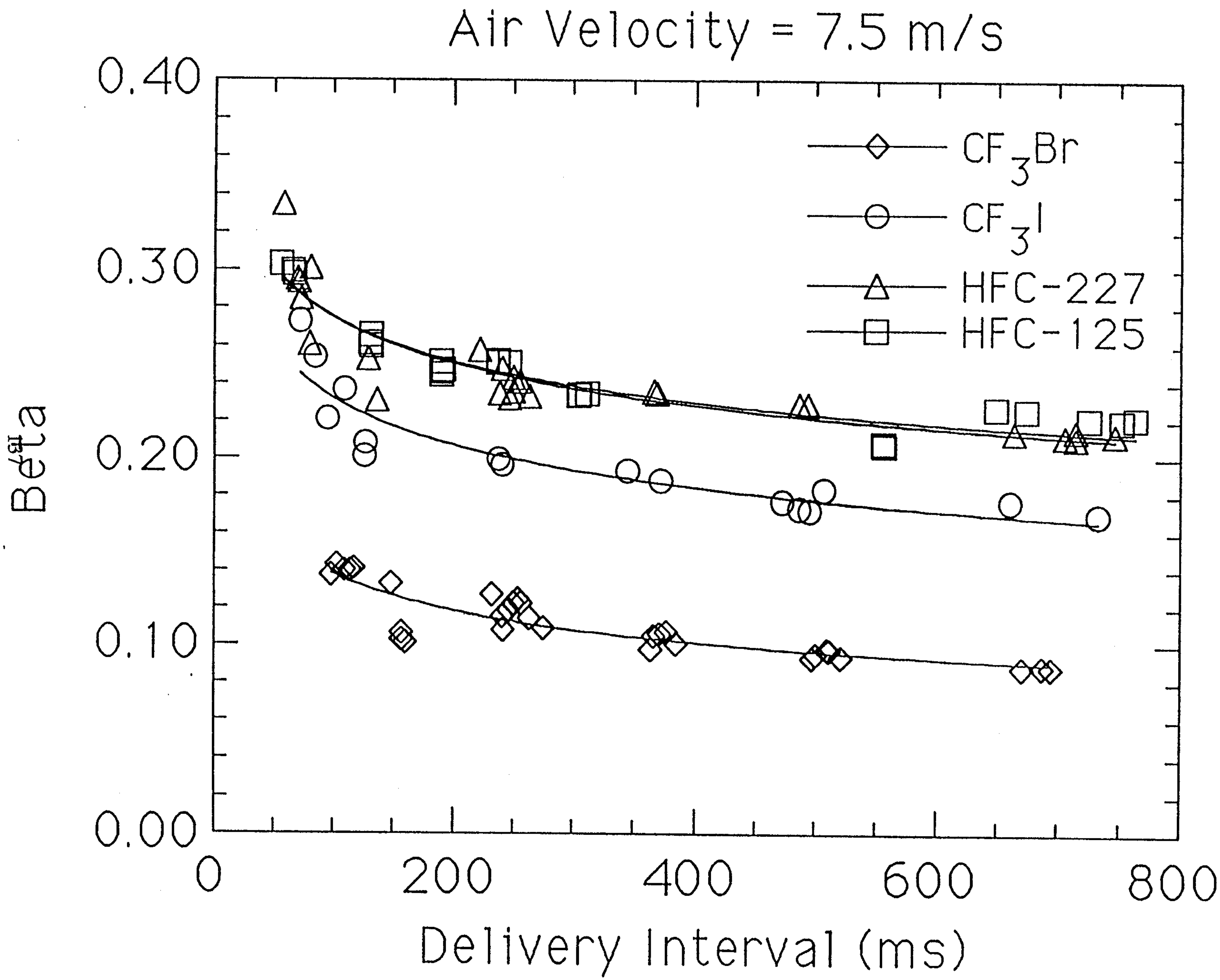
R = 25·5

R = 118



delivery interval = 700 ms
Mass (g)
Velocity (m/s)
CF3Br
CF3I
HFC-125
HFC-227
Blow-out
0
5
10
15
20
25
30
35

136



Air Velocity = 7.5 m/s
Beta
Delivery Interval (ms)
0.00
0.10
0.20
0.30
0.40
0
200
400
600
800
CF3Br
CF3I
HFC-227
HFC-125

AGENT ENTRAINMENT INTO RECIRCULATION ZONE

- Predict X_i as function of Δt, Velocity

Assumptions

- To extinguish flame, $X_i(\Delta t) \geq X_c$.
- Zone length (L) assumed constant.
- Instantaneous mixing occurs.
- Spray characteristics unimportant.

AGENT ENTRAINMENT INTO RECIRCULATION ZONE

Results

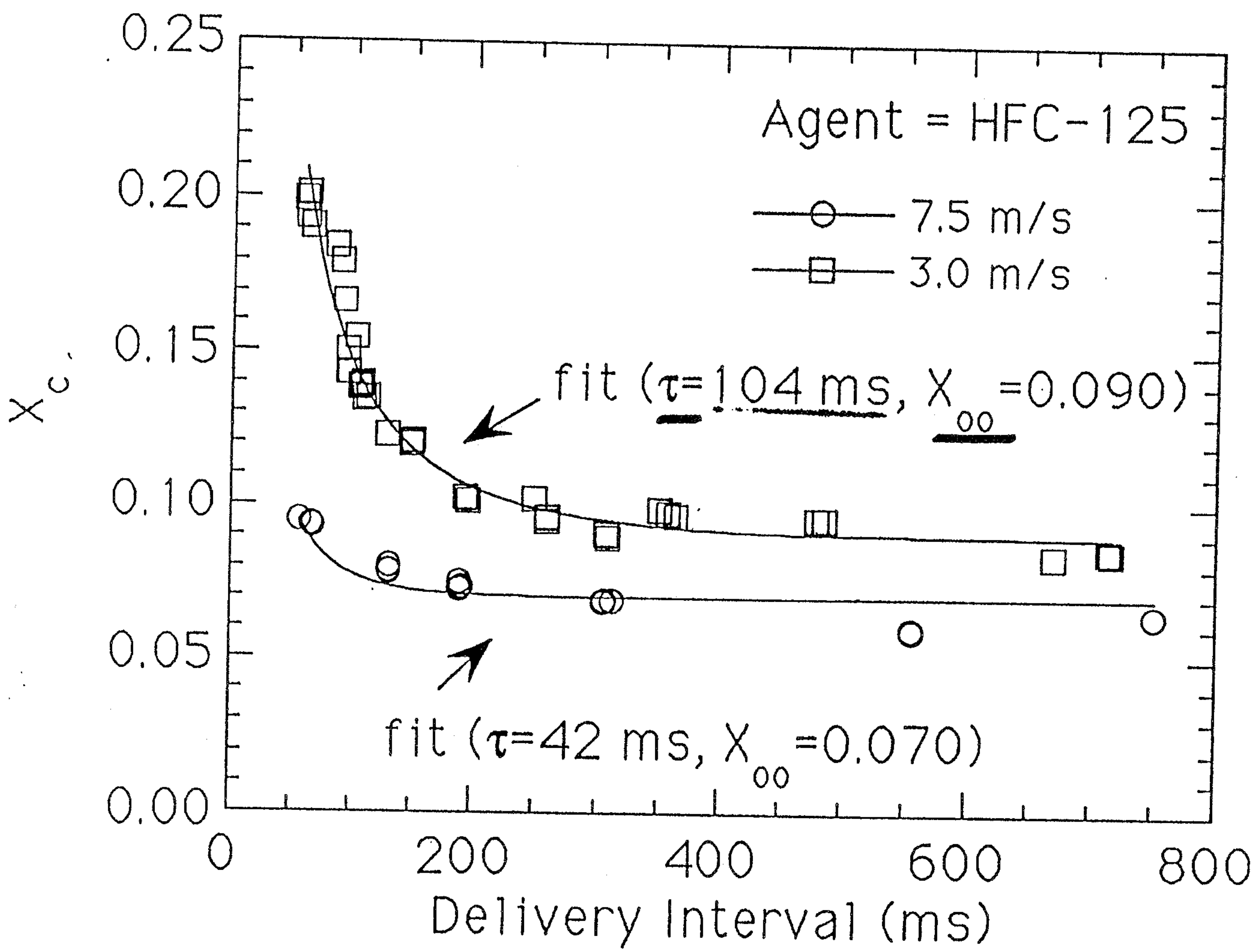
$$X_c(\Delta t) = \frac{X_\infty(\Delta t \gg \tau)}{1 - e^{(-\Delta t/\tau)}}$$

- Δt = injection interval.
- $\tau \approx L / V_{air}$
- $\Delta t_c \geq -\tau \cdot \ln(1 - X_\infty)$; i.e. $\Delta t_c \propto \tau$

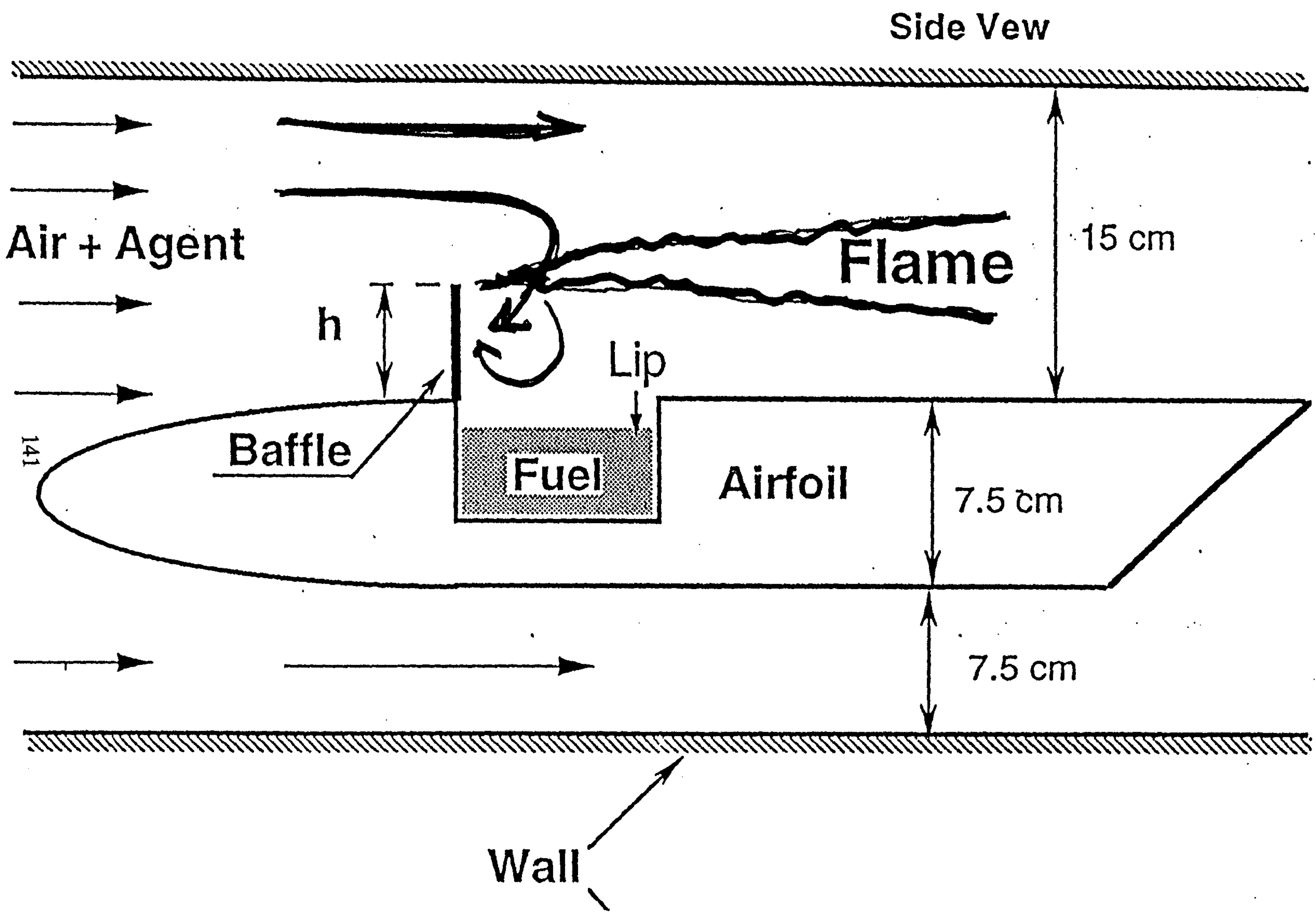
Limitations

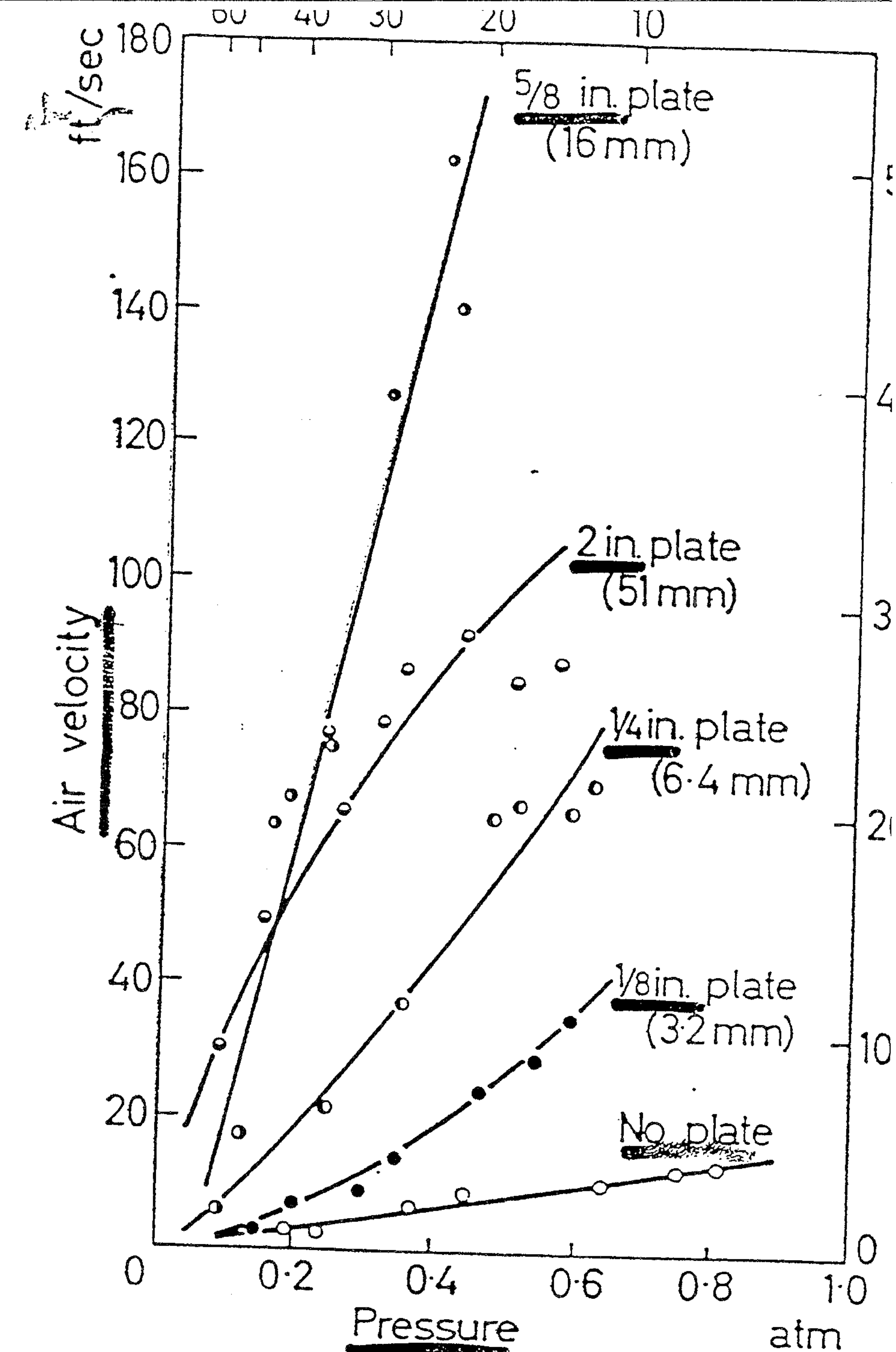
- X_∞ is not predicted, but is a function of agent chemistry.

Figure 3



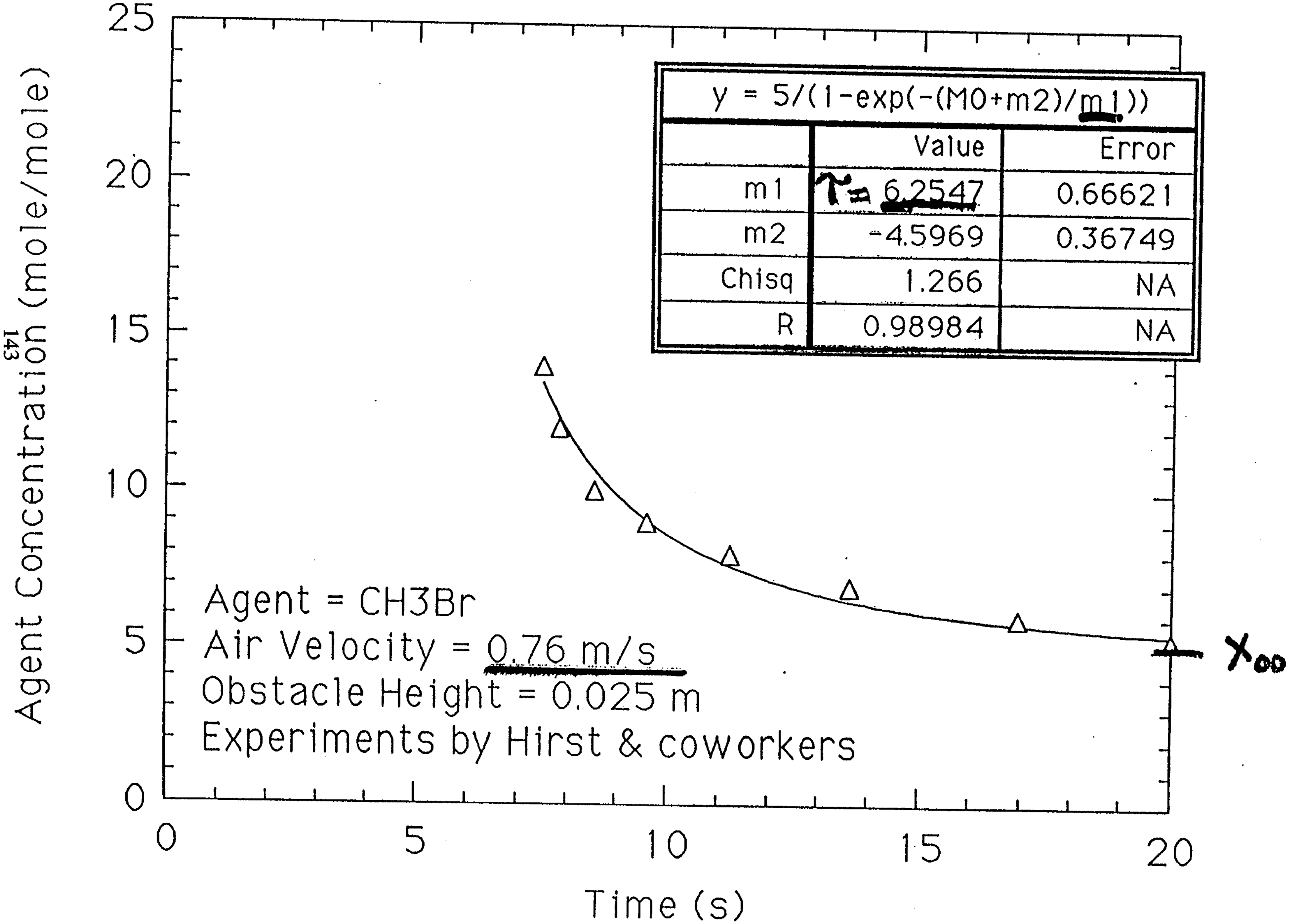
Agent = HFC-125
7.5 m/s
3.0 m/s
fit (τ=104 ms, X₀₀=0.090)
fit (τ=42 ms, X₀₀=0.070)
Xc
Delivery Interval (ms)
0.00
0.05
0.10
0.15
0.20
0.25
0
200
400
600
800


