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NWC TP 5921

Reduction of Fuel Fire Cook-Off Hazard of Rocket Motors

by
Ronald F. Vetter
Propulsion Development Department

JUNE 1977

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F. H. M. Kinley, Capt., USN .... Commander

R. M. Hillyer .... Technical Director (Acting)

FOREWORD

This final report describes an experimental investigation conducted during the period January 1974 through September 1976 on the reduction of the fuel fire cook-off hazard of rocket motors. The work was conducted by the Naval Weapons Center (NWC), China Lake, California, and sponsored by the Naval Air Systems Command under AirTasks A3303300/216B/WF31332300, A3303300/008B/5F31332301 and A03W3300/008B/6F31330300.

This report has been reviewed for technical accuracy by Dr. Carl Anderson.

Released by
B. W. HAYS, *Head*
Propulsion Development Department
9 May 1977

Under authority of
R. M. HILLYER
Acting Technical Director

NWC Technical Publication 5921

Published by . . . . .Technical Information Department
Collation . . . . Cover, 33 leaves
First printing . . . . 210 unnumbered copies

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NWC TP 5921	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) REDUCTION OF FUEL FIRE COOK-OFF HAZARD OF ROCKET MOTORS		5. TYPE OF REPORT & PERIOD COVERED Final January 1974-September 1976
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) RONALD F. VETTER		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Weapons Center China Lake, California 93555		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS AirTask A03W3300/008B/ 6F31330300
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Weapons Center China Lake, California 93555		12. REPORT DATE June 1977
		13. NUMBER OF PAGES 64
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution limited to U.S. Government agencies only; test and evaluation; 5 April 1977. Other requests for this document must be referred to the Naval Weapons Center.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

See reverse side of this form.

(U) *Reduction of Fuel Fire Cook-Off Hazard of Rocket Motors*, by Ronald F. Vetter. China Lake, Calif., Naval Weapons Center, June 1977, 64 pp. (NWC TP 5921, publication UNCLASSIFIED.)

(U) Tests of rocket motors in a fuel fire were conducted to try to determine failure mechanism(s) and type of reaction. Several concepts were explored in an effort to devise a method of producing mild reactions. Details of these tests are presented as well as a failure mechanism hypothesis and recommendations for designers.

CONTENTS

INTRODUCTION

The technique of positioning an energetic device or component in an aircraft fuel fire to determine its reaction is not new; however, use of this technique to obtain data necessary to improve the safety aspects of such devices or components did not receive a great deal of attention until catastrophe struck. As a result of the *USS Forrestal* (July 1967) and *USS Enterprise* (January 1969) aircraft carrier fires, with loss of lives as well as much equipment, in-depth investigations were conducted including extensive cook-off testing of in-Fleet weapons. Bombs and warheads were, of course, the major concern, and funding was allocated to provide thermal protection for such ordnance.

The Naval Weapons Laboratory (NWL), Dahlgren, conducted the initial cook-off tests of in-service rockets and rocket motors.[1] The primary protection method evaluated in these early efforts was thermal insulation, and the weapons emphasized were the 2.75-inch FFAR and Zuni launcher pods plus many bombs. Further baseline data were established when NWL tested several air-launched guided weapons.[2] Subsequently, a working group meeting on cook-off problems, held at NWC, China Lake, on 9-10 May 1973, established three goals for rocket motors in a fuel fire situation. These goals were to (1) extend time to reaction, (2) show a mild reaction, and (3) be nonpropulsive. In 1973, a testing and requirements military standard was initiated aimed at establishing a standard fuel fire, and defining reaction categories and acceptable criteria for times and types of reactions to be allowed.

This report does not address the problem of retrofitting in-service weapons. Rather, it is a summary of rocket motor testing (with instrumentation) in fuel fires and an attempt to provide a more specific definition of failure mechanism(s). Of the many rocket motors tested at both NWL, Dahlgren, and NWC, China Lake, the Mk 78 Mod 0 Shrike appeared to have the mildest reaction. Alternate constructions and materials were, therefore, devised to attain results similar to or better than the mild burning reaction typical of the Shrike rocket motor.

Initial efforts at NWC concentrated on providing a means of explosively cutting the rocket motor pressure vessel wall. This approach was terminated, however, because of problems associated with added aerodynamic drag, handling and aeroheating protection of the explosive and initiation device, as well as added personnel hazards during processing and Fleet use, and increased costs (items per se and qualification).

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[1] Naval Weapons Laboratory. *Rocket Motor Survivability in Fire*, by C. P. Hontgas. Dahlgren, Virginia, NWL, November 1970. (NWL TR-2508, publication UNCLASSIFIED.)

[2] ———. *Survivability of Air-Launched Guided Weapons in a Fire Environment*, by J. A. Robinson. Dahlgren, Virginia, NWL, January 1973. (NWL TR-2943, publication UNCLASSIFIED.)

Yet another concept, an explosive bolt to separate the motor/warhead joint clamp in the missile, was explored using the Mk 36 Sidewinder missile. This explosive bolt method would allow motor/warhead separation after which the motor is relatively nonpropulsive. The cook-off reaction in the Mk 36 motor was typical pressure vessel rupture sometime after the explosive bolt reacted. However, a problem of incomplete severing of the bolt was encountered[3] and further effort was not funded. The author remains convinced that such an approach, i.e., a design feature which allows separation of pressure relief port closures, would not be sufficient to provide a nonpropulsive condition in a cook-off situation (due to pyrolyzing of the propellant which then ignites) unless the pressure relief vent is contiguous to the specific initial pressurization site. This specific site is not the bore of the grain.

MIL-STD-1648(AS), issued in March 1974, describes criteria and test procedures for ordnance exposed to an aircraft fuel fire. Unfortunately, no handbook has been issued providing recommendations to designers for conforming to this Military Standard. This report may perhaps provide a first step toward such design guidance. Since January 1974, NWC has conducted extensive literature searches and further study of available test data. In addition, we have assisted other test programs in an effort to obtain new data. To elucidate the mechanisms of failure and find the key to achieving mild burning instead of high pressure (violent) rupture or explosion of rocket motors, laboratory test methods were utilized and were a major part of the first year's effort.

FAILURE MECHANISM HYPOTHESIS

Figure 1 was prepared in an attempt to provide a concise expression of the complex cook-off situation. Briefly, the primary process is energy transport from the heat of the fire into the rocket motor until various simultaneous transport processes create mechanical failure. The propellant's high energy is released by combustion which occurs wherever the temperature and pressure exceed a threshold. Some energy is released (exothermic) without ignition and some energy is absorbed (endothermic) in addition to raising the temperature of the materials. The following detailed sequence assumed a relatively clean (not foaming or charring) separation of liner from the motor case wall. (Such a separation is believed beneficial and will be discussed in detail later.)

At initial heating, the steel vessel thermal expansion creates bondline tension (grain port diameter enlarges). Next, the primer, insulation, liner and propellant heat up. Eventual pyrolysis (usually of the primer and part of the liner) results in volume increase and separation of these materials by the gases formed. These effects result in a tension load in the case and cause the grain, insulation, etc., to be compressed while also creating shear and peeling loads in bondlines (Figure 2). Heat from the flame through the case then warms the gas next to the case. Because of the reduced conductivity (diffusivity) across the gas layer, the temperature of the steel case rises

[3] Naval Weapons Center. *Low Hazard Motor, Non-Propulsive Devices,* by J. Diebold to C. J. Thelen. China Lake, Calif., NWC, 16 July 1973. (NWC Memo Reg. 4545-002-74, publication UNCLASSIFIED.)

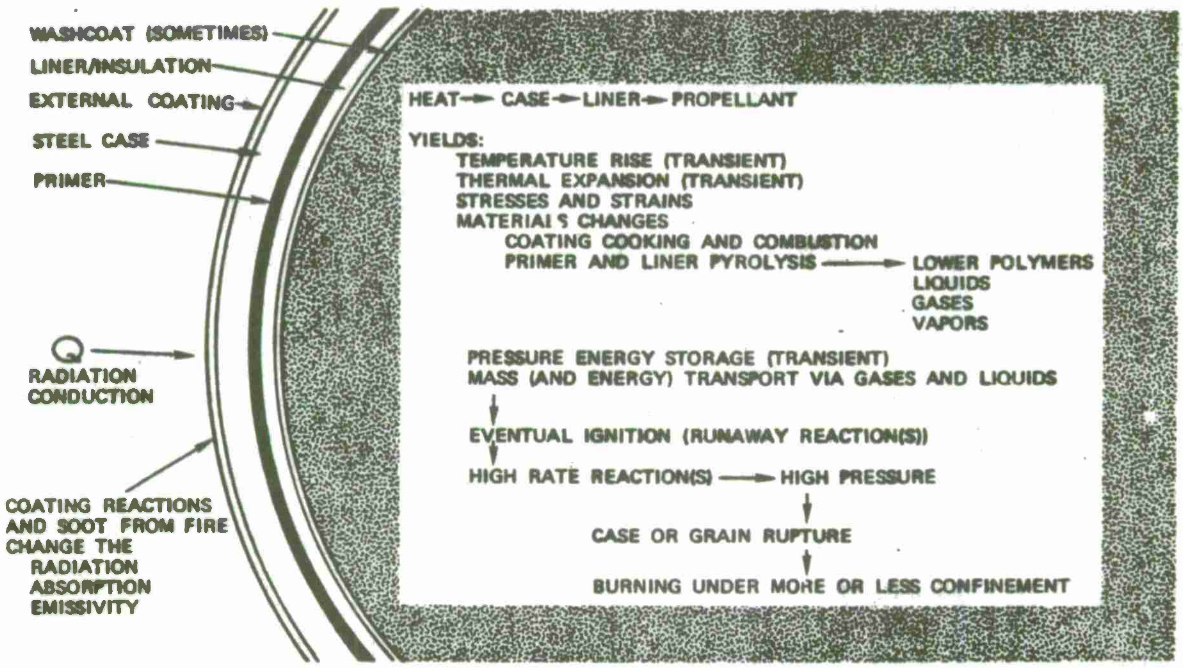

FIGURE 1. Sequence of Cookoff Process.