Side Vew
Air + Agent
Flame
15 cm
h
Lip
Baffle
Fuel
Airfoil
7.5 cm
7.5 cm
Wall

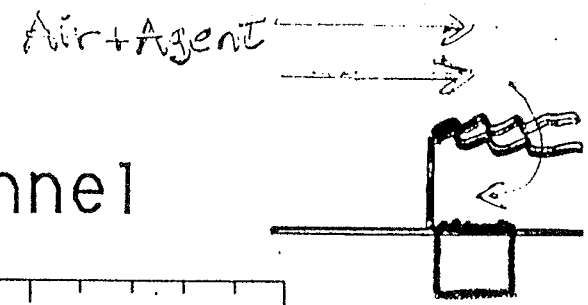


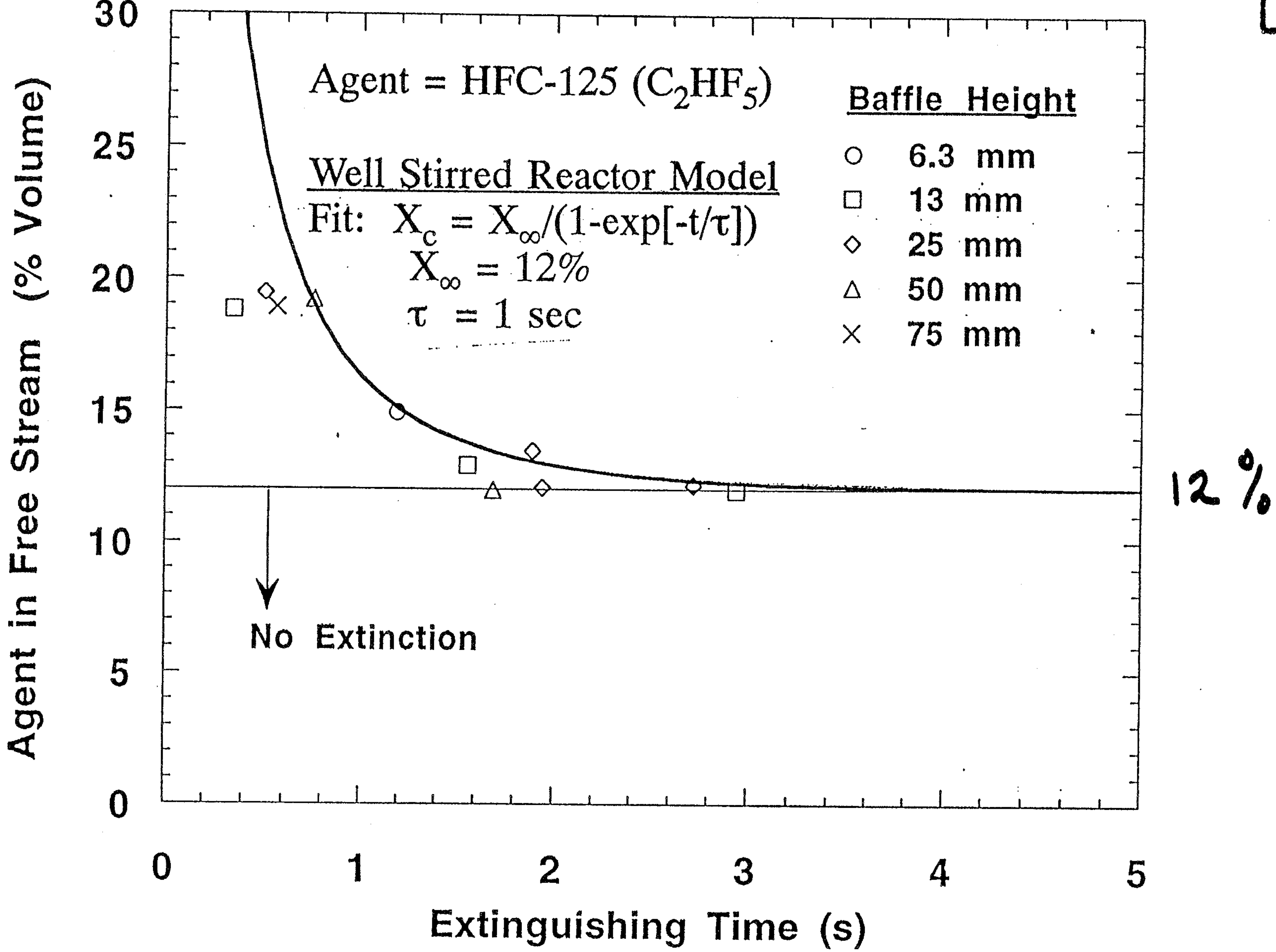
ure 11. The effect of plates at the front o tank (kerosine)

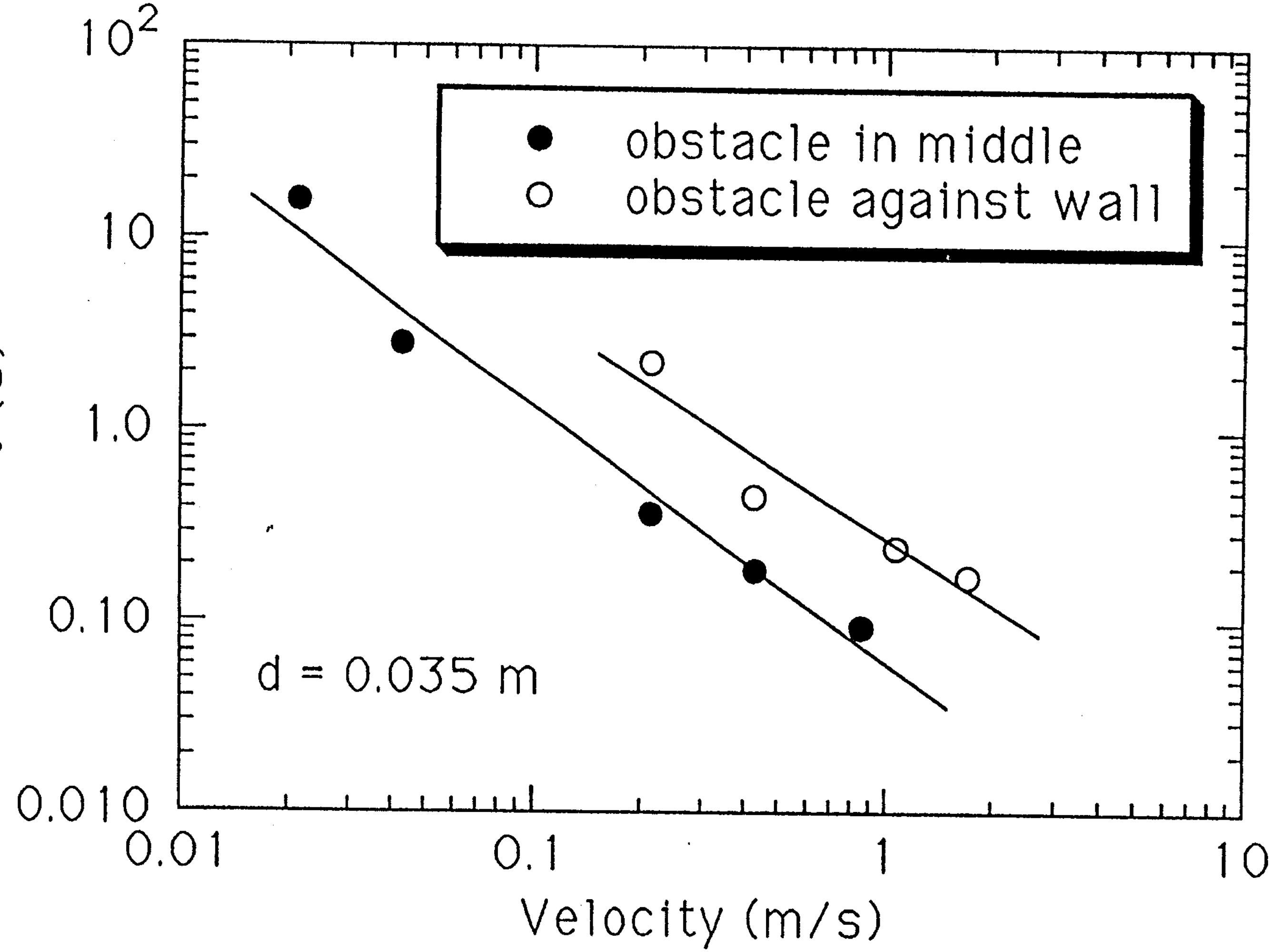
MIXING TIME DETERMINATION FOR POOL FIRE SUPPRESSION



Pool Fires in Wind Tunnel






obstacle in middle
obstacle against wall
d = 0.035 m
τ (s)
Velocity (m/s)
10^2
10
1.0
0.10
0.010
0.01
0.1
1
10

CONCLUSIONS

- In general, baffle stabilized pool fires are <u>more dangerous</u> than baffle stabilized spray fires because:

  1. Long mixing times associated with agent entrainment into the recirculation zone of an obstacle against a wall.

  2. Higher agent concentration is required to achieve extinction.

  A fire of this sort may occur in an engine nacelle when a fuel puddle is located downstream of a rib.

- A fire with a heated oxidizer flow requires more suppressant to extinguish.

SPECIES CONCENTRATION MEASUREMENTS

William M. Pitts
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

Coworkers: George Mulholland, Brett Breuel, Dick Harris, Mike Glover, Darren Lowe, Steven Chung, Rik Johnsson, Yonas Makai (PL), David Hess (CSTL)

Solid Propellant Gas Generator Workshop
NIST, June 28, 1995

NIST

REAL-TIME CONCENTRATION MEASUREMENT

PROJECT OBJECTIVE

The objective of this effort is to evaluate possible methods for real-time measurements of concentrations of alternative fire fighting agents for dry-bay and nacelle fire applications. If one or more feasible approaches are identified early in the investigation, a demonstration system will be developed for characterization under actual test situations.

MAJOR TASKS

1. Review of the Concentration Measurement Literature
2. Evaluate and Test Instrumentation Developed with Air Force Funding
3. Evaluate and Test Hot-Film Probes
4. Development of Operating Procedures (Optional)

NIST

OUTLINE

1. Introduction
2. Fire Extinguishing Agent Sensor (FEAS)
3. Differential Infrared Rapid Agent Sensor (DIRRACS)
4. Combined Aspirated Hot-Film/Cold-Wire Probe
5. Statham Analyzer and Halonyzer
6. Literature Review

NIST

TIME RESOLUTION REQUIREMENTS

- Dry-bay application requires fire extinguishment in tens of milliseconds.

- In order to characterize concentration behavior must be able to make real-time measurements significantly faster than the event.

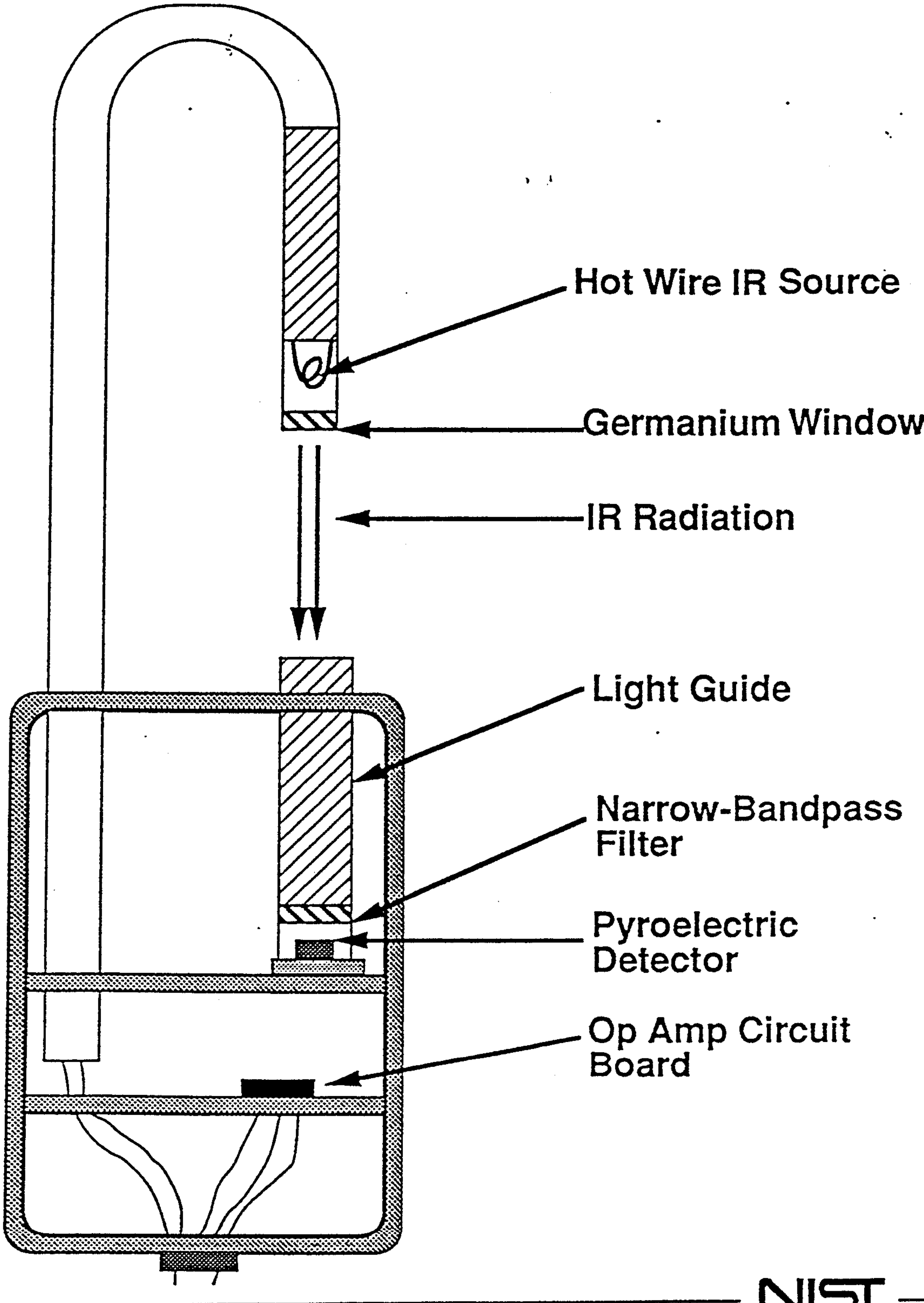
- A temporal resolution of one millisecond (1 kHz data rate) was chosen as design goal.

- Note that the required temporal resolution places constraints on spatial resolution.

- Compare current requirement with temporal response of existing Statham and Halonyzer instruments (0.25 s).

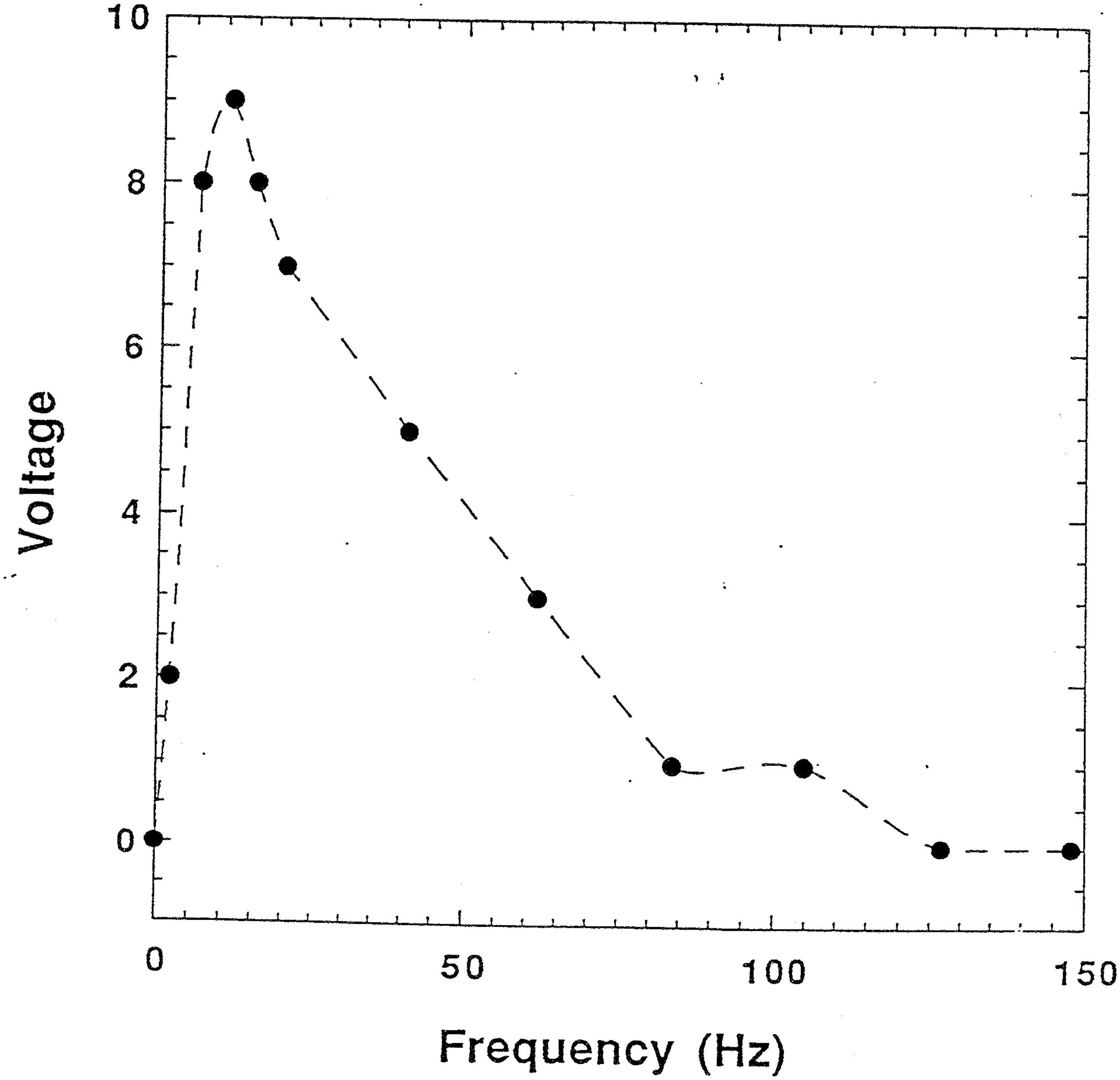
NIST

John Brown Associates Fire Extinguishing Agent Sensor (FEAS)



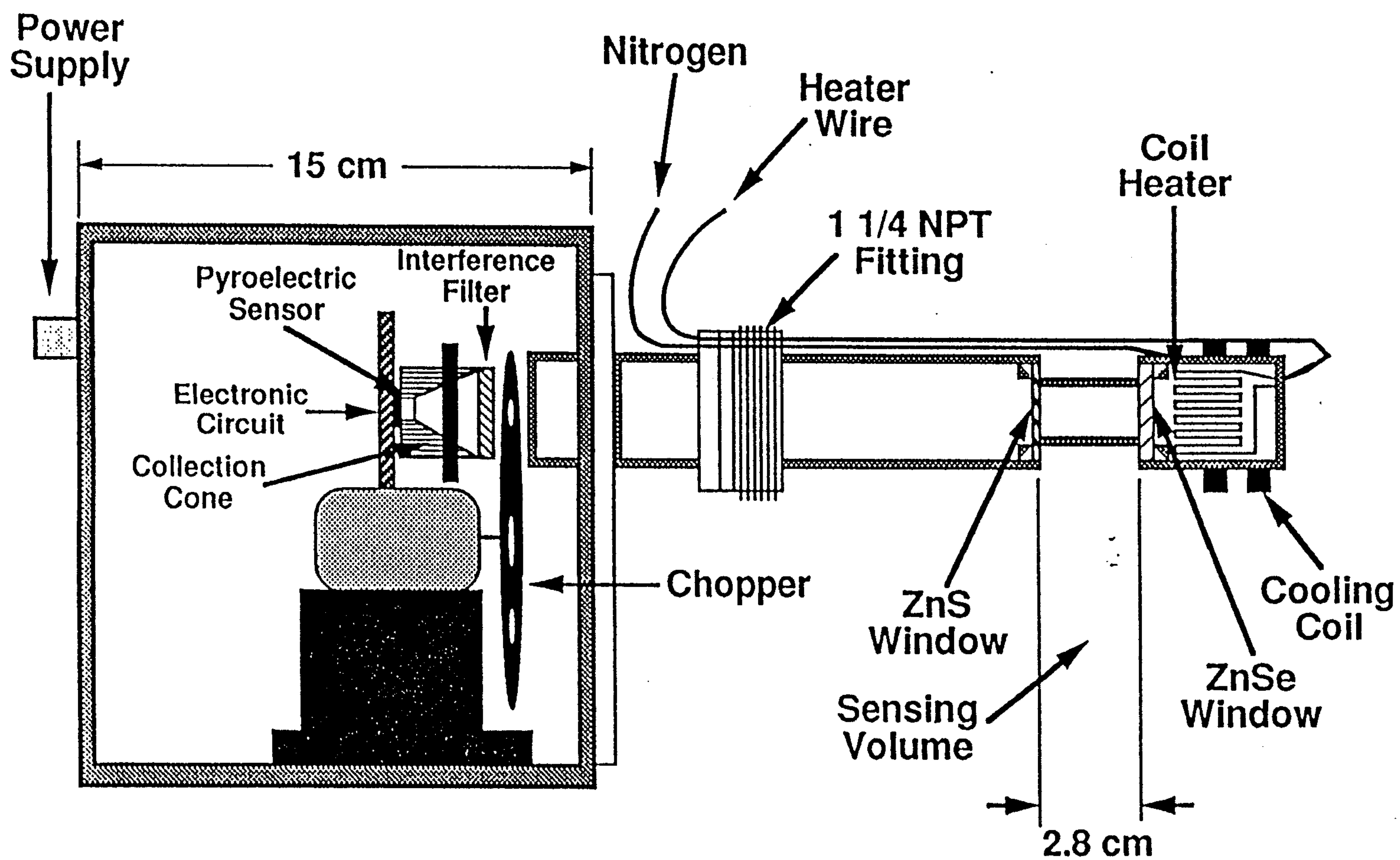
NIST

FREQUENCY RESPONSE OF THE FEAS



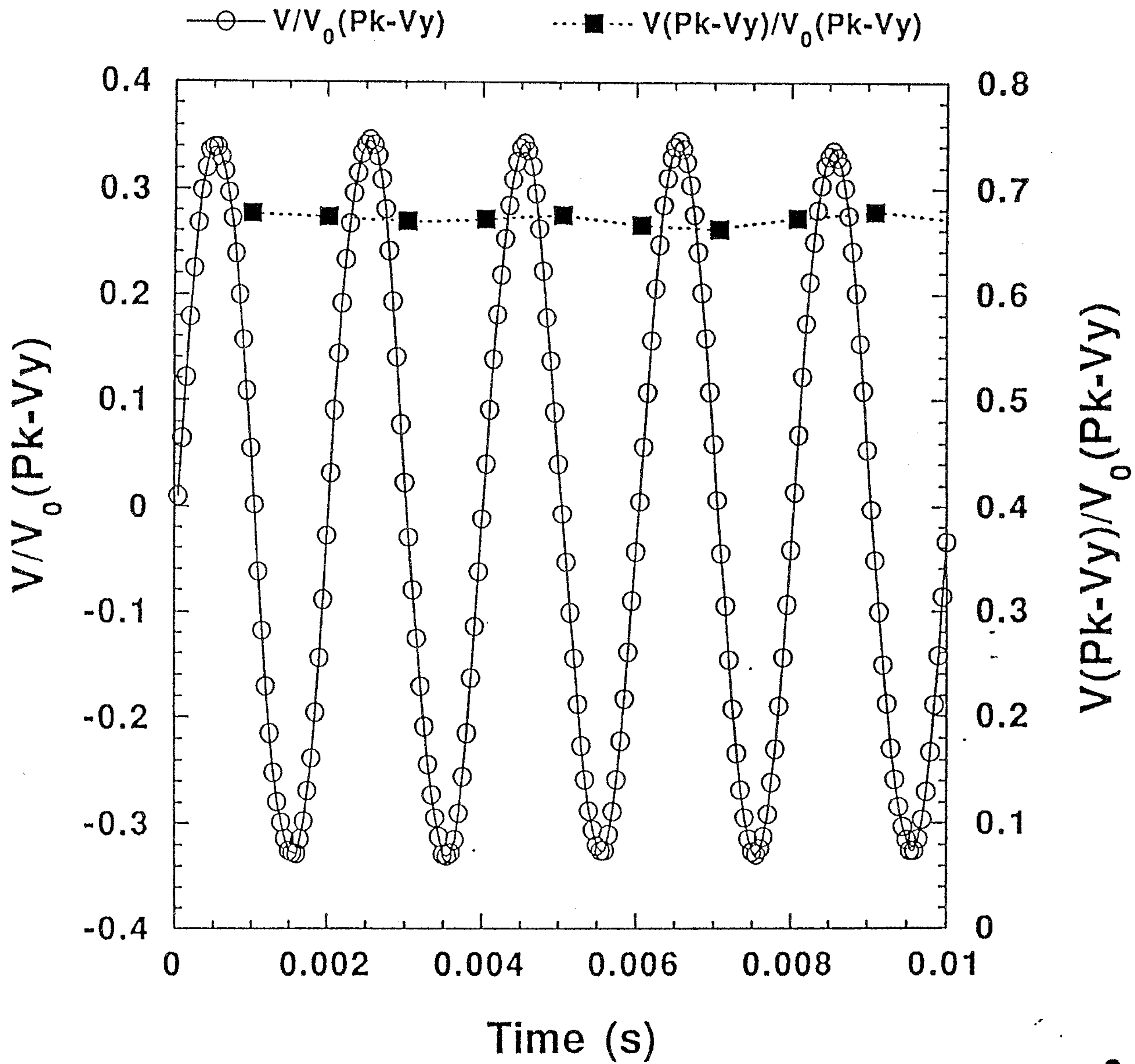
NIST

SCHEMATIC FOR THE DIFFERENTIAL INFRARED RAPID AGENT CONCENTRATION SENSOR (DIRRACS)