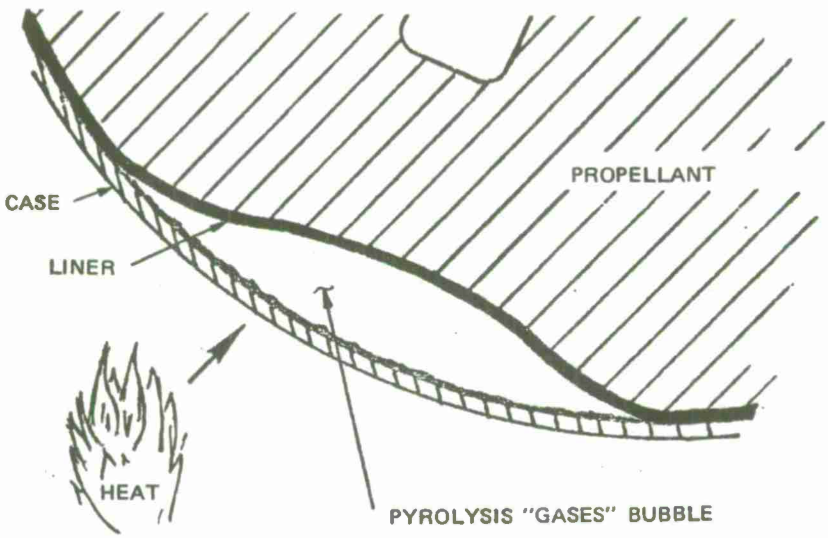

FIGURE 2. Cross Section of Case After Pyrolysis Gases Have Been Generated From the Case Primer and a Part of the Liner. Note that the pyrolysis gases bubble forms on the bottom part of the case in a fire and that clean separation is typical of liner which does not form an adhesive char. The hotter surface of the liner will be liquidus (melting) and a boiling heat transfer exists for a time on the inner wall of the case into the bubble.

faster when the gas bubble(s) exists. The gas temperature also rises, and the pressure rises, dependent upon deformations (e.g., grain perforation compresses) which increase the bubble volume. These pressurized bubbles put a strain on the bondline (where still intact), grain, insulation, and liner materials and load the case wall. Undesirable violent pressure rupture could result from high rate gas generation.

Massive gas production would be due to reaction products from the propellant or explosive, but a logical ignition mechanism must be shown. Simple heat flow does not seem sufficient in view of experimental data. In flame heating tests, primers, liners, and insulators yield liquids and gases at temperatures near or below 200°C, and sometimes separate from the steel substrate. A failure analysis must consider the pressure and volume changes plus the mechanical deformations and materials failures due to these loads in conjunction with degrading thermoviscoelastic strength characteristics. The ignition seems to be via mass transport of hot gas-liquidus through or around the liner. Deformation and cracking of the grain web, or grain exposure by peeling liner, would also lead to hot gas flow over the propellant. Ignition and burning generates high pressures, high burning (reaction) rates, and high temperatures which promote further cracking, deformation, and pressure until pressure vessel integrity no longer exists (i.e., explosion) or a vent is formed to provide sufficient gas dumping. Such venting of high pressure gases will produce thrust and propel the vented object.

Some of the rocket motors subjected to fuel fires under NWL, Dahlgren, Naval Missile Center (NMC), Pt. Mugu, and NWC, China Lake, auspices yielded mild deflagration. The Mk 78 Mod 0 Shrike was a case of particular interest; NWC tested two of these motors for NMC after nearly identical items, under the prior designation Mk 53 Mod 3, were tested at NWL. Both motors remained in place throughout the test except that much of the bottom of the steel pressure vessel was missing. The audio/visual sequence of events was a "report" after about one minute, followed by low-pressure propellant burning. After some time, there was louder burning or chuffing and some visible added flame. Thermocouple data, combined with these observations, indicated that the case ruptured from relatively low pressure gas. Also, the propellant grain remained intact and burned from OD to ID (perforation) at near ambient pressure. This enlarged the hole. When the web was consumed, ignition of the entire bore surface occurred but only low pressure was generated.

It was hypothesized that a sufficiently high (perhaps >700°C for steel) case temperature, brought about by reduced heat flow where a gas pocket existed between the case and liner, would culminate in a low pressure vessel failure. Since the thermal conductivity of a gas will generally be a small fraction of a solid, this means that heat entering the steel does not transfer on into the liner, etc., at the same high rate which exists before the gas bubble is formed.

Test results have not disproved this general "model", but neither has the "model" provided sufficient guidance to analyze a design candidate and calculate the probability of mild burning as a reaction.

RECOMMENDATIONS FOR DESIGNERS

From the point of view of fire safety, it is strongly recommended that strip laminate or similar pressure vessel construction be used so that the adhesive degrades to near zero strength in flames. This can be easily achieved with fiber reinforced plastic cases. Such cases may offer a better insulation and thereby lengthen the time to initiation of propellant. The author does not prefer longer initiation times unless (1) there is no likelihood of increased violence when reaction does occur and (2) there is no significant probability that a "slow" cook-off situation will occur due to retained heat (insulator, etc.). These concerns are based upon the usual result of simple external insulation on a standard metal pressure vessel.