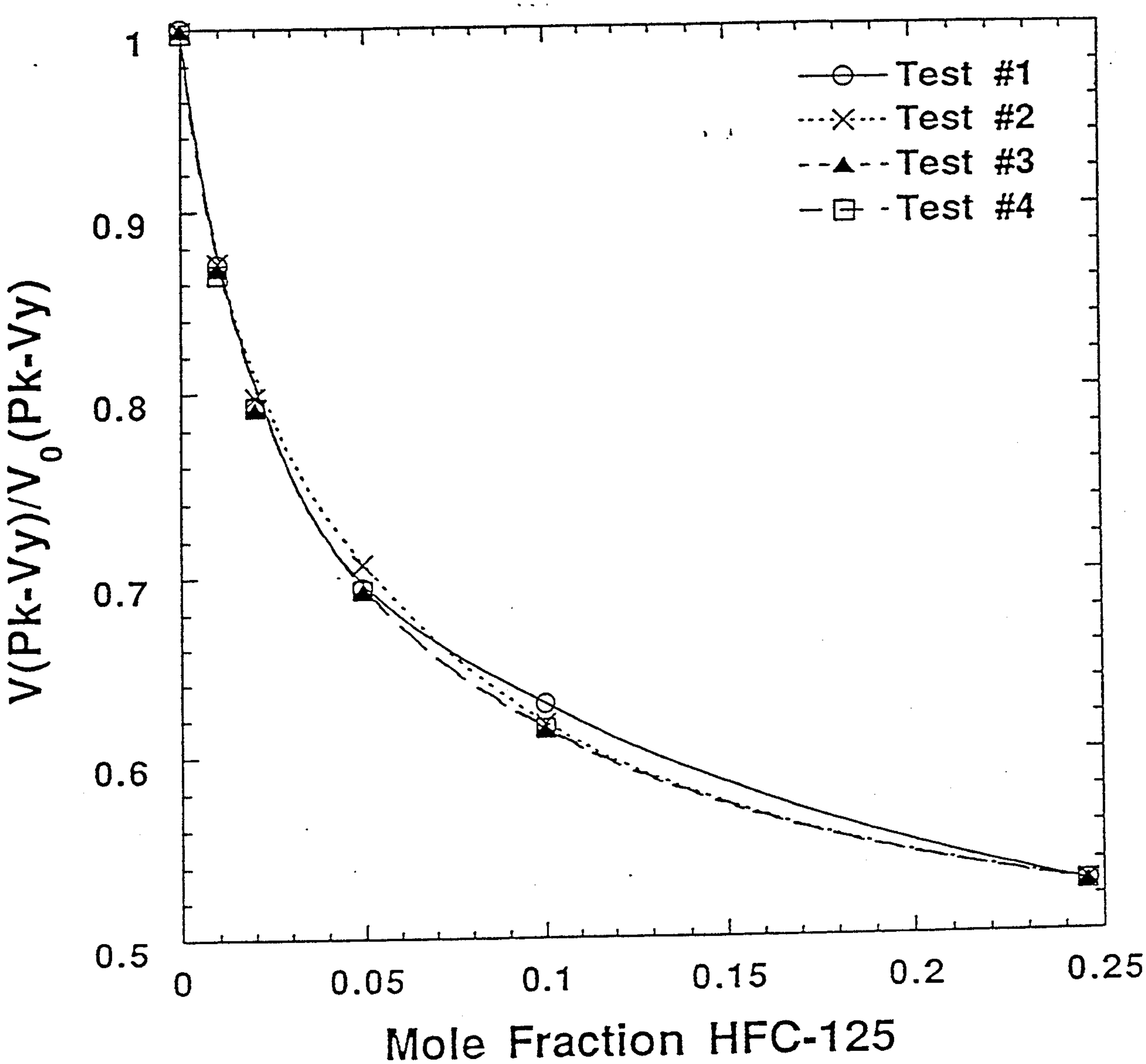


NIST

DIRRACS OUTPUT VOLTAGE

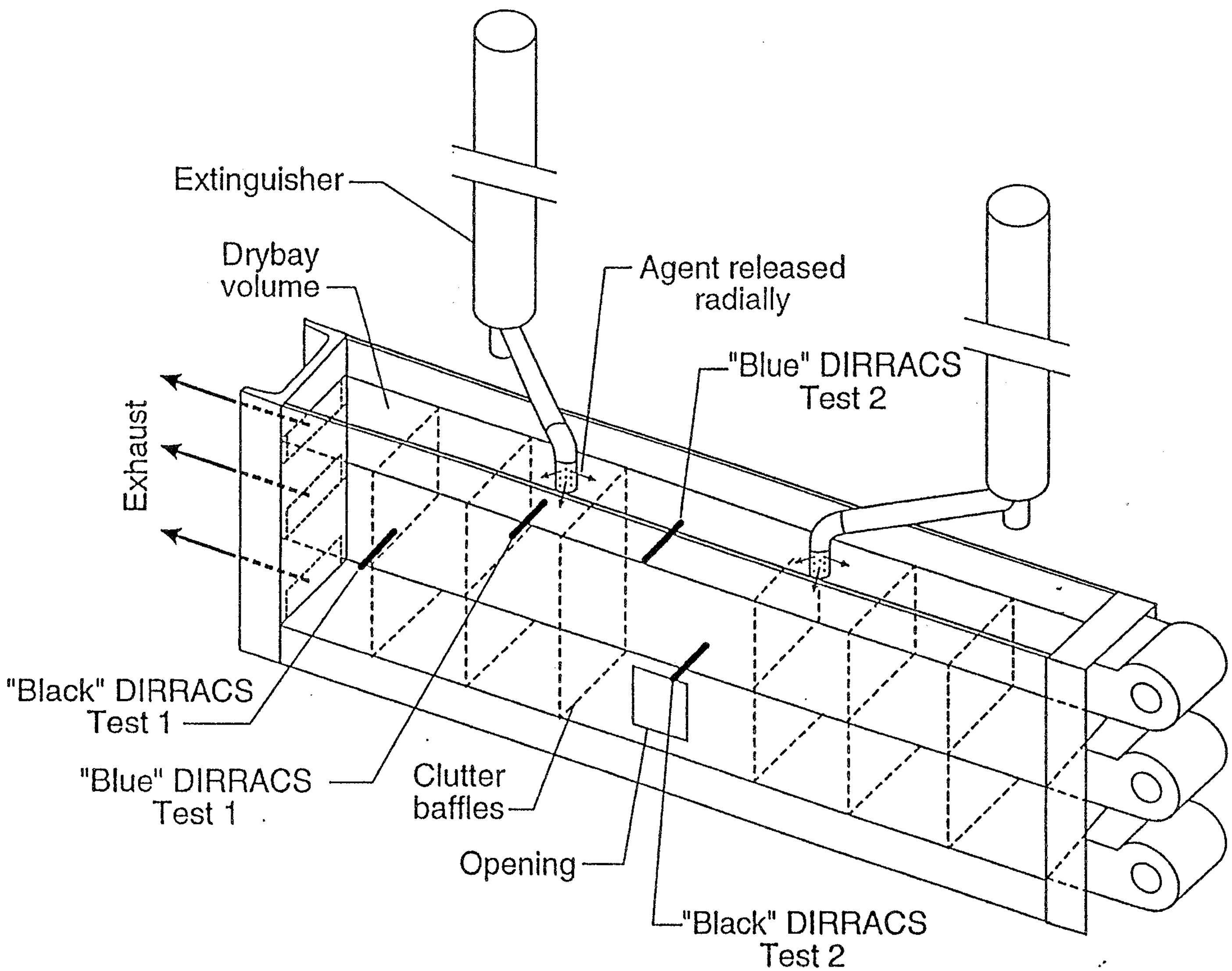


DIRRACS CALIBRATION

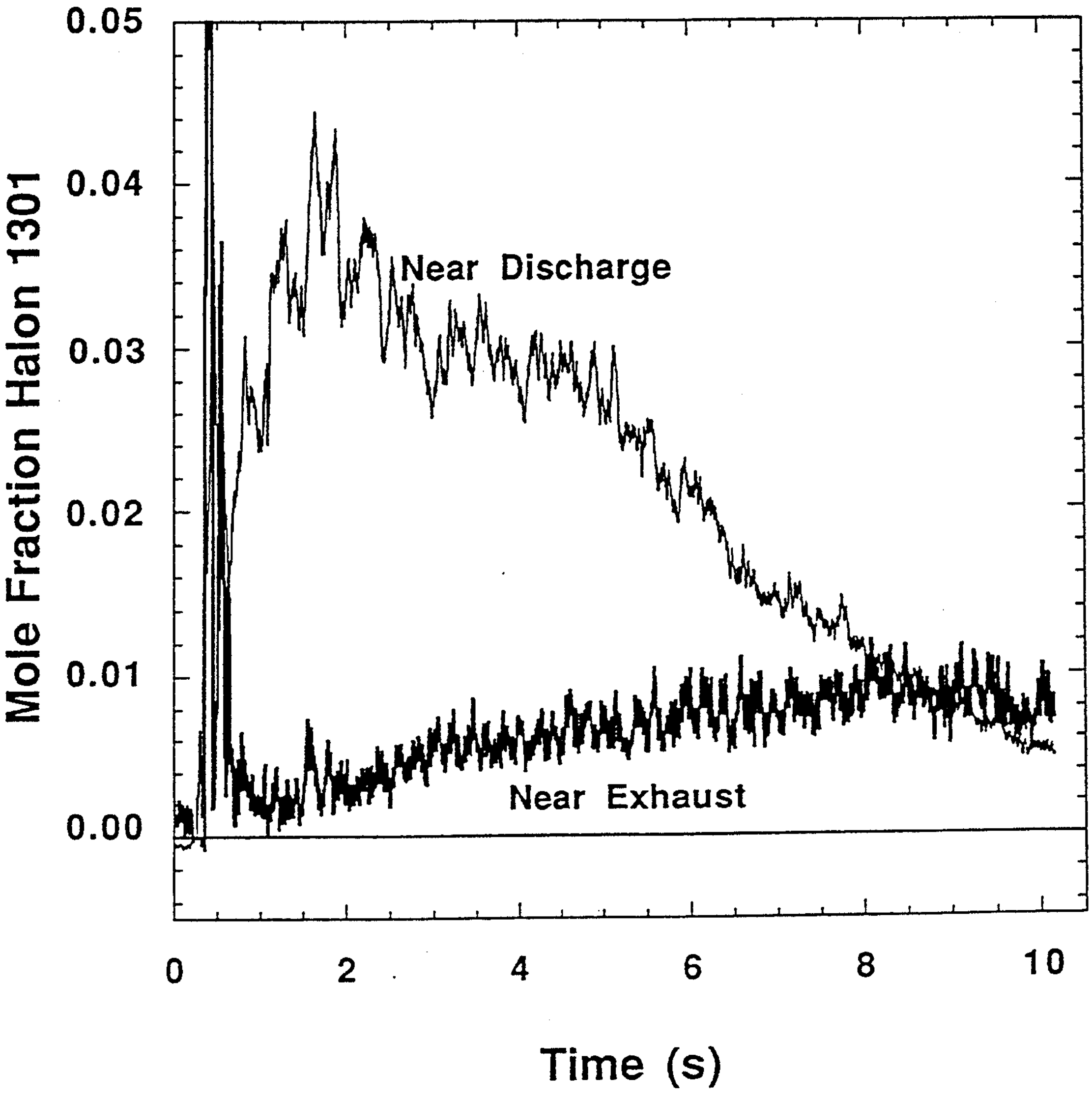


NIST

WRIGHT-PATTERSON DRY-BAY TEST FACILITY

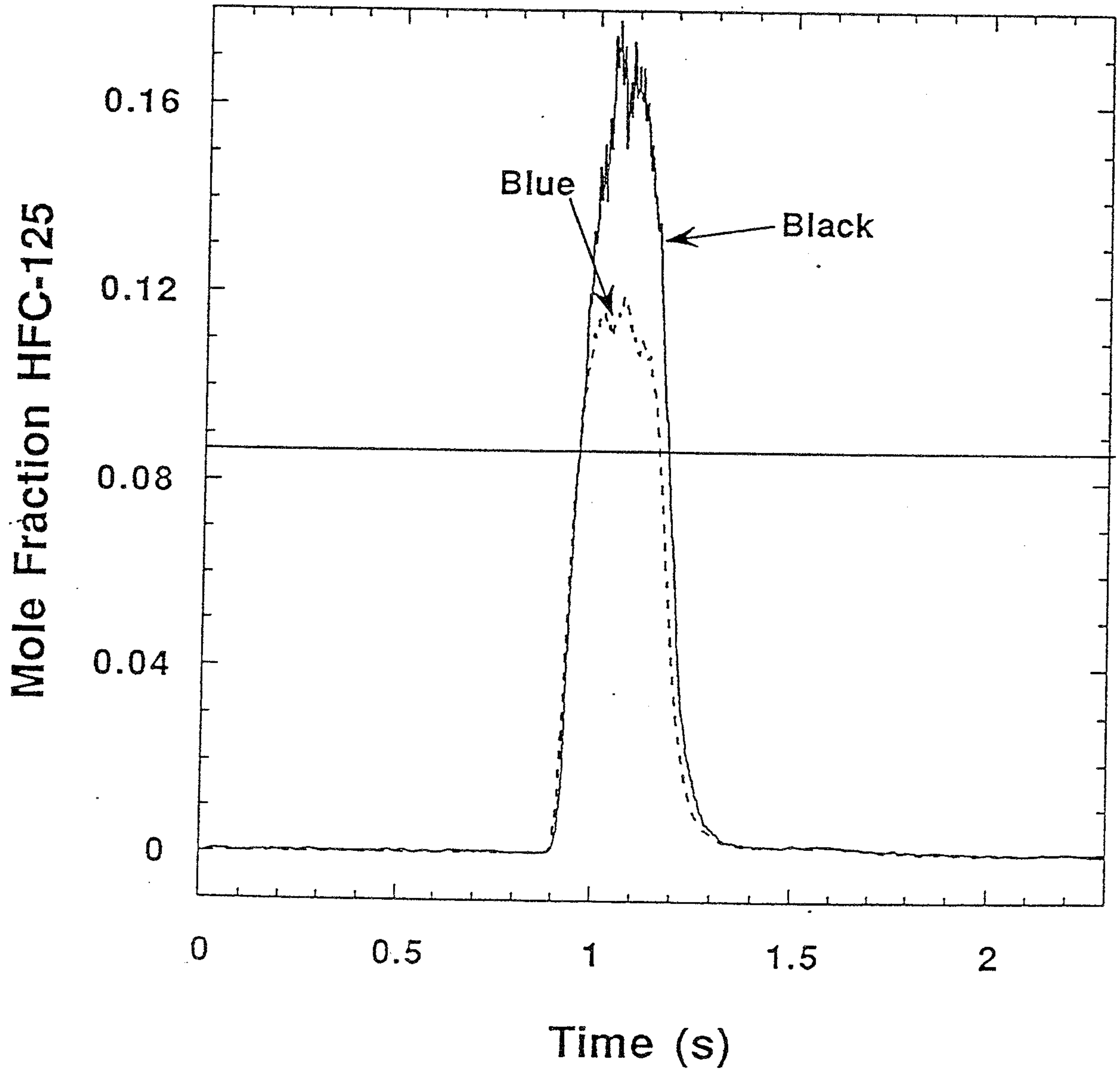


CONCENTRATION MEASUREMENTS DURING AGENT RELEASE INTO WRIGHT-PATTERSON AFB DRY-BAY FACILITY



NIST

DIRRACS CONCENTRATION MEASUREMENT IN TURBULENT SPRAY-FLAME BURNER FACILITY



NIST

CURRENT STATUS OF DIRRACS

- Feasibility demonstrated.
- Sensitivity to flow velocity must be eliminated.
- Reduction of sampling volume is desirable.

COMBINED ASPIRATED HOT-FILM/ COLD-WIRE CONCENTRATION PROBE

- Hot-film anemometer measures heat loss from heated cylinder, normally used for velocity measurement, but also responds to concentration and temperature variations.

- Volume flow rate through a choked orifice only depends on upstream pressure, stagnation temperature, and gas molecular weight.

- Placing hot-film in aspirated tube containing choked orifice eliminates most sensitivity to velocity and creates probe sensitive to concentration and temperature changes.

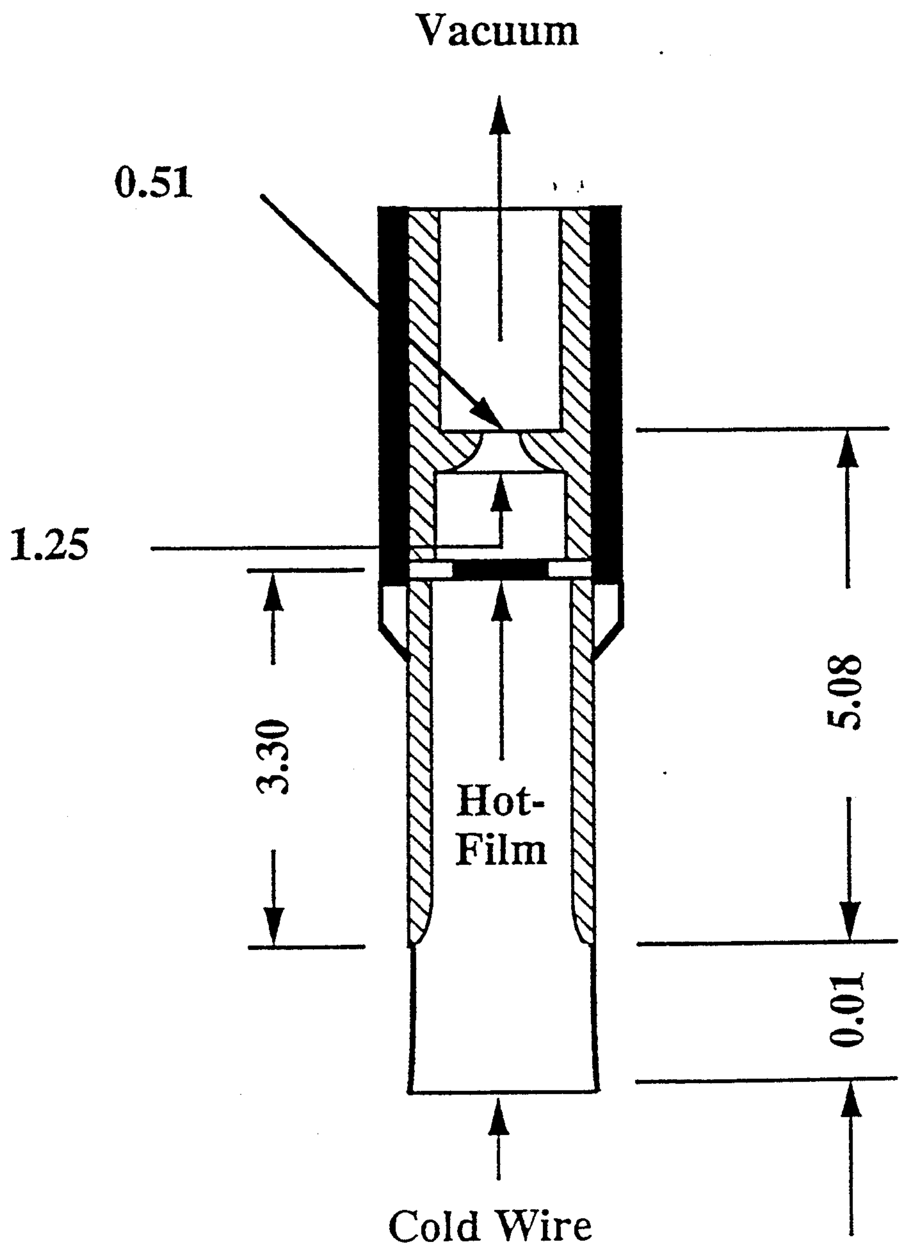
- Utilize a cold wire as a resistance thermometer to record temperature.

- Proper calibration of the combined aspirated hot-film/cold wire probe allows concentration to be measured in binary mixtures.

- Sampling volume $\approx$ 1 mm^3, temporal resolution $\approx$ 1 ms

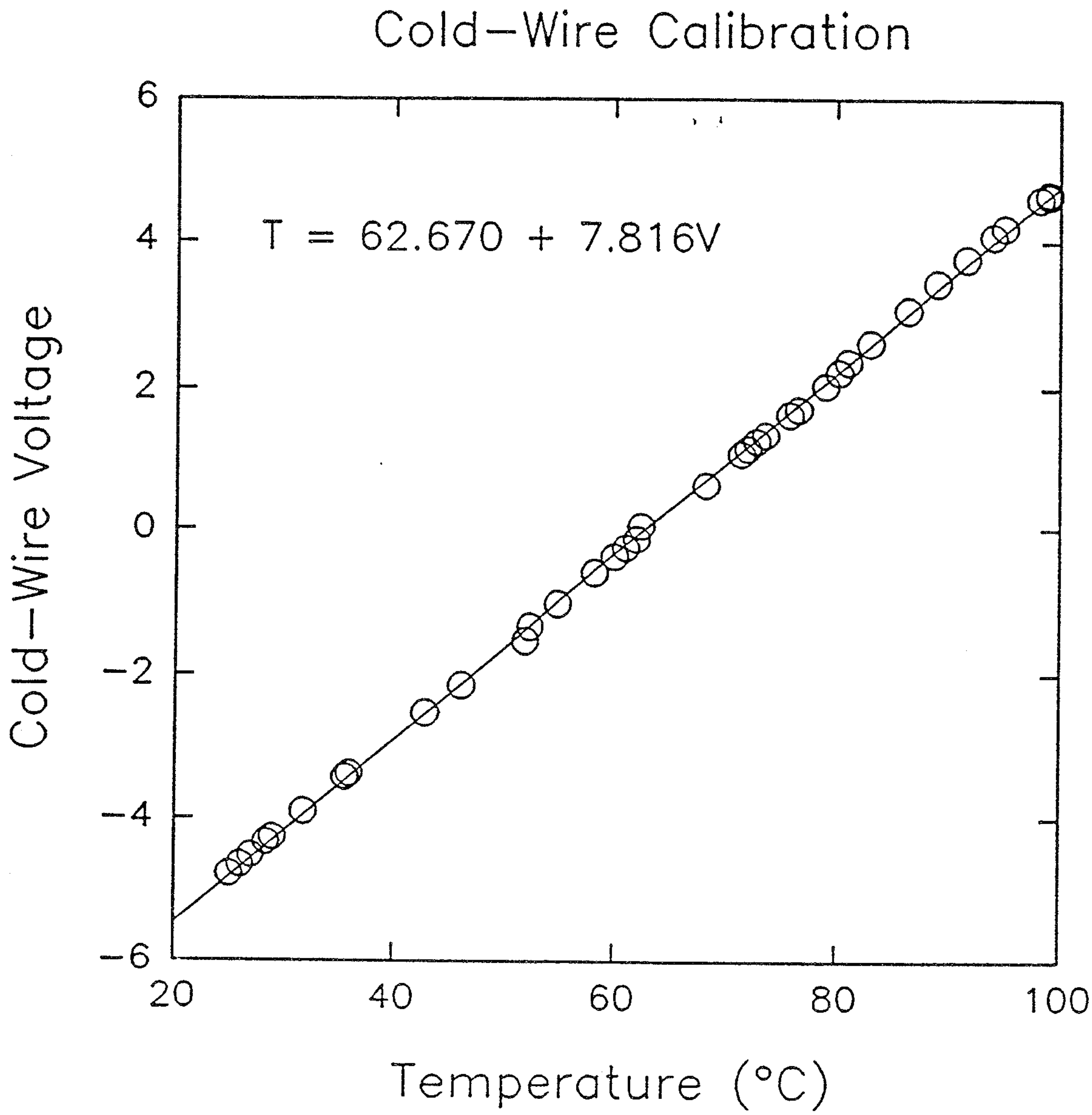
NIST

COMBINED ASPIRATED HOT-FILM/COLD-WIRE CONCENTRATION PROBE (TSI MODEL 1440S)

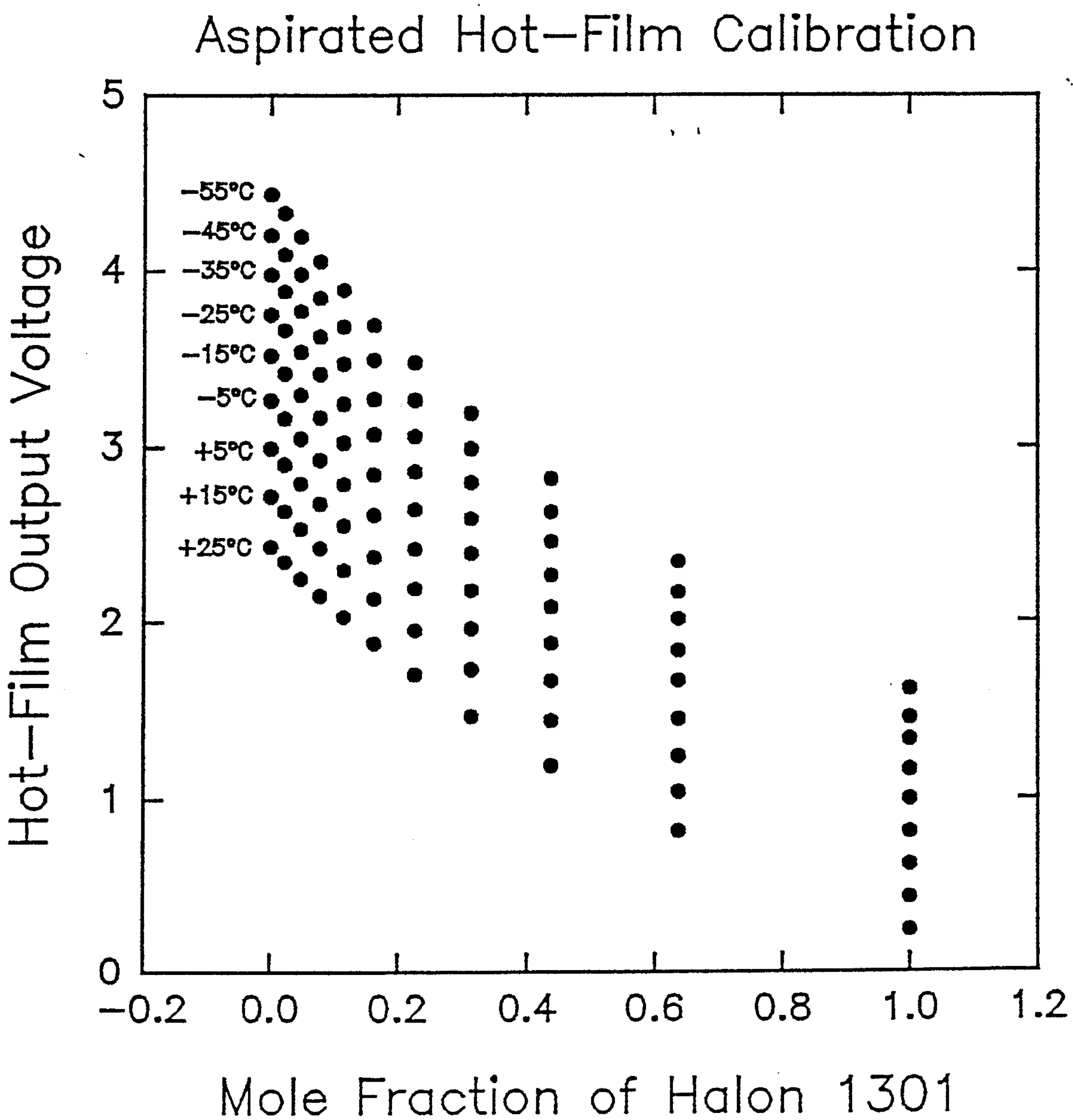


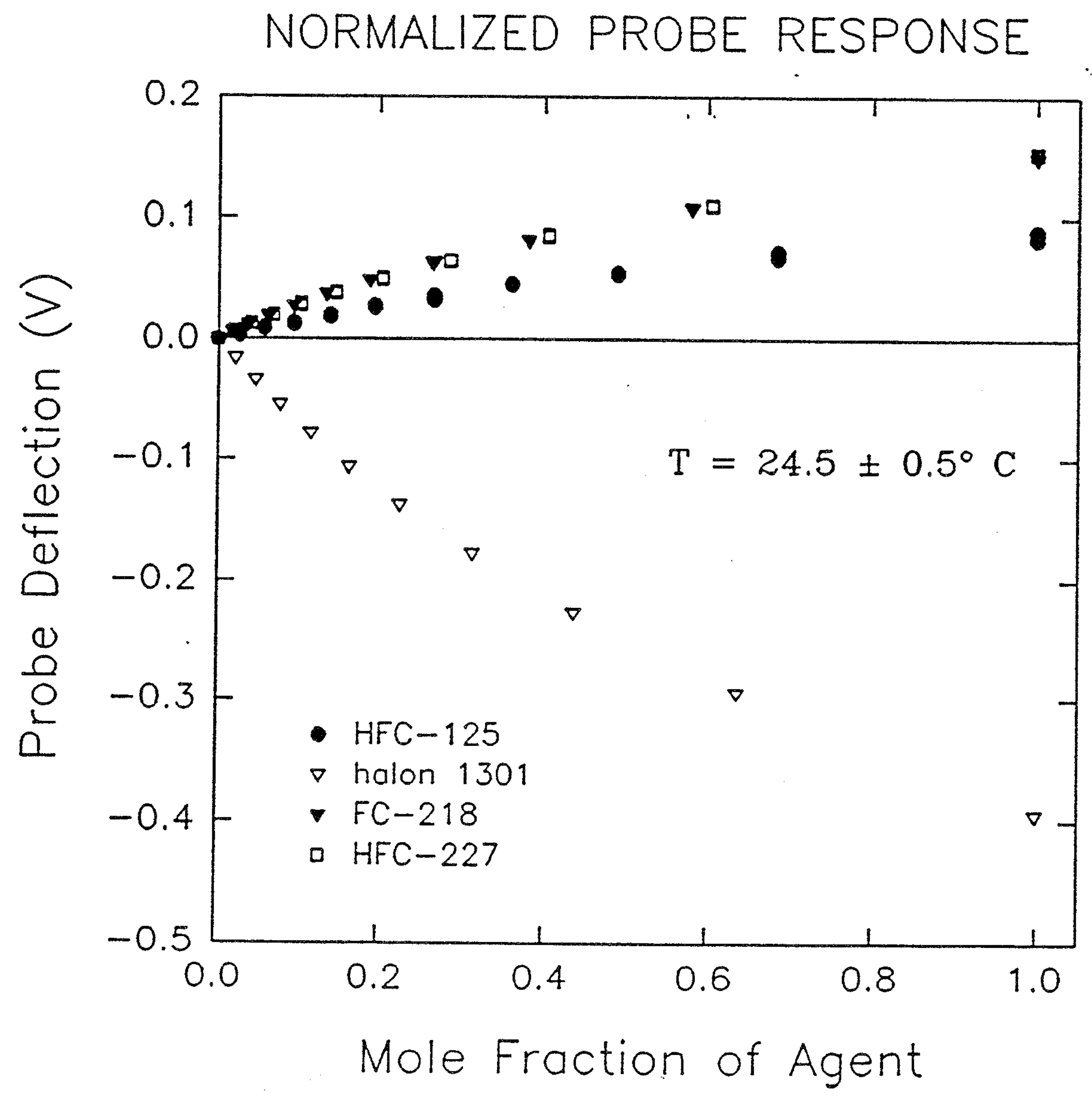
* All Measurements are in mm

NIST

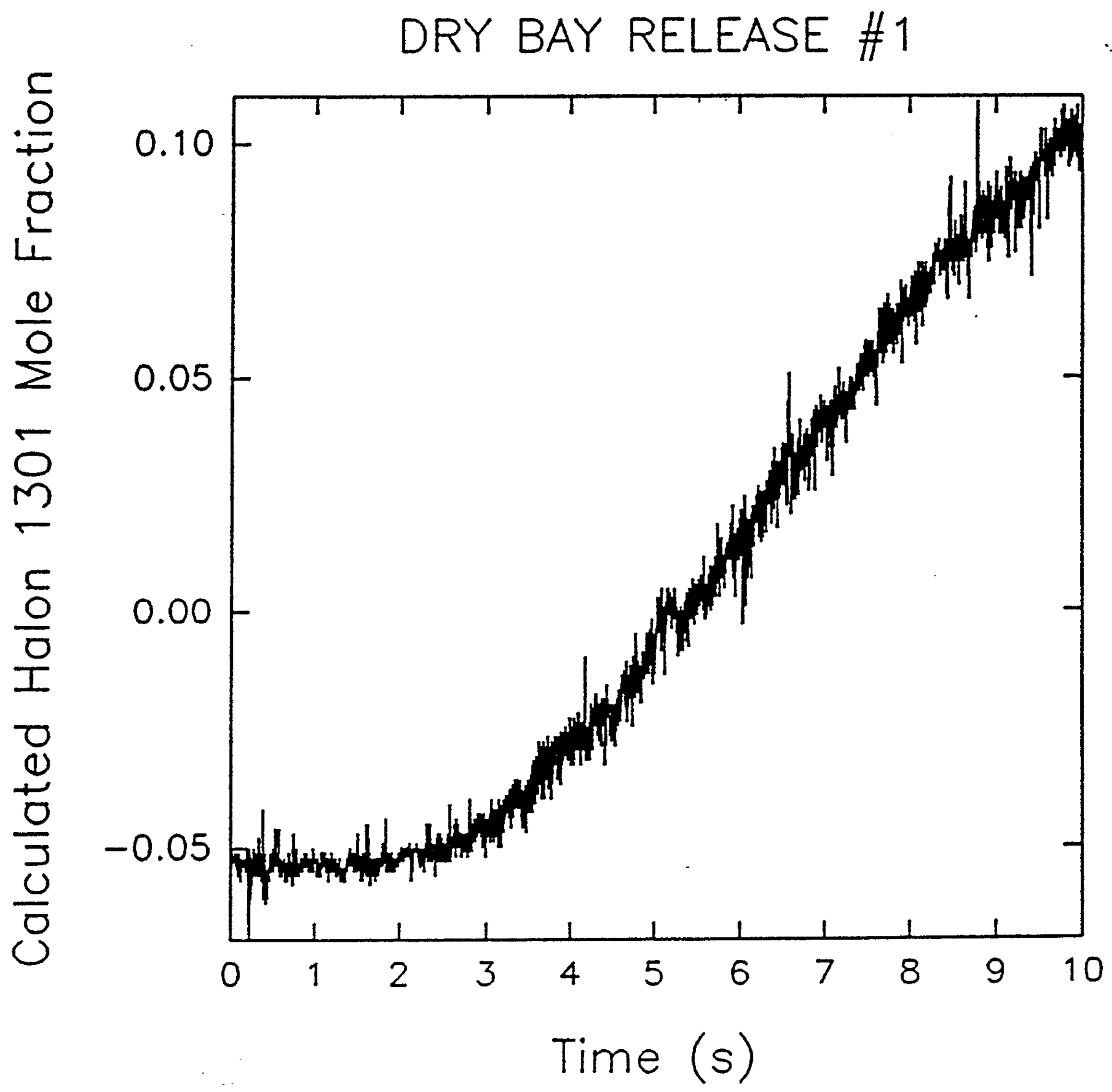

Cold-Wire Calibration
T = 62.670 + 7.816V
Cold-Wire Voltage
6
4
2
0
−2
−4
−6
20
40
60
80
100
Temperature (°C)

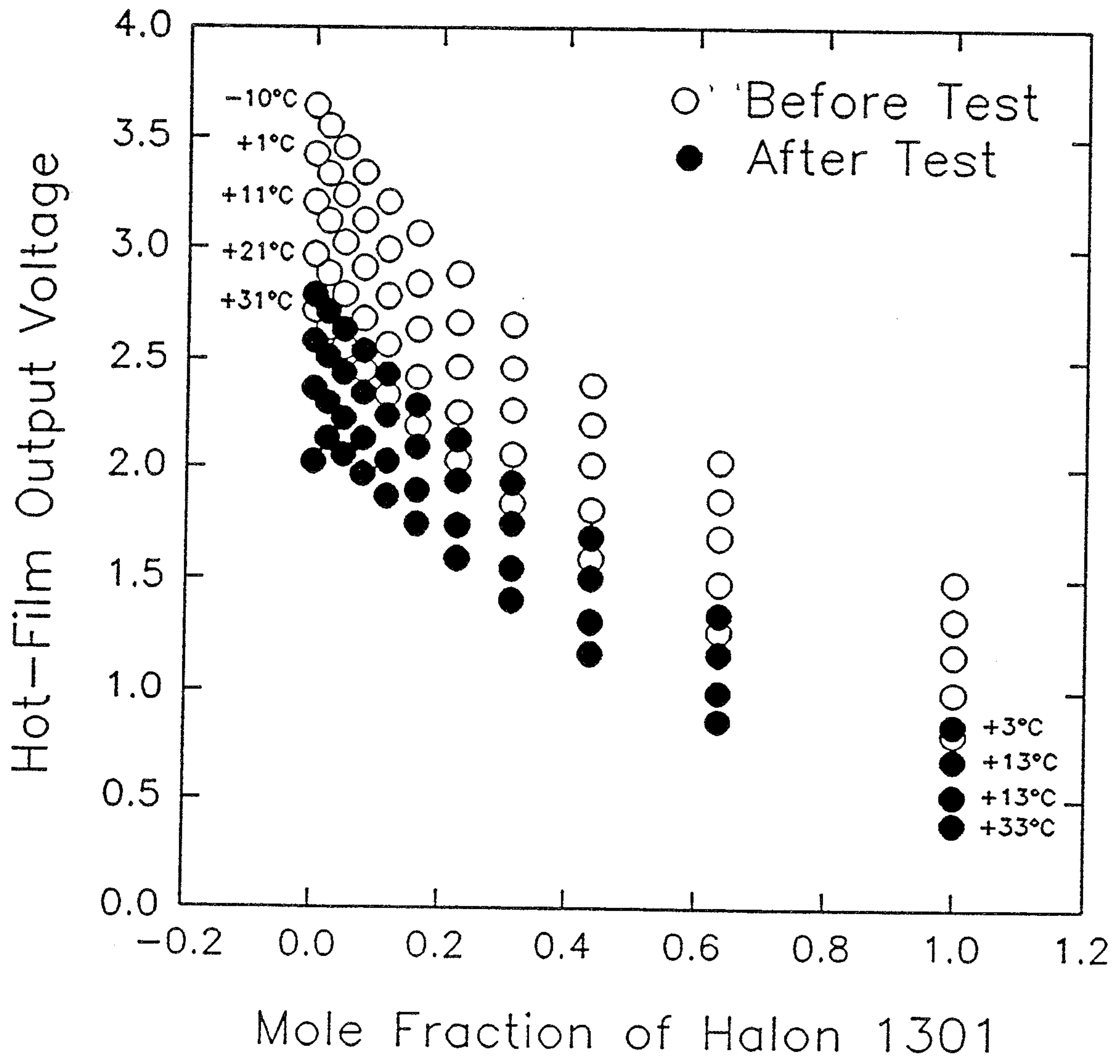
NIST


Aspirated Hot-Film Calibration
Hot-Film Output Voltage
Mole Fraction of Halon 1301
-55°C
-45°C
-35°C
-25°C
-15°C
-5°C
+5°C
+15°C
+25°C
0
1
2
3
4
5
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
NIST


NORMALIZED PROBE RESPONSE
Probe Deflection (V)
Mole Fraction of Agent
T = 24.5 ± 0.5° C
HFC−125
halon 1301
FC−218
HFC−227
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
−0.5
0.0
0.2
0.4
0.6
0.8
1.0

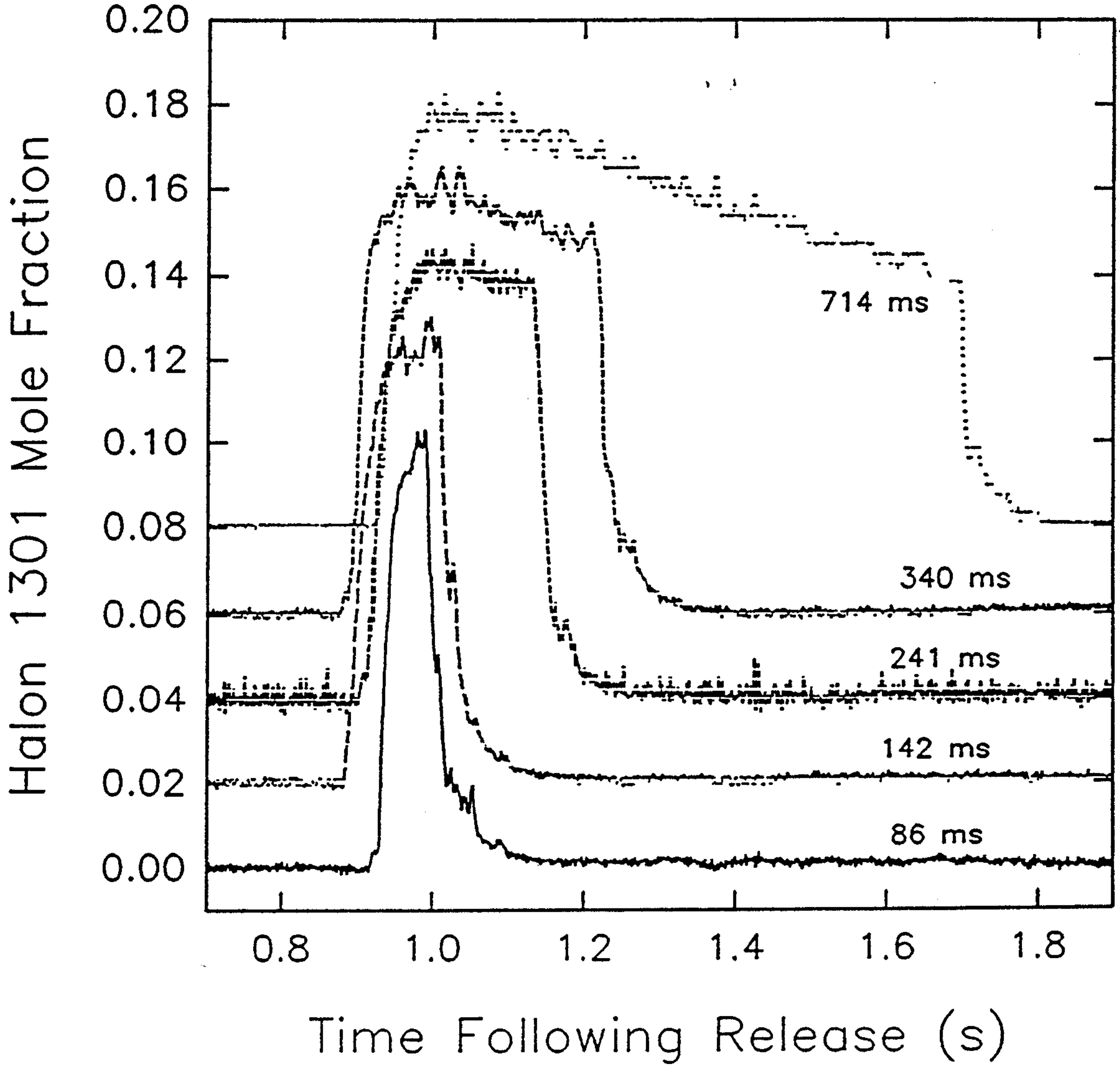
NIST


DRY BAY RELEASE #1
Calculated Halon 1301 Mole Fraction
0.10
0.05
0.00
−0.05
0
1
2
3
4
5
6
7
8
9
10
Time (s)



Before Test
After Test
-10°C
+1°C
+11°C
+21°C
+31°C
+3°C
+13°C
+13°C
+33°C
Hot-Film Output Voltage
Mole Fraction of Halon 1301
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2

NIST


Halon 1301 Mole Fraction
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
714 ms
340 ms
241 ms
142 ms
86 ms
0.8
1.0
1.2
1.4
1.6
1.8
Time Following Release (s)

CURRENT STATUS OF COMBINED ASPIRATED HOT-FILM/COLD-WIRE PROBE

- Probe is subject to clogging during actual dry-bay tests (attributed to use of squib charge).
- Probe has an unexpected sensitivity to velocity fluctuations.
- Probe is capable of accurate measurements of agent concentration with high temporal and spatial resolution.
- Probe sensitivity depends on gas pairs considered.
- Additional development <u>might</u> lead to a probe which could be used in dry-bay and nacelle test facilities.

NIST

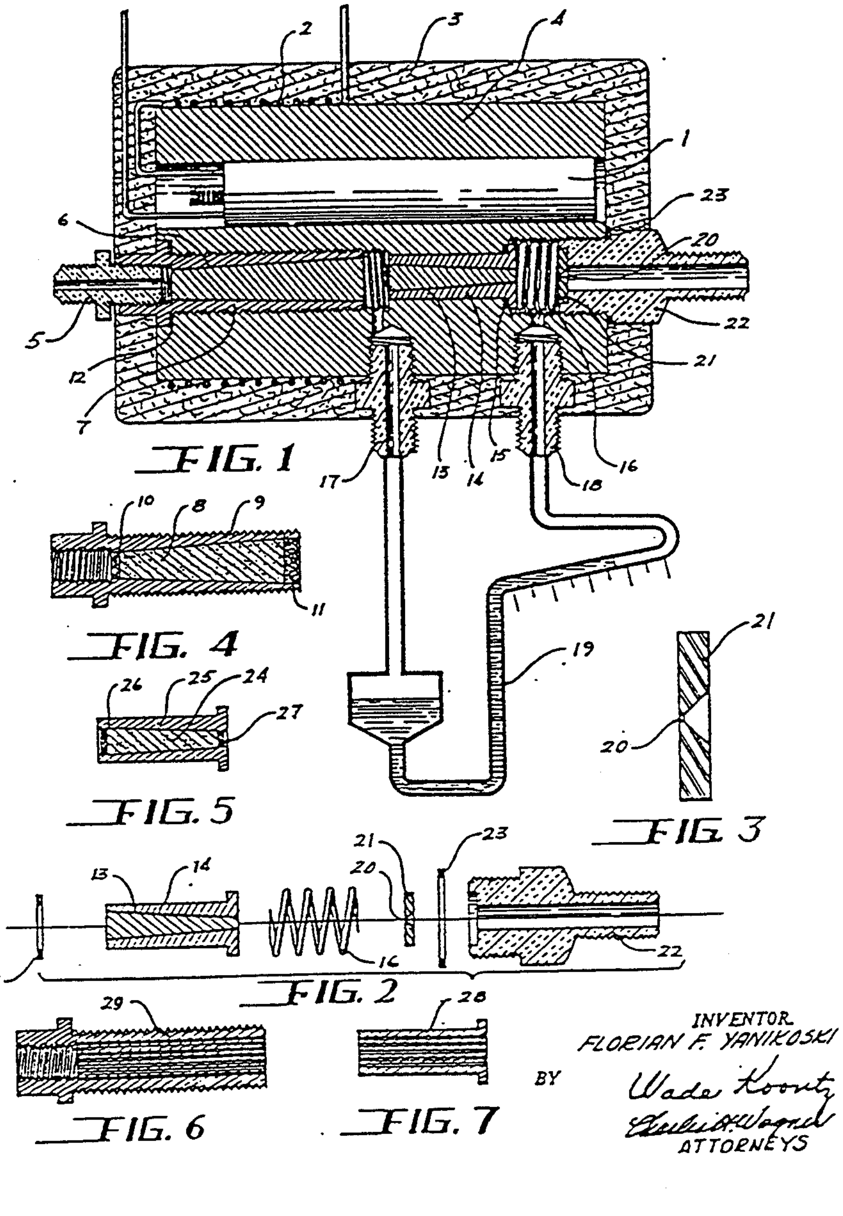
SCHEMATIC FOR A "GAS ANALYSIS APPARATUS" REPRODUCED FROM THE UNITED STATES PATENT OF YANIKOSKI (1952)

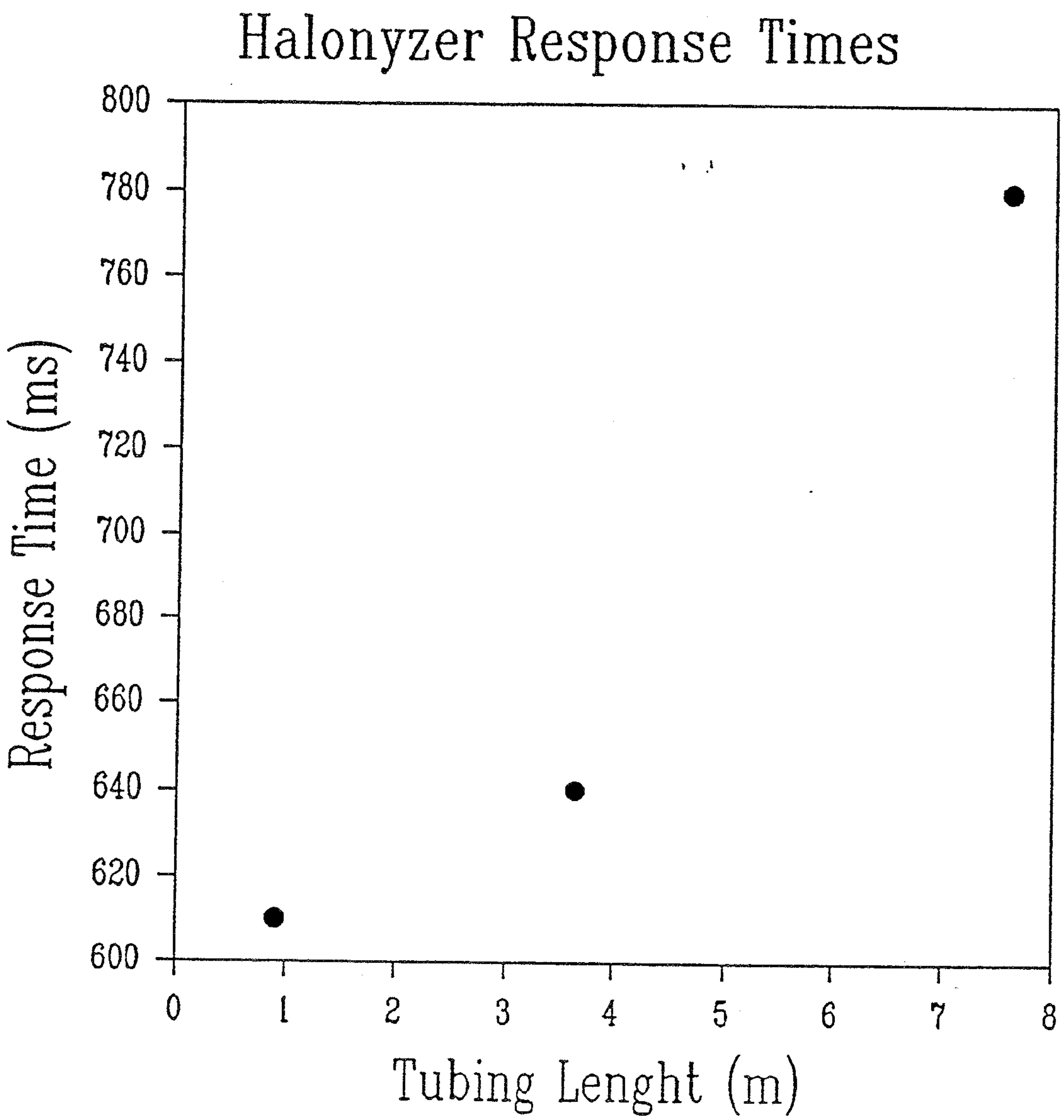
DEC 2 10 34 '69

Feb. 26, 1952 F. F. YANIKOSKI 2,586,899

GAS ANALYSIS APPARATUS

Filed Oct. 18, 1946





Response times for a Halonyzer concentration reading to change from 0 to 95% for a step increase in halon 1301 mole fraction to 100% as a function of sampling tube length. Data provided by W. Meserve and D. Van Ostrand of Pacific Scientific.