What is needed is a pressure vessel which has "zero strength" at the time the propellant first ignites. The containment of liner pyrolysis products by this vessel must also be avoided since this leads to deformations and mechanical failures due to pressure (see Appendix A). This can be done by employing construction with rigidity and ends attachment via normal steel welding, but with side-wall (perforated or) slitted and overwrapped with fiber/adhesive. This type construction will withstand aeroheating and other environments but "go to pieces" in flames.

Aluminum motors were not tested since they are seldom used and were not beneficial in the few 2.75-inch and Zuni single motor tests. However, some SR-105 units made for the Air Force by Aerojet perhaps should be tested in cook-off fires.

Some (high) probability of mild reaction exists for certain standard steel rocket motors; e.g., the Mk 78 Mod 0 Shrike and several Agile designs, had mild reactions in fuel fires. Explicit thermal stability of the propellant is one factor. Another strong influence is the burning rate of the propellant once ignited at some (small) location. Lowered burning rate as well as pressure and temperature sensitivities of burning rate are desirable. This is related to the abruptness of pressure rise. Inertia and mechanical strengths (tensile, adhesion, cohesive, bending, moduli) determine the failure mode.

It is believed that the mild-burning-reactions were the result of softened steel when propellant ignited. The hot ($>650°C$) steel deformed at low pressure and did not allow high pressure to develop. High pressure bootstraps itself exponentially because higher burning rate occurs and gas is created at a higher rate generating more pressure until rupture. The proximate cause of the steel softening is postulated to be insulation by liner pyrolysis gases. It has been noted that polyether polyurethanes unbond cleanly from heated metal. This is quite important in that clean separation puts a gas in the thermal flow path. Typically, the thermal conductivity of a gas is several orders of magnitude less than solid phase material–thus, good insulation! A tarry or foamy pyrolysis product does not provide such good insulation and heat continues to flow into the liner and propellant at high rates which keeps the steel rather cool. A boiling liquid or sublimating solid on the steel will also tend to keep the steel cool.

In summary, a clean-separating "bladder" is recommended with fore and aft sealing sufficient to keep pyrolysis gases from leaking into the bore where they can ignite a large propellant surface area. Only a small amount of gas is desired since too much deforms the grain and may result in propellant being exposed to hot gases or liquids which will ignite the propellant. Liner/propellant unpeeling or grain cracking do not require high pressures in some configurations.

LABORATORY TESTING

The observation that something was better about the Mk 78 Mod 0 configuration, i.e., softened steel edges and low noise levels at case opening which indicated low pressure and high case temperature, presented the technical challenge of explaining why. The previous paragraphs on failure mechanism reflect the response, but additional data were gathered to help elucidate the physical processes and thereby develop acceptable design guidelines.

The laboratory test goal was to gain further insight into the weak link(s) of motor construction relative to high thermal input. Four-inch squares (10 x 10 cm) of 0.3-cm mild steel plate were coated with various materials in a fashion similar to rocket motor construction. These plates were then heated over propane/air burners with thermocouple temperature measurements and photographic and visual observations. The initial sample plates had small discs of propellant over the center test section. These were soon deleted because it was obvious that nearly all a rocket motor's primer, adhesive, insulator, and liner materials would decompose in such a transient heating situation before the propellant could be significantly heated, much less brought to ignition temperature. Several dozen samples were fabricated and tested using typical materials, with emphasis on materials used in past or planned full-scale motor cook-off tests. Table 1 summarizes these data in a manner considered meaningful. The visible initiation of a gas bubble has become the primary datum. A pseudo-heating-rate derived from the temperature at this time is also presented. The table does not include any description of bubble dimensions, growth rate, gas release by leaking from edge, overall loss of adhesion, nor the character of the tenacious foam, frothy liquid, or clean separation of the material from the substrate. It is believed that a correlation may exist between the character of the pyrolysis of polyether polyurethane (SD-746 and SD-723 liners) and the favorable cook-off results of the Mk 78 Mod 0 rocket motor. These urethanes "unzip" upon heating to form a low viscosity, nonsticky liquid and generate gases which coalesce, usually quickly, into a single bubble which grows to the edges in a short time.

The pseudo-heating rate of the rocket motor pressure vessel case wall, measured by thermocouples in cook-off tests, varies considerably about a 4°C per second value and usually increases above the temperature where liner decomposition occurs.

Bubble formation at lower temperature when fiberglass plates were tested indicates another effect beyond a difference in thermal diffusivity (insulation value). The fiberglass/epoxy burned and was obviously softened. Endothermic activity on the flame-exposed face of the plates was noted (thermocouple temperature drop) during most tests at nearly the same time as bubble formation. This may be due to the epoxy depolymerizing (yielding gas?) or water vaporization, other contaminants or reactions.

TABLE 1. Laboratory Burner Heating Tests.