11.5 Literature Search For Additional Diagnostics for High-Speed Alternative-Agent Concentration Measurement

- 11.5.1 Introduction
- 11.5.2 "Standard" Chemical-Analysis Techniques
  - 11.5.2.1 Gas-Solid and Gas-Liquid Chromatography.
  - 11.5.2.2 Mass Spectrometry.
  - 11.5.2.3 Standard Optical Absorption Techniques.
- 11.5.3 Fiber-Optic-Based Measurements of Concentration
  - 11.5.3.1 Introduction To Fiber Optics.
  - 11.5.3.2 Spatially Resolved Absorption Concentration Measurements Using Fiber Optics.
  - 11.5.3.3 Other Fiber-Optic-Based Concentration Measurement Approaches.
- 11.5.4 Additional Optical-Based Techniques
  - 11.5.4.1 Raman Spectroscopy.
  - 11.5.4.2 Coherent Anti-Stokes Raman Spectroscopy (CARS).
  - 11.5.4.3 Rayleigh Light Scattering.
  - 11.5.4.4 Fluorescence Concentration Measurements.
  - 11.5.4.5 Mie Scattering Concentration Measurements.
  - 11.5.4.6 Specialized Concentration Measurements Based on Optical Absorption.
  - 11.5.4.7 Optical Speckle Technique.
  - 11.5.4.8 Miniature Mach-Zehnder Interferometer.
- 11.5.5 Acoustic Absorption

TECHNIQUES RECOMMENDED FOR CONSIDERATION BASED ON LITERATURE REVIEW

- Time-resolved mass spectrometry.

- Mid-infrared absorption used in conjunction with fiber optics for spatial resolution.

- Near-infrared absorption used in conjunction with fiber optics for spatial resolution.

OXYGEN CONCENTRATION MEASUREMENTS USING DIODE LASERS

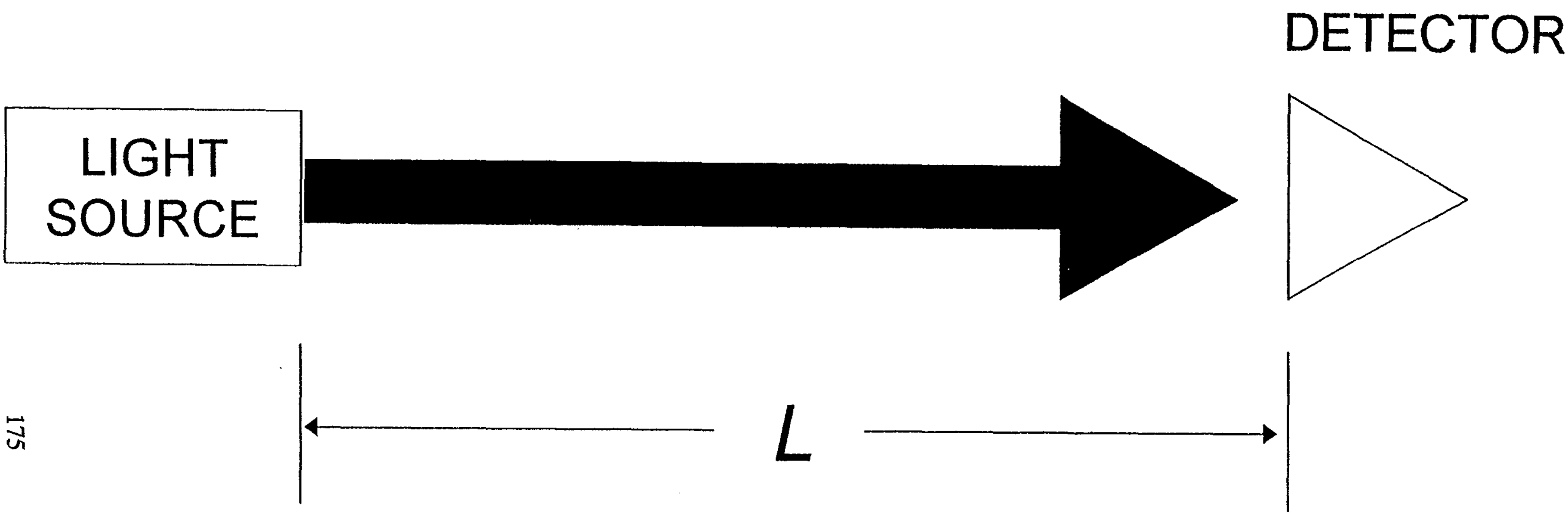
David Bomse
Southwest Sciences, Inc.
Santa Fe, NM
505-984-1322

Gas Generator Workshop
NIST
June 28, 1995

WHY USE DIODE LASERS?

- High selectivity avoids interferences
  - + O_2, CO, CO_2, H_2O, HF, NO, NO_2, HCN, HCl
- High sensitivity
  - + trace gas detection, OR
  - + rapid response
- Remote sensing using fiber optics or open paths
  - + intrinsic safety
  - + probe harsh environments

OPTICAL SPECTROSCOPY

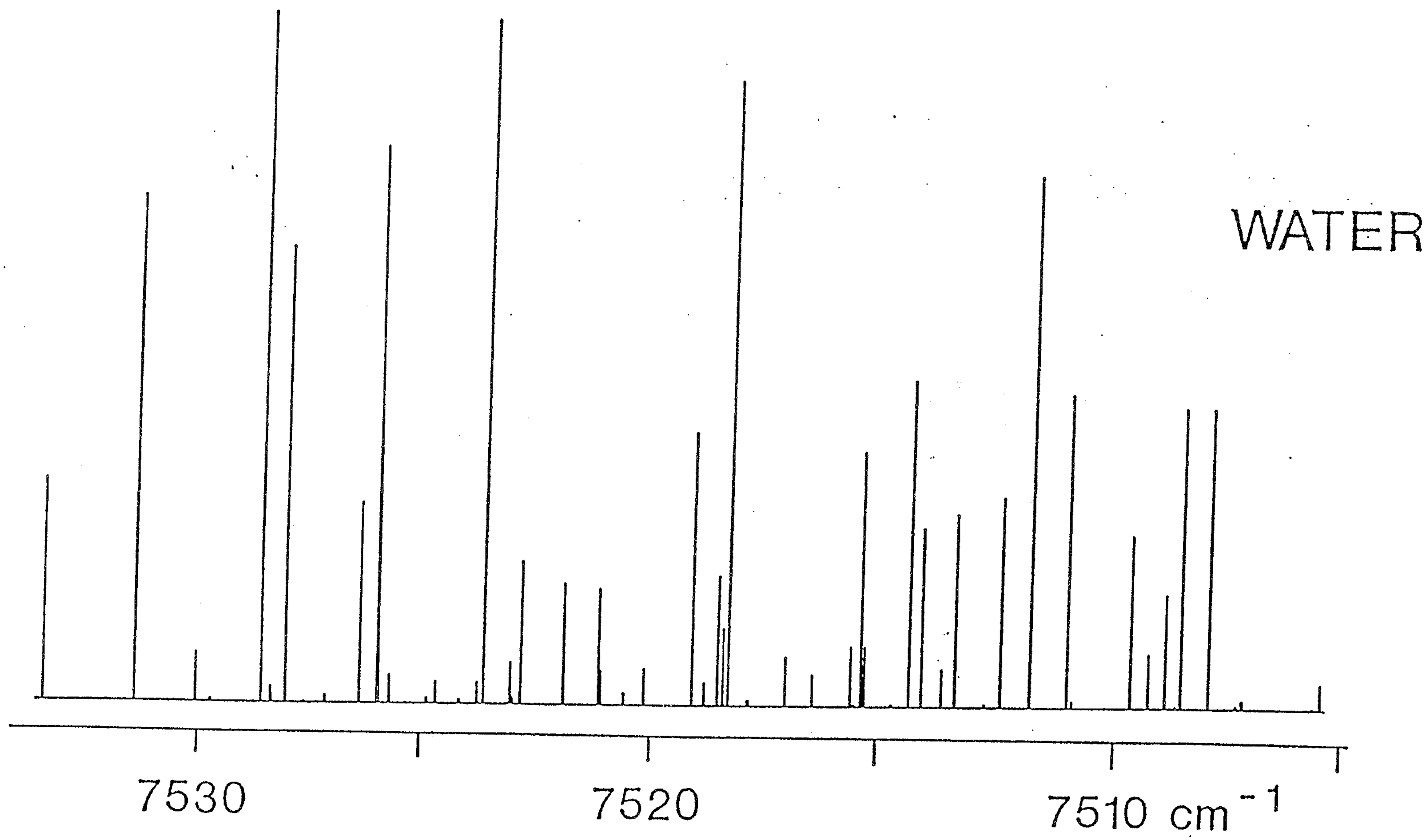


$$\frac{I}{I_0} = \exp\left(-n\,\sigma L\right) = \exp\left(-\alpha\right)$$

$\boxed{\text{SENSITIVITY DEPENDS ON } \alpha_{MIN}}$

OPTICAL SPECTROSCOPY

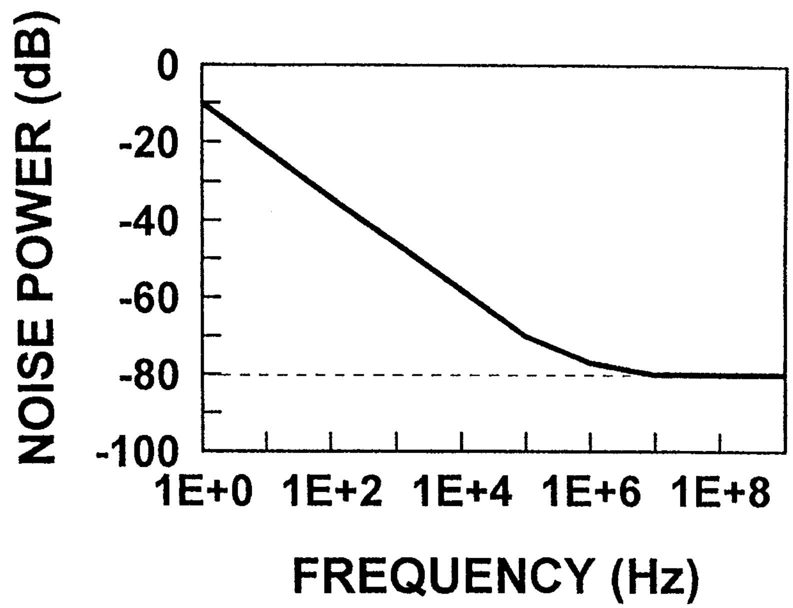
NARROW ABSORBANCE LINEWIDTHS
PROVIDE SELECTIVITY

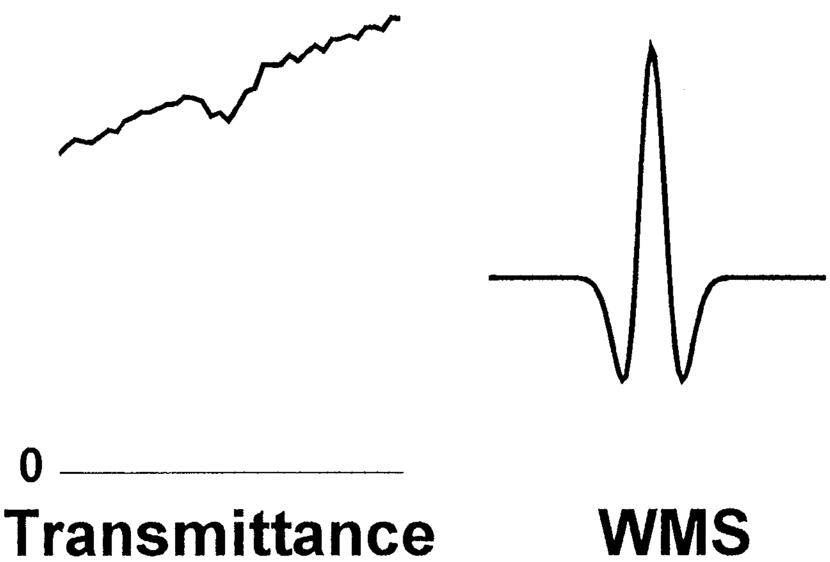


WMS DETECTION

Increase Sensitivity By Shifting Detection Band to High Frequency

Modulate Laser Frequency at *f*, Detect at 2*f*





Advantages of Diode Laser WMS:

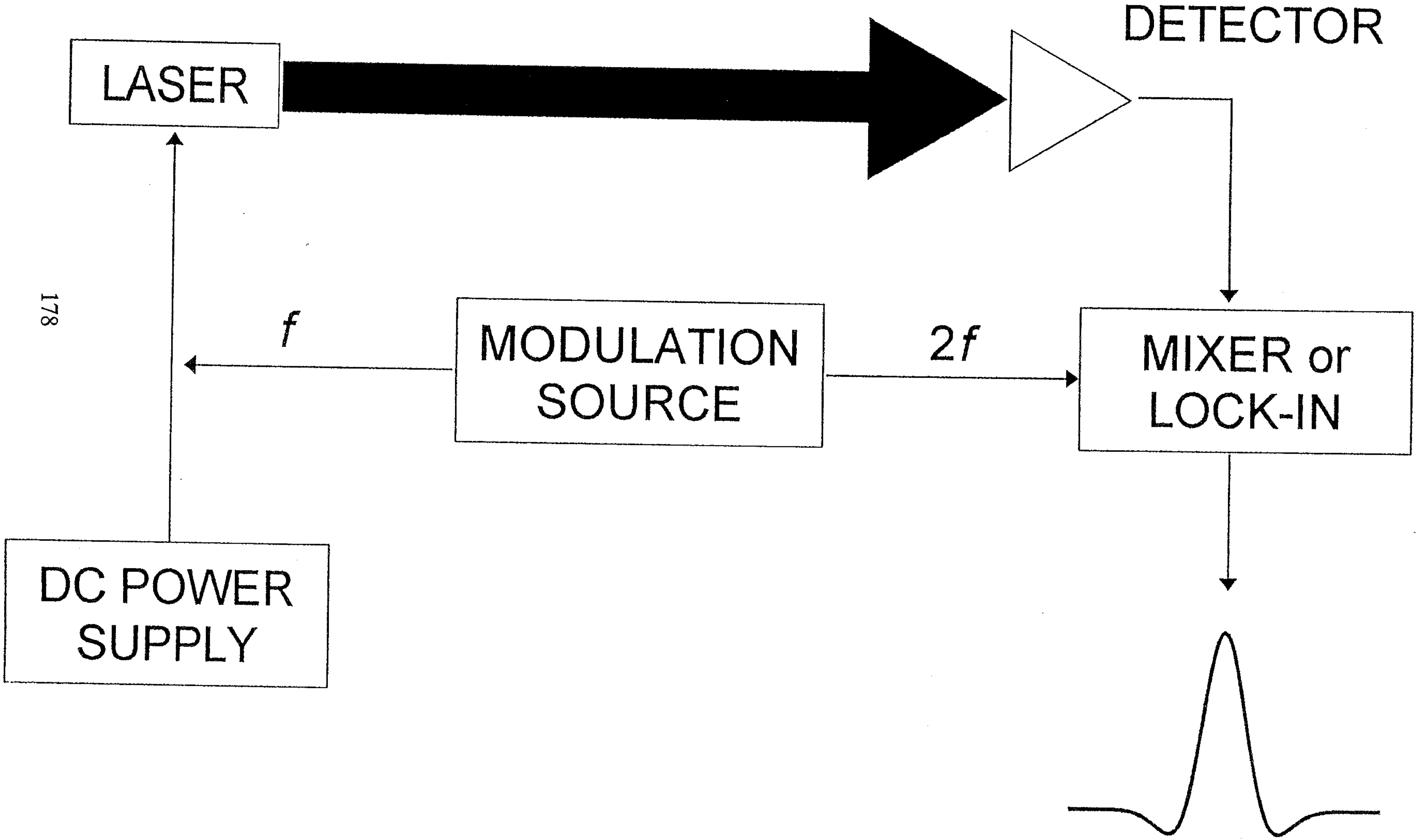
Exceptional Sensitivity $\alpha \sim 10^{-7}$

Selectivity $\Delta\nu \sim .001\ cm^{-1}$

Rugged Solid State Device

Fiber Optic Compatible

WAVELENGTH MODULATION SPECTROSCOPY



GAS DETECTION LIMITS

- 10 cm path length & 10 msec response time

GAS	DETECTION LIMIT	LASER WAVELENGTH
O_2	800 ppm	(761 nm)
HF	0.17 ppm	(1321 nm)
CO	275 ppm	(1565 nm)
CO_2	430 ppm	(1602 nm)
HCl	0.75 ppm	(1740 nm)
HCN	25 ppm	(1548 nm)
NO_2	90 ppm	(760 nm)

FIELD APPLICATIONS

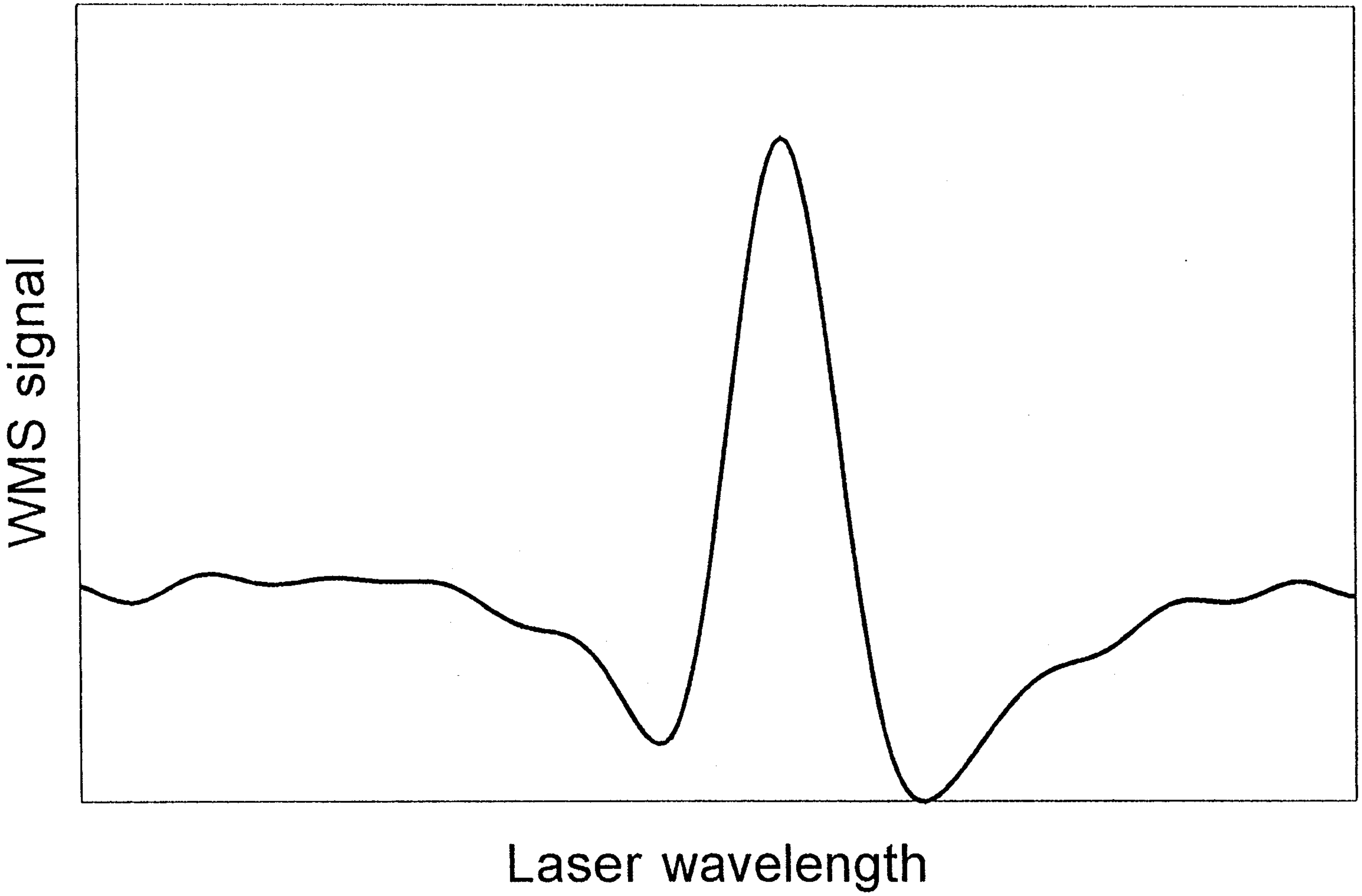
- Airborne hygrometer

- Methane fluxmeter

- Microgravity combustion experiments

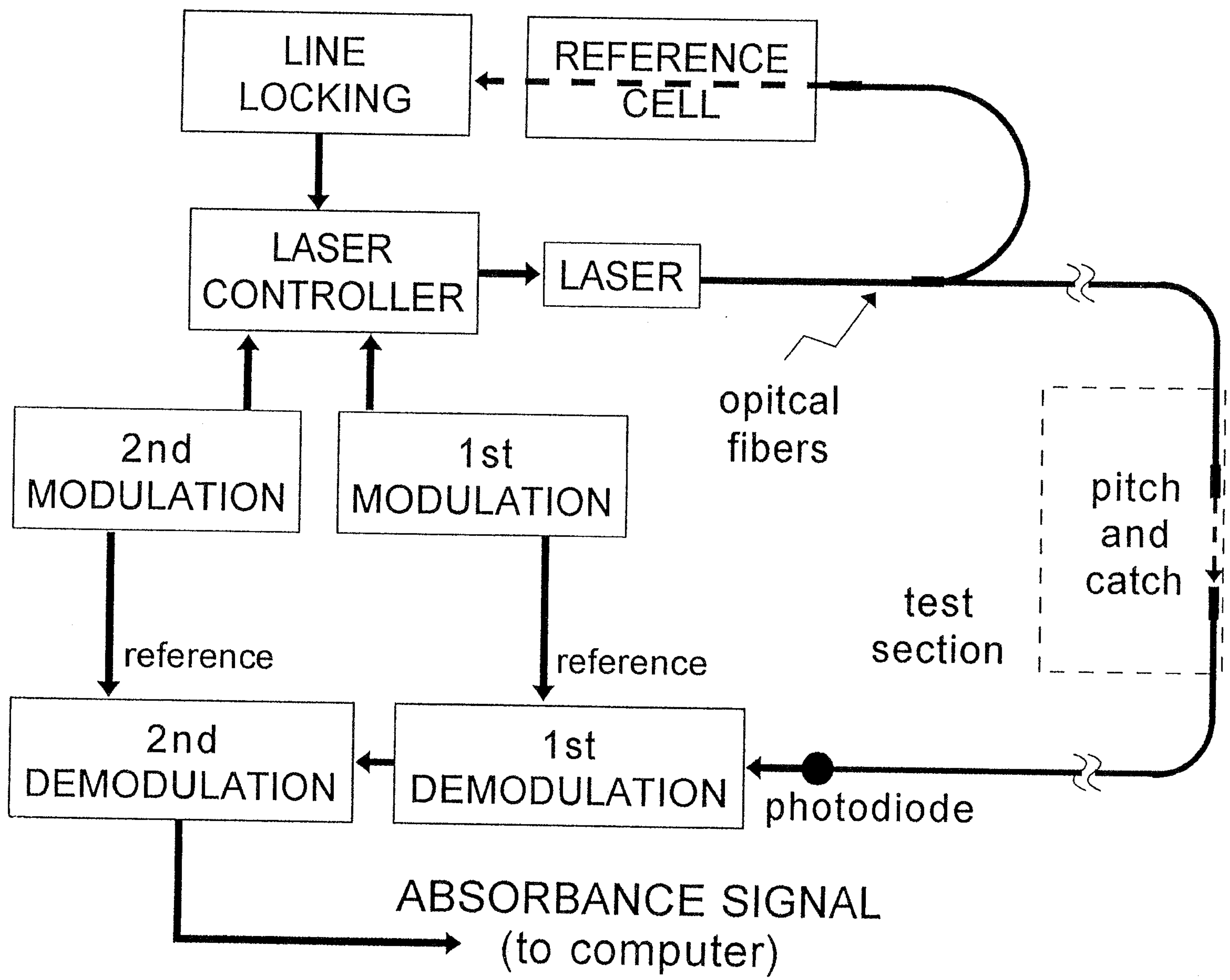
- Industrial open path monitor

Oxygen in 1 atmosphere air
20 cm optical path
10 msec response time



Southwest Sciences, Inc.
Santa Fe, NM
505-984-1322

INSTRUMENT DESIGN USES PATENT-PENDING DUAL MODULATION



USAF SPGG Advanced Development Program

I. Structure

  A. Phase I

  B. Phase II

  C. Phase III

II. Issues

III. Conclusions

IV. Questions

Structure of the Program

Phase I

--optimization for transport aircraft

--testing/modifying in AENTF at Wright-Patt

Phase II

--system tests

--testing at Davis-Monthan AFB

Phase III

--flight testing at Edwards AFB

--final report preparation

AIR FORCE MATERIEL COMMAND

WRIGHT LABORATORY

Phase I

Optimization

--test bed will be CFM-56 engine found on KC135-R

Testing at AENTF

--many conditions within an engine nacelle will be simulated

--analysis of physical relationships

» nacelle volume vs. propellant required

» airflow rate vs. propellant required

» air temperature vs. propellant required

--data obtained on concentrations

Phase II

System tests

- --safety of flight
- --analysis of effects of employment
- --vibration
- --maintainability
- --reliability
- --personnel safety
- --location and distribution of generators

Davis-Monthan tests

- --hang engine on aircraft wing
- --simulate flight conditions
- --test overpressurization, corrosion

Phase III

Flight testing

- --flight demonstration vs. qualification
- --in-flight discharge
- --verify system compatibility
- --long-term effects on propellant

ISSUES

- need data for transport aircraft
- long distribution distances, > 40 ft
- hot engine casings causing reignition
- chemical vs inert gas generator
- physical relationships with gas generators
- retrofits--bottle shape, size
- overpressurization
- inadvertent discharge, personnel safety, etc.
- concentration measurements

Conclusions

Technology output

--methodology to be used for all future large aircraft applications

--design information on propellant config. and arrangement for cubic ext. spaces

--data on plumbing size for distribution and mitigation of overpressurization

--flow rate requirements

--effects of agent release on surrounding engine structure

--sizing for different fire conditions

--guidance on maintenance, safety, and aircraft integration

NAWC
Aircraft Division
NAVAL AIR WARFARE CENTER

INERT GAS GENERATORS Used for Fire Protection Aboard Navy Aircraft

Sponsored By: James Homan
Naval Air Systems Command
Presented By: Marco Tedeschi
Naval Air Warfare Center
Aircraft Division Lakehurst

June 28, 1995

NAWC
Aircraft Division
NAVAL AIR WARFARE CENTER

AIRCRAFT FIRE PROTECTION APPLICATIONS

- F/A-18 E/F
  - ENGINE NACELLE
  - DRY BAY
- V-22
  - DRY BAY

INERT GAS GENERATOR

- DEMONSTRATED (AIRBAG) TECHNOLOGY
- FIRE EXTINGUISHING MECHANISM
- PROPELLANT CONSTITUENTS AND EFFLUENTS
  - Generator Efficiency
- GAS GENERATOR CONSTRUCTION
  - Casing Construction & Propellant Processing

F/A-18E/F ENGINE NACELLE TESTING

- TEST ARTICLE CONFIGURATION
- TEST CONDITIONS & PROCEDURES
  - Variable Distribution, Sequence, Number of Generators
- RESULTS AND CONCLUSIONS
  - Four 1lb Generators @ 1500 ms

NAWC
Aircraft Division
NAVAL AIR WARFARE CENTER

F/A-18E/F DRY BAY TESTING

- DRY BAY SIMULATOR CONFIGURATION
- TEST CONDITIONS & PROCEDURES
  - Variable Threat, Number & Locations of Generators
- RESULTS ANDCONCLUSIONS
  - 7 Generators Sequenced 2,2,2,1 @ 10 ms intervals
  - 50% Effluent by Molar Dispalcement Method

V-22 DRY BAY TESTING

- TEST SET-UP AND CONDITIONS
- TEST PROCEDURES
  - Various Dry Bay and Gas Generator Sizes
- RESULTS AND CONCLUSIONS
  - 525g Mid-Wing, 250g Aft Cove Generators
  - 100% Effluent Concentration By Molar Displacement

TECHNICAL ISSUES AND CONCERNS

- CORROSIVE BY-PRODUCTS
- SINGLE GRAIN PERFORMANCE
  - Decrease Pill Erosion, Lower Weight, Manufacturability, and Performance Concerns
- SYSTEM QUALIFICATION / EFFLUENT CONCENTRATION
  - Gas Measured with 'Continuous' Response

NAWC
Aircraft Division
NAVAL AIR WARFARE CENTER

CONCLUSIONS

- PROVEN HIGH EFFECTIVENESS
- MINIMAL WEIGHT & VOLUME IMPACT TO AIRCRAFT
- REDUCED MAINTENANCE
- ENVIROMENTALLY RESPONSIBLE
- FUTURE NAVY AIRCRAFT
- NEW APPLICATIONS

Navy Qualification of Solid Propellant Gas Generators for Aircraft Fire Suppression

NAVAL SEA SYSTEMS COMMAND

NSWC

Naval Surface Warfare Center
INDIAN HEAD DIVISION

Presented to the
National Institute of Standards and Technology Solid Propellant Gas Generator Workshop
28-29 June 1995

by

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Indian Head, Maryland 20640

CAD/PAD Department

(Cartridge Actuated Devices/Propellant Actuated Devices)

- **Lead service activity providing life cycle engineering support**
- **Designated Joint Program Office (JPO) for CAD/PAD**
- **Acquisition management including engineering support**
- **Energetic materials support**
- **Destructive and non-destructive testing**
- **Technical consultation/monitoring for customer projects**
- **Quality evaluations**

Objective

- To present how NAVSURFWARCEN Indian Head Division, the lead service facility is handling the service release or qualification of the SPGG as an electro-explosive device for aircraft fire suppression applications.

Solid Propellant Gas Generators are Federal Stock Class 1377 Items

- Per Handbook H-2 SPGG are FSC 1377 items
- Cartridge and Propellant Actuated Devices and Components.
  - Safety-in-flight explosive items
  - Escape system explosive components (mechanical, gas, ballistic, electric, laser)
  - Fire extinguisher cartridges
  - Stores separation cartridge
  - Thrusters
  - Explosive bolts
  - Cutters, guillotines
  - Initiators
  - Gas Generators (pressurization, flotation)
  - Explosive loaded devices not specifically classified elsewhere.

FSC 1377 items are tested to the requirements of:

- MIL-D-21625 Design and Evaluation of Cartridges for Cartridge Actuated Devices.
- MIL-I-23659 Initiators, Electric, General Design Specification for
- MIL-STD-1385 Preclusion of Ordnance Hazards in Electromagnetic Fields; General Requirements for
- Specific aircraft system specification additional requirements
- MIL-STD-2000 Propellant, Solid, Characterization of
- NAVSEAINST 8020.5A Qualification and Final (Type) Qualification Procedures for Navy Explosives Materials

Navy SPGG Test Program

- MIL-D-21625 provides over-all design evaluation
  - Design and construction requirements
  - Explosives selection
  - Electrical requirements (MIL-I-23659 & MIL-STD-1385)
  - Service life
  - Logistic issues (Nomen.,NSN,HC,DWG,markings,etc)
  - Design Feasibility Testing (DFT)
  - Design Verification Testing requirements (DT-IA) (establish design freeze)
  - Service Release Testing requirements (DT-IIA)(Qualification)
  - Packaging requirements
  - Data requirements
- MIL-I-23659 and MIL-STD-1385 provides for electrical requirements
  - MIL-I-23659 provides for design requirements and handling safety
  - MIL-STD-1385 addresses HERO requirements
- The contractor system specifications provide for additional testing not covered by the military specifications and standards
  - Explosive atmosphere
  - NBC
  - Fluid exposure

Hazards Of Electromagnetic Radiation on Ordnance (HERO)

- MIL-STD-1385 primary HERO specification
- NAVSEA OD 30393 HERO Design Guide
- HERO referenced in MIL-I-23659 and MIL-D-21625
- Naval Surface Warfare Center, Dahlgren is HERO authority for Navy
- HERO driven by shipboard EM/RF environments
- HERO addressed at system, component and handling levels

Explosive Hazard Classification

- CFR 49 Parts 100-199 Transportation
- NAVSEAINST 8020.8B DOD Ammunition and Explosives Hazard Classification Procedures
  - Joint DOD Explosive Safety Review Board
- Current SPGG HC is 1.3C (Class B) from DOT
- Goal SPGG HC is 1.4C or S
  - Less restrictive storage requirements
  - Less costly transportation

Service Life Assignment

- Initial 3 years install life and 5 years total life
- Additional testing required to support extending initial installed life\total life
- Navy philosophy is demonstrated reliability verses predicted reliability
- Quality Evaluation (QE) testing of stockpile and fleet returned assets used to support increase in service life.

SPGG PROGRAMS

- Current Programs:
  - F-18E/F 7 SPGG (1 configuration)
  - MV-22 17 SPGG (4 configurations)
- Potential Program:
  - F-22
  - KC-136R
- Future Programs:
  - JAST
  - Second source plans

EXPLOSION SUPPRESSION FOR INDUSTRIAL APPLICATIONS

by

Franco Tamanini
Research Division, Explosion Section
Factory Mutual Research Corporation

Prepared for Presentation at the Solid Propellant Gas Generator Workshop
National Institute of Standards and Technology
Gaithersburg, MD, June 28-29, 1995

GENERAL BACKGROUND

- PROTECTED SYSTEMS

  * Laminar and turbulent vapor/air mixtures (Propane typical).

  * Dust explosions for ST 1 & 2 dusts ($K_{st} \leq 300$ bar m/s).

  * Test data for volumes up to about 250 m^3.

  * Proprietary design methods developed by hardware manufacturers.

- TYPICAL CHARACTERISTICS

  * Several types of agents used, including powders (Sodium bicarbonate, Mono-ammonium phosphate), water and pressurized liquids (Halon replacements). Water unsuccessful in suppressing gas explosions.

  * Suppressant quantities of 5-30 liters per unit. Several units may be required for one installation.

  * Suppression system activated by UV or pressure detector.

  * Pressurizing agent, typically nitrogen, at 40-60 bar (600-900 psi).

  * Activation time: 1-2 msec. Agent delivery time: 10-100 msec.

EXPLOSION SUPPRESSION RESEARCH AT FMRC

- GOAL

  Develop an understanding of the mechanisms of explosion suppression and establish the effectiveness of new agents, or new delivery methods, in suppressing high-challenge explosions.

- COMPLETED WORK

  * Carried out suppression tests in the 2.5-m^3 pressure vessel for near-stoichiometric methane/air mixtures using mono-ammonium phosphate (MAP), sodium bicarbonate (SB), and water as suppression agents.

  * The two powder agents (MAP and SB) were found to be successful at suppressing explosions in both quiescent and turbulent mixtures.

  * No successful suppressions obtained with water.

- WORK IN PROGRESS

  * Perform additional gas explosion suppression tests by experimenting with novel delivery methods to maximize the effectiveness of water as a suppression agent. Propellant-based gas generators seen as presenting a means to improve effectiveness of water.

EXPLOSION SUPPRESSION RESEARCH AT FMRC

- EXPERIMENTAL FINDINGS

* Inerting concentrations of the two powder agents from 20-liter sphere tests with a 10% methane/air mixture:

Sodium bicarbonate (Ansul Plus 50C):	975 g/m^3
Mono-ammonium phosphate (Ansul Foray):	575 g/m^3

* Suppression tests in the 2.5-m^3 vessel performed for the following parameters:

Amount of suppression agent:	3 Kg
Pressure of driver gas (nitrogen):	50 barg
Detection pressures:	1, 3, 5, 8 psig (0.07, 0.21, 0.34, 0.55 barg)
Mixture conditions:	Laminar (u_l = 0.42-0.58 m/s)
	Turbulent ($u_{t,eq}$ = 1.14-1.71 m/s)

* For the single concentration used (1,200 g of agent per m^3 of protected volume), the two powder agents (SB and MAP) found to be always successful in suppressing the explosion and to have similar effectiveness.