Temperature when first bubble detected, °F	Temperature when first bubble detected, °C	Pseudo heating rate (ΔT/Δt), °C/s	Sample description
112	44	4.4	SD723/20% CaF in SP-40X415/0.1 cm fiberglass
169	77	3.0	SD723/20% CaF in SP-40X415/0.2 cm fiberglass
175	80	2.8	SD723/SP-66X5457/0.2 cm fiberglass
182	83	2.9	SD723/SP-40X415/0.2 cm fiberglass
185	84	4.3	SD746-2/0.1 cm fiberglass
201	93	6.6	SD723/SP-40X415/0.1 cm fiberglass
208	98	4.8	SD723/0.1 cm fiberglass
247	120	1.9	SD746-2/APD-150/epoxy/0.3 cm steel
256	124	1.8	SD723/RPD-150/epoxy/0.3 cm steel
256	124	3.2	SD723/0.2 cm fiberglass
270	132	3.9	SD723/SP-40X415/0.3 cm steel
287	142	5.0	SD746-2/SP-40X415/0.3 cm steel
305	152	5.0	SD746-2/SP-66X5457/0.3 cm steel
305	152	6.9	LC-4/SP-40X415/0.3 cm steel
310	154	6.4	LC-4/20% CaF in SP-40X415/0.3 cm steel
323	162	4.4	SD746 + TiO_2 + Kynol/SP-40X415/0.3 cm steel
330	166	6.9	LC-4/20% CaF in SP-40X415/0.3 cm steel
336	169	5.8	LR-13 with copper nail through 0.3 cm steel
348	176	4.5	LRV-7/SP-40X415/0.3 cm steel
360	182	3.3	60% CaF in R-45M HTPB/0.3 cm steel
380	193	4.2	UF2158/Kraft paper/Eastman 910/0.3 cm steel
390	199	4.2	LR-13/0.3 cm steel
395	202	13.7	SD746-2/0.05 cm steel tube
400	204	5.6	SD723/VP-2894/0.3 cm steel
404	206	4.7	SD723 (clamped Lucite cover)/0.3 cm steel
413	211	5.0	UF2158/LR-13/0.3 cm steel
426	219	4.8	SD723/0.3 cm steel
431	222	3.7	LRV-7/Seaguard blue primer/0.3 cm steel
431	222	3.8	LRV-11/Seaguard/0.3 cm steel
432	222	5.8	LC-4/SP-40X415/0.3 cm steel
442	228	5.4	SD723/VP-2983/0.3 cm steel
448	231	5.5	LC-2/20% CaF in SP-40X415/0.3 cm steel
451	232	5.6	SD723/CP-2757/0.3 cm steel
453	234	5.4	SD723/Seaguard/0.3 cm steel
453	234	4.6	SD746 + TiO_2 + Kynol/Seaguard/0.3 cm steel
457	235	5.3	SD723/VP-2849/0.3 cm steel
466	241	21.6	SD723/0.05 cm steel tube
475	246	5.2	Polyisoprene/234B/205/0.3 cm steel
475	246	5.6	LC-2/SP-40X415/0.3 cm steel
486	252	5.2	LC-2/VP-2894/0.3 cm steel
511	266	3.4	LRV-5/Seaguard/0.3 cm steel
519	271	3.6	LRV-11/0.3 cm steel
519	271	5.1	Polyisoprene/Chemlock 234B/205/0.3 cm steel
524	273	4.2	DC93-104/SS4155/0.3 cm steel
533	278	3.3	LC-50/Seaguard/0.3 cm steel
537	281	3.5	LC-48/Seaguard/0.3 cm steel
547	286	4.7	LC-2/VP-2849/0.3 cm steel
563	295	4.7	LC-2/VP-2757/0.3 cm steel
572	300	4.9	RTV615 with 10% ammonium oxalate/0.3 cm steel
586	308	4.4	LC-2/VP-2983/0.3 cm steel
628	331	3.9	LRV-6/SP-40X415/0.3 cm steel
641	338	3.8	LRV-6/Seaguard/0.3 cm steel
645	340	4.3	LC-2/Seaguard/0.3 cm steel
660	349	3.5	DC Q-3-6548/0.3 cm steel
666	352	3.3	CTPB with oxamide/Seaguard/0.3 cm steel
680	360	4.2	RTV615 with 10% ammonium oxalate/0.3 cm steel
770	410	3.1	DC03-6548/Seaguard/0.3 cm steel
950	510	3.0	RTV615/0.3 cm steel

LC-4 and LC-2 are CTPB-based liners with LC-2 being the most representative liner for in-fleet motors. With these liners, gassing (bubbles) occurred at higher temperature with more heat conducted into the liner mass. These were more tar-like with viscous, foamy, large bubbles formed. The gas did not generally escape via the edges but caused the LC-2 to continue to swell until a quite large expanded froth existed under a stretched skin. In contrast, the polyether urethane liners became released from the substrate and gases boiled out.

The third series of plates used several Union Carbinde (UC) vinyl butyral resin-based wash primers. There are a number of ingredients in each of these primers. The VP2894 has a lead chromate pigment which may account for its thermal stability apparently being lower than the other primers which contain zinc chromate. Tests using the LC-2 liner all had higher bubble formation temperatures than for the SD-723 liner, as is usual, and were tar-like after heating. Another group of samples contained fibrous reinforcement. This makes the results less reliable since it is difficult to visually observe the bubble formation because of material strength. Unlike any other material, the DC-93-104 silicone "bubbled" small "jets" of gas through the material without unbonding.

Three candidate liner formulations, of a type showing good promise as low smoke/smokeless liners, were prepared on the steel squares and tested over a propane air burner. All three contained varying percentages of oxamide in R45M prepolymer with several curative systems and other minor ingredients. All gave similar results; first bubbles formed between 266-281°C (511-537°F) and release occurred from the Seaguard blue primer on the steel. The hot liner surface had a velvety/foamy appearance with little melt.

Because the cook-off process is complex and the results of repetitive tests are not exactly reproducible, it is not obvious that any one liner and/or primer is best. A preliminary hypothesis can be drawn that the pyrolysis directly yielding low molecular weight (non-tar) products will be best because a gas phase layer is produced at lower temperatures thereby more effectively insulating the propellant.

INITIAL SMALL SCALE COOK-OFF TESTS

The NWC Thermal Research Branch developed a small cook-off bomb (SCB) device comprised of a reclaimed gas generator canister (steel) with special closure and mounted between bolted plates. The tubular outside diameter (OD) is electrically heated to simulate heat from a fire, and temperature and pressure can be monitored. Although this is a sealed vessel, propellant/liner tests using SCBs were made for comparison with explosive/liner tests, etc. Two primer/liner combinations were tested with both inert and live propellant. Four SCBs with live propellant were classed as "mild ruptures." Typical data showed case inside diameter (ID) and liner/propellant thermocouple temperature rises followed by a slow pressure rise after some delay time. This was then followed by high rate pressure jumps until rupture.

In addition to the SCBs, test items of 4-inch diameter tubing (to simulate motors) were fabricated and tested. Two of these used electrical heating bands and were not very satisfactory because of very low rate of heat input as well as some instrumentation and sealing problems. A third unit was heated with a simple propane/air heating rig. Though better, this still was not satisfactory because the pressurized air bottle was exhausted before the test could be completed. Further modification and direct use of an air compressor resulted in a suitable heating rate.

Another 4-inch-diameter steel tube and two 4-inch-diameter phenolic/glass cloth tubes were fabricated into test specimens and fitted with thermocouples, a pressure tap tube, Stanley 40X415 primer, LC-2 liner, and Batch 7038 inert propellant. When the steel tube was cooked over the propane/air burner, the heating rate was satisfactory but the temperature leveled at a value somewhat below that typical of the full-scale aviation fuel test pit. Gassing of the liner occurred with pressure-rise start detected at 176 seconds. However, gas venting at the ends provided pressure relief so that only a 103 kPa (15 psi) pressure was achieved. The venting gas ignited in the air at one end and flamed until extinguished after the test. Another modification to the test apparatus provided a shielded support cradle. This further raised the initial heating rate at the mid-point test section of the tube but did not significantly change the tube ID temperature at 5 minutes.

In the first phenolic/glass cloth tube test, gas pressure started to rise very quickly (case ID reached about 93°C (200°F) after 23 seconds) and appeared to vent at one minute. The propane/air flame was stopped after seven minutes but the item's entire OD continued to flame. Internal temperatures were lower, as expected with this material, and pressure vessel strength was rapidly degraded.

Table 2 summarizes these test results relative to the temperature at which pressure was, in some manner, detected. The relatively low heating rates (compared to motors in fuel fires) and low ultimate temperature (undoubtedly due to lower energy heat sources) plus the total sealing when using SCBs and low pressure leaks when using tubes diminish the usefulness of these rupture mode data.

FUEL FIRE COOK-OFF TESTS

A summary of the fuel fire cook-off tests is presented in Table 3.

Two Mk 78 Mod 0 Shrike rocket motor tests were conducted at NWC under sponsorship of NMC. Both motors remained in place throughout testing, but much of the steel pressure vessel bottom was missing (melted or burned away). The audio/visual sequence of events was: a report after about one minute, followed by low pressure burning. At NWC's request, the second Mk 78 Mod 0 Shrike test included chamber pressure measurements. In this test, several psi pressure, followed by a higher pressure spike, was measured at the time of initial reaction.

A Mk 53 Mod 1 Shrike motor was instrumented after removal from storage and tested under NMC funding. Holes were hand-drilled into forward and aft grain ends from star tips to case wall or liner to permit installation of thermocouples and lengths of copper tubing. Sealing around the wire or tubing and inhibiting of the propellant forming the side wall of the hole was "accomplished" by injection of catalyzed epoxy resin. The cook-off test objective was to measure (via the tubing) pressure generated at the liner/case wall as well as internal to the grain bore. Though this was accomplished, the use of instrumentation compromised the validity of this test relative to uninstrumented Mk 53 Mod 1 motors. The weak link was the epoxy sealing and inhibiting which apparently failed and allowed hot gases to flow down one of these holes. The motor burned propulsively due to the added burning surface area provided by the six holes, as evidenced by holes in the case at most of these locations after the test. Relatively normal burning time and noise output were noted after ignition occurred, but the cook-off reaction time was shorter than average. However, the objective of measuring pressure at the liner, albeit grossly, was achieved. Approximately 53 seconds into the test, bore pressure rose over about one-half second to 415 kPa (60 psig) then decayed somewhat to 21 kPa (3.1 psi), rose again to about 48 kPa (7 psi) then rose offscale. There was no indication of pressure in the tubing to the liner until the bore pressure first peaked at 41 kPa (6 psi). Liner pressure then went to about 480 kPa (70 psig) and rose slowly to about 550 kPa (80 psig) before steeply spiking to 3.4 MPa (490 psig). These spikes obviously correspond to grain ignition; the bore pressure gauge mounted on the inert igniter hardware ejected at the spike. The ejection was not planned; it may have been the result of mis-assembly of a retainer snapring into a groove.

TABLE 2. Small Scale Cook-Off Tests.

Case ID temperature when pressure rise detected, °C	Case ID temperature when pressure rise detected, °F	Pseudo-heating rate, °C/s	Heating source, E (electric) F (flame)	Item description
93	199	2.7	F	Inert propellant/LC-2/SP-40X415/10 cm phenolic glass tube
150	300	1.0	E	Inert RDS-543/SP-40X415w/20% CaF/SCB
155	311	0.06	E	Inert RDS-543/LR-13w/20% CaF/SP-40X415/10 cm steel tube
195	383	0.08	E	Inert RDS-543/SD-723/SP-40X415/10 cm steel tube
217	423	2.8	E	RV-7-7009/SD-723/SP-40X415w/20% CaF/SCB
255	491	2.3	E	RV-7/SD-723/SP-40X415/SCB
270	518	2.5	E	RV-7/SD-723/SCB
300	570	2.5	E	Inert RDS-543/SD-723/SP-40X415w/20% CaF/SCB
330	626	0.5	F	Inert RDS-543/LC-2/10 cm steel tube
(365)	(690)	2.5	E	RV-7/SP-40X415w/20% CaF/SCB
527	981	2.9	F	Inert propellant/LC-2/SP-40X415/10 cm steel tube

TABLE 3. Summary of Fuel Fire Cook-Off Tests.

Test item description	Results/comments
Mk 78 Mod 0 Shrike	Several psi chamber pressure measured followed by a higher spike at initial reaction
Mk 53 Mod 1 Shrike	Propulsive burning (epoxy sealing and inhibiting failure at *added* tubing)
Harm motor (inert)	Case thermally softened and plastically deformed
Agile Unit 2	Burned per MIL-STD-1648 (much case steel melted and burned away and case was completely severed at forward dome)
Agile Unit 1 (standard Agile)	Deflagration per MIL-STD-1648 (head end almost completely separated from rest of case)
Agile Unit 4	Burned per MIL-STD-1648 (bore expansion began at initial case heating followed by rapid collapse of bore diameter at 103 seconds)
Agile Unit 3	Deflagration per MIL-STD-1648 before 5 minutes
Mk 36/50 motor (refurbished) with LR-13 liner and TPH-1143 propellant	Deflagration per MIL-STD-1648 (case rupture caused ejection of small (many burning) pieces)
Mk 36 motor with polyether polyurethane liner	Exceeded deflagration per MIL-STD-1648 (violent pressure rupture of entire case)
Fiberglass tube baseline test motor with LR-13 liner and RV-13 propellant	Burning per MIL-STD-1648 (nonviolent reaction)
Mk 52 motor with LR-13 liner	(Mild) Deflagration per MIL-STD-1648 (motor case remains came to rest directly below original location)
Mk 52 motor lined with LC-2	Exceeded deflagration per MIL-STD-1648 (full metal thickness case tears)
Mk 52 motor with LRV-1 liner and RV-13 propellant	Deflagration per MIL-STD-1648 (possible travel of grain segment)
Mk 36 Sidewinder with HTPB liner and low smoke propellant	Deflagration per MIL-STD-1648 (nozzle and grain ejected following burn-through of motor aft end)
Mk 36/50 with LRV-1 liner and RV-13 propellant	Mild deflagration per MIL-STD-1648 (nozzle ejected and motor flew out of holding straps)

An inert HARM prototype motor was subjected to fire, but the test item and test were less than perfect. It is interesting to note, however, that approaching three minutes into the test, thermocouples welded to the case ID showed discontinuities at temperatures nearing 650°C (1,200°F), and the motor case bottom had a small hole (~0.6 cm diameter) in a pressure blister (metal thinned and stretched). After the test, degraded inert propellant was extruded from the hole, the nozzle, and forward igniter closure. The silicone insulation in the aft motor sections was degraded and deformed, and no evidence of the SD723 polyurethane liner was found. Apparently it was liquified (vaporized?) and extruded out. In summary, without any energetic material, the case was thermally softened and plastically deformed—apparently by gases—at nearly the same time as cook-offs have occurred on most live motors tested. The HARM project group tested a live prototype but a number of hardware difficulties and a very slow starting fire rendered the data of little value.

AGILE

One each of four Agile motor constructions were subjected to cook-off testing. The first was the standard baseline design incorporating polyisoprene forward and aft stress relief boots with forward extension of the aft boot providing case insulation from combustion gases after booster burnout. These boots, and the case between them, were covered with R45M-based liner before the propellant was cast. The second unit was as above except that the boots were extended to form a continuous bladder bonded to the case ID with Chemlock adhesive. The third motor had a bladder similar to that of motor two but installed after the entire case ID and ends were coated with liner modified to contain 53.5% calcium formate gassing agent. Motor four had short end-relief boots on each end and the calcium formate-modified liner covered the case ID with an overspray coat of regular liner under the propellant.

Except for one HARM preliminary unit, these motors were all different than any previously cooked-off in that HTPB propellant and liner were used. The polyisoprene may also have been a new material in cook-off testing. All the motors had four insulated tube-ways from head to aft through the motor, 90 degrees apart, near the case wall. A brief description of what apparently occurred in each of these tests leaves much data unrelated. The test reports should be consulted by those seriously interested.[4-7]

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[4] Naval Weapons Center. *Agile Mod II Ordnance Section Cook-Off Test; Final Report on* (U), by Scott M. O'Neil. China Lake, Calif., NWC, 30 May 1974. (NWC Memo Reg. 4570-544-74, publication CONFIDENTIAL.)

[5] ------. *Agile Mod II Ordnance Section Cook-Off Test; Final Report on* (U), by Scott M. O'Neil. China Lake, Calif., NWC, 5 June 1974. (NWC Memo Reg. 4570-546-74, publication UNCLASSIFIED.)

[6] ------. *Agile Mod II Ordnance Section Cook-Off Test No. 3; Final Report on* (U), by Scott M. O'Neil. China Lake, Calif., NWC, 21 June 1974. (NWC Memo Reg. 4570-548-74, publication CONFIDENTIAL.)

[7] ------. *Agile Mod II Ordnance Section Cook-Off Test No. 4; Final Report on* (U), by Scott M. O'Neil. China Lake, Calif., NWC, 3 July 1974. (NWC Memo Reg. 4570-501-75, publication CONFIDENTIAL.)

Unit 2 was the first motor tested and yielded a mild report (case rupture) at 114 seconds. Grain port pressure and a linear potentiometer showed activity nearly immediately upon case heating. Pressure was noted at about 22 seconds. Propellant burning after case rupture (bottom) was at low pressure, apparently over an increasing surface area, until after 163 seconds when the internal port thermocouples started registering temperature jumps typical of flame. Loud (higher pressure) burning occurred from about 170 to 185 seconds. The bottom half of the case was swelled oversize and much steel melted and burned away and the case was completely severed at the forward dome. The aft section was rotated about 120 degrees from its original position (apparently when the internal perforation burned). This test met the MIL-STD-1648 definition of burning.

For motor 1 (standard Agile), burning ignition occurred at 74 seconds with low level burning noise until 105 seconds. Nothing further was heard until 120 seconds when louder, chuffing burning started. The loud burning started to decay at 147 seconds and stopped at 158 seconds. This reaction was quite mild but, since the case was much less heated when the steep pressure rise occurred, the rupture was at higher pressure and apparently nearly separated the head end from the rest of the case. The grain was ejected later (when internal port burning occurred) and landed approximately 4.5 meters (15 feet) away in the pit where it burned. This was a deflagration per the MIL-STD-1648 definition and it occurred before 5 minutes. Aft end warm gas apparently (per thermocouples) leaked into the port at 48 seconds and again just before 74 seconds (when the case ruptured), while internal ignition seemed to start aft at about 113 seconds with full burning at about 119 seconds.

Motor 4, with calcium formate gassing agent in the liner, was very mild in initial reaction. A very slight burning sound was detectable at 103 seconds. The noise increased at 120 seconds until 150 seconds when no sound was heard. A "whistle" at 159 seconds led into quite loud burning from 163 to 183 seconds when all burning ceased, except for the JP-5. Bore chamber pressure started to rise at 42 seconds and was relatively high–approximately 170 kPa (25 psi) from 105 to 135 seconds. Pressure then decayed until approximately 165 seconds when a spike occurred. The linear potentiometer again showed bore expansion at initial case heating and rapid collapse of bore diameter at about 103 seconds. The bore thermocouples showed flame spikes over a rather extended time span from 150 to 170 seconds. The reaction was deemed to have been burning per MIL-STD-1648 definitions.

The final test, motor 3, yielded a case burst at 96 seconds with television-visible incandescence, then visible flame again at 103 seconds. Burning noise was heard at approximately 105 seconds. Propellant flame continued until 170 seconds, although not audible after 160 seconds. Case rupture was at high pressure, and more tearing and bending occurred than in the other tests. Also, the aft end (bottom mostly) was the failure locus. All instrumentation was affected at 96 seconds, including several flame thermocouples, the pressure gauge, and two added accelerometers. It is of interest that the aft bore thermocouples showed rises at 65, 70 and 75 seconds which continued upward until apparent flame on all the bore thermocouples at 96 seconds. Nothing moved very far, so the test result might be considered burning per the definitions, but the ignition of the grain bore caused a more energetic rupture than the other three tests and some pieces of propellant may have ejected.

13-CM DIAMETER MOTOR WITH LOW MELTING RIVETS

A previously fired Mk 36/50 motor case was refurbished, fitted with twelve small aluminum rivets to refill twelve holes about the case, lined with LR-13, and cast with TPH-1143 propellant. The propellant was poorly cast and had many voids. When this rocket motor was subjected to a JP