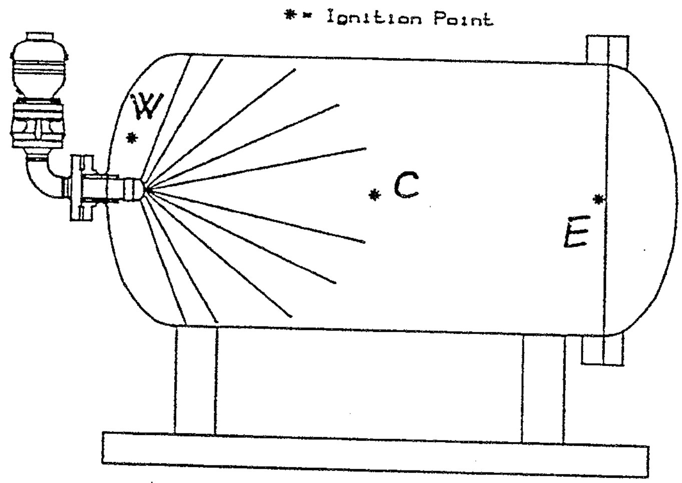
* Failure by the water to achieve suppression in most runs. No appreciable improvement from the use of nozzle with smaller injection holes and addition of CO_2 to the nitrogen charge. Full unvented pressure developed by explosions where suppression failed.

* Location of the ignition source found to have a small effect on the performance of the suppression system. Surprisingly, mixtures ignited behind the injection nozzle are the easiest to suppress.

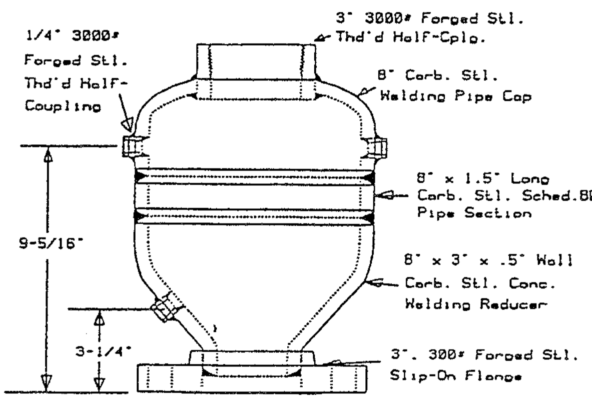
* Increased challenge to the suppression system due to presence of turbulence in the mixture, leading to higher suppressed pressures.

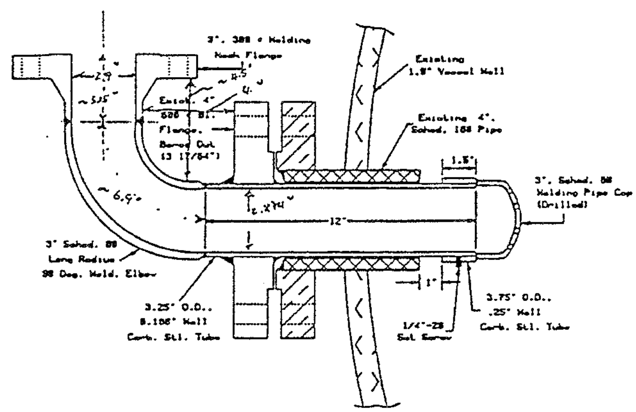
EXPERIMENTAL FACILITY

1. FMRC 2.5-M^3 FACILITY



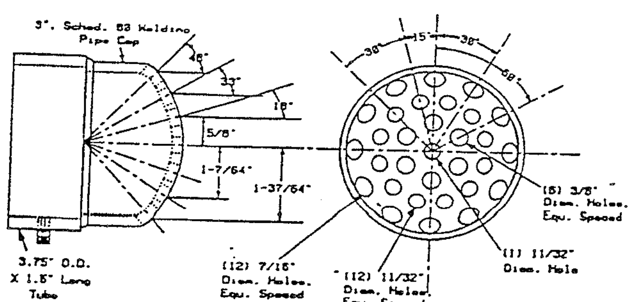
2. SUPPRESSION VESSEL/PIPING





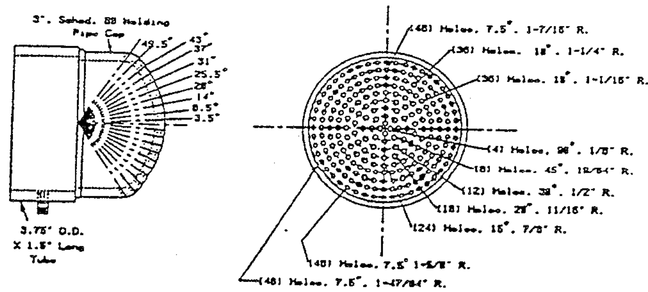
3. INJECTION NOZZLES

NOTE: All Holes to be Chamfered. Both Sides



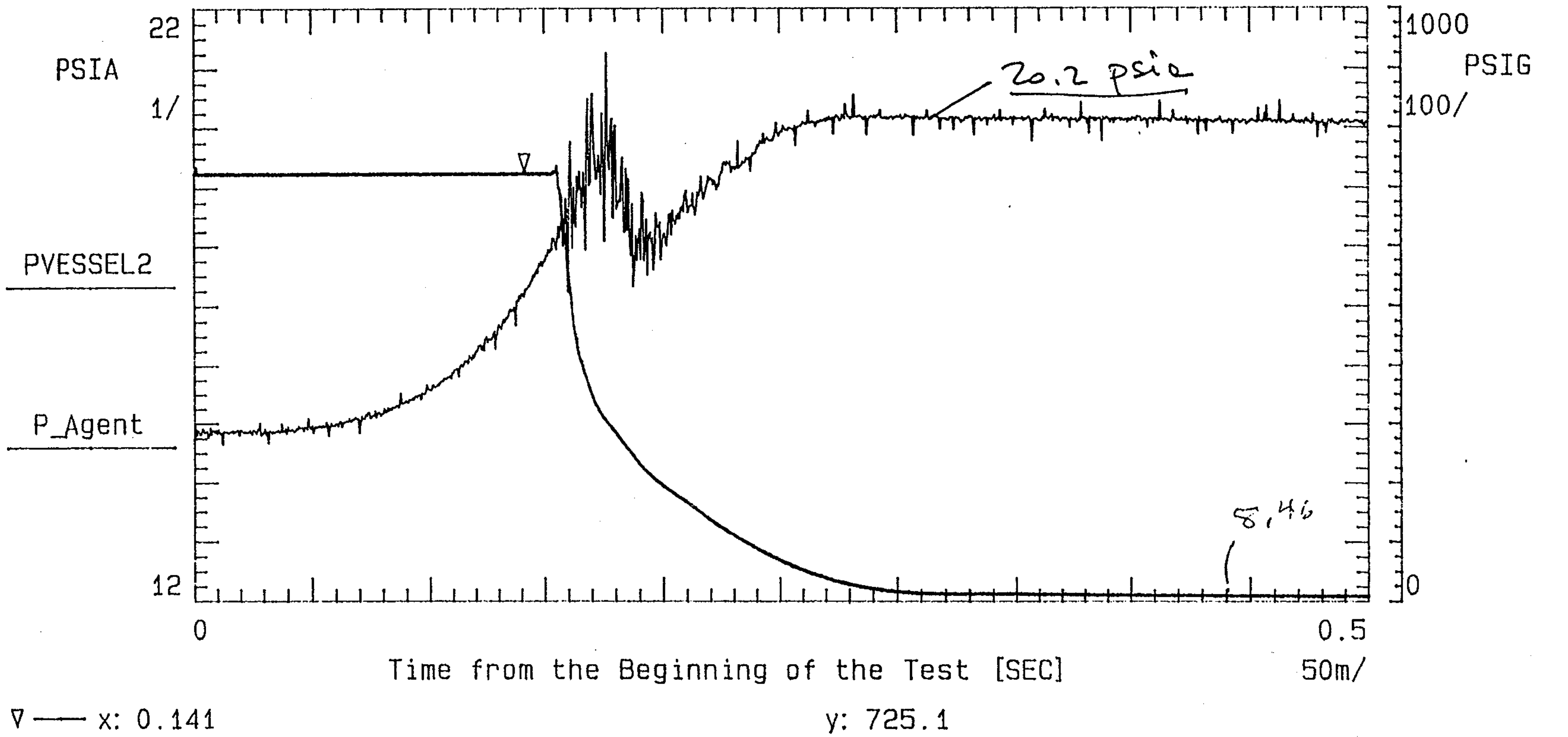
Drilling Pattern for 1st Nozzle

NOTE: All Holes to be 1/8" Dia., Chamfered BOTH Sides. Total No. Holes - 282.

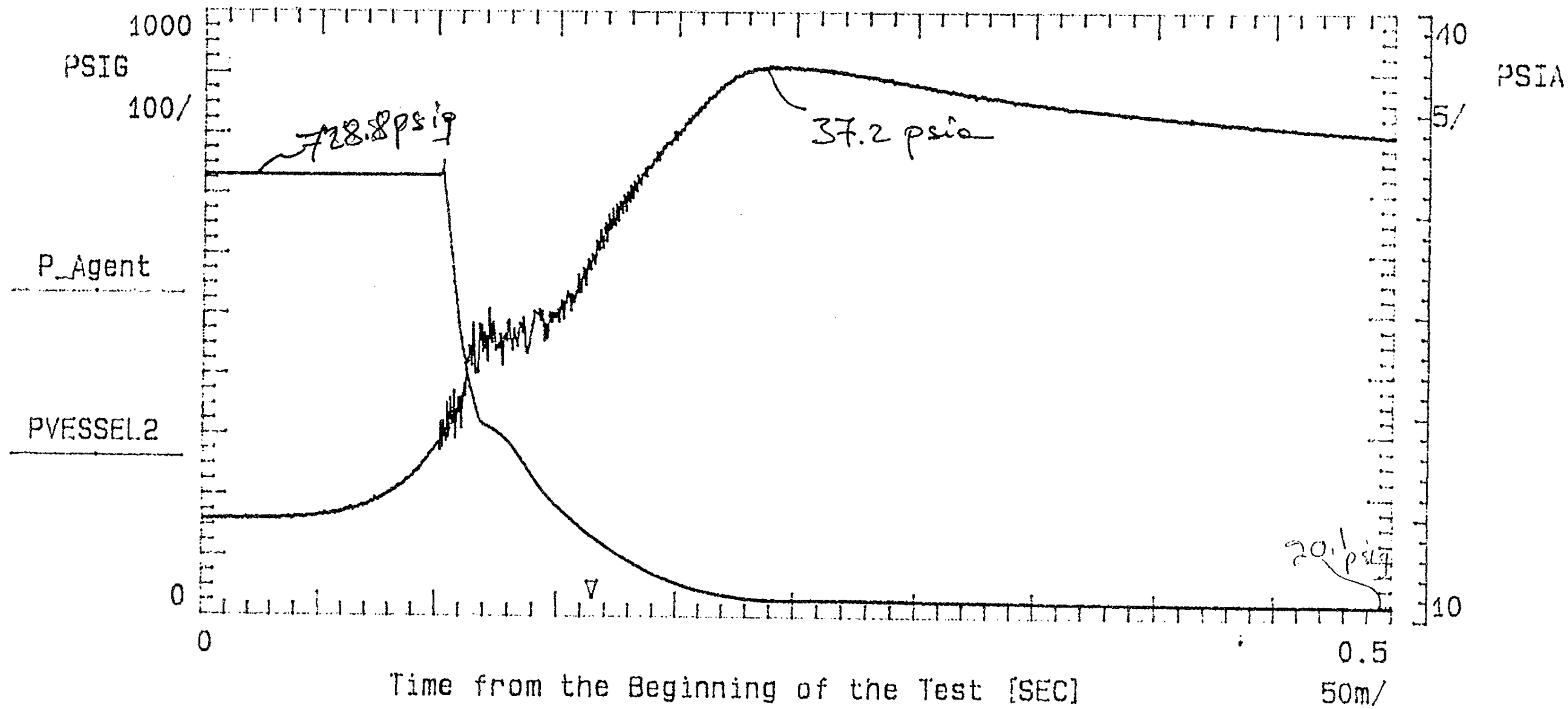


Drilling Pattern for 3rd Nozzle

supprs0014 --> Explosion Suppression Test, 10.86% CH4/Air Mix, 3Kg MAP, PS@3, C.I. -- # 0014



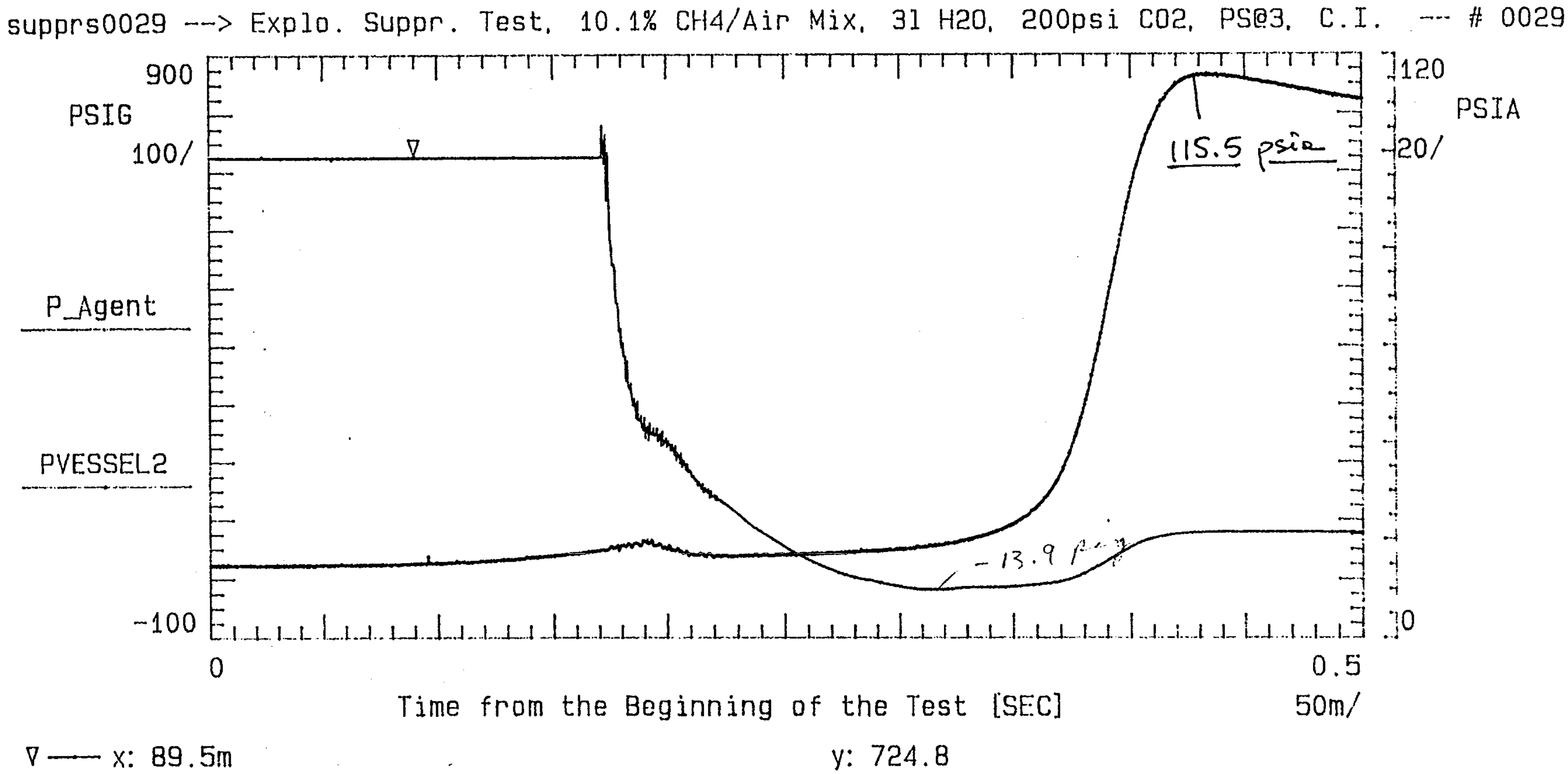
supprs0037 --> Explo. Suppr. Test, 9.99% CH4/Air Mix, Turb., 3Kg MAP, PS@3, Ctr Ig. -- # 0037



∇ x: 0.1645

y: 27.53

214



supprs0029 --> Explo. Suppr. Test, 10.1% CH4/Air Mix, 31 H2O, 200psi CO2, PS@3, C.I. --- # 0029
900
PSIG
100/
P_Agent
PVESSEL2
-100
120
PSIA
20/
0
115.5 psia
-13.9 psig
0
0.5
Time from the Beginning of the Test [SEC]
50m/
x: 89.5m
y: 724.8

ENHANCEMENT OF WATER AS SUPPRESSION AGENT

- SUPPRESSION MECHANISMS

  * Combination of direct interaction of the suppression agent with the flame front, and inerting of the unburnt mixture.

  * Water droplets produced by the delivery system estimated to have a diameter in the range 100-150 µm.

  * Droplets 10 times smaller (10-15 µm) are needed for water to be effective as an inerting medium.

  * Pre-heating of the water charge may provide a means to enhance fragmentation of the stream and, therefore, extinction effectiveness.

- DISSOLVED GAS/STEAM FLASHING

  * At pressures of 15-20 bar, water dissolves an equal volume of carbon dioxide. No improvement in extinction effectiveness found by the use of carbonated (200 psi of CO_2) over plain water.

  * Equivalent amount of volume expansion can be obtained by steam flashing of about 0.7% of a water charge (corresponding to about 4°C of superheating).

  * Water superheated to 200°C (392°F) would produce a flashed fraction of about 18% (Steam inerting of a 2.5-m^3 volume achieved with 3 liters of "hot" water).

USE OF SOLID PROPELLANT GAS GENERATORS IN INDUSTRIAL EXPLOSION SUPPRESSION SYSTEMS

- POTENTIAL ADVANTAGES

  * Storage of suppression agent at ambient pressure (and temperature) up to the time of system activation.

  * Ability to preheat the agent during deployment (improved fragmentation, partial flashing of charge).

  * Non-decaying pressure during agent delivery for faster deployment at fixed maximum design pressure.

- POTENTIAL DISADVANTAGES

  * Higher cost than traditional systems based on pressurized driver gas.

  * DOT classification of propellant (storage, maintenance, handling, etc.)

  * Burden of proof of new technology.

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A workshop on solid propellant gas generators was held on June 28-29, 1995 at the National Institute of Standards and Technology under the sponsorship of the Building and Fire Research Laboratory. Gas generator technology was first proposed as alternative to halon 1301 (CF_3Br) for in-flight fire protection. Because the technology is still in a developing stage as a fire suppression method, there is no standard test apparatus for evaluating the performance of gas generators, and there remain many unanswered technical questions for the potential users. The specific objectives of the workshop were (1) to identify certification procedures, (2) to determine which critical parameters were required to characterize the performance of a gas generator, (3) to develop a standard test method for gas generator evaluation, (4) to identify other potential applications, and (5) to search for next generation of propellants. The participants at the workshop included representatives from aircraft and airframe manufacturing industries, airbag and propellant manufacturers, fire fighting equipment companies, military services, government agencies, and universities. The agenda of the workshop encompassed eleven presentations on various topics relevant to the applications of gas generators as a fire fighting tool, followed by several discussion sessions. Various important issues related to the achievement of the objectives set forth were addressed, and recommendations regarding what role NIST should play in this new technology were suggested.

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)

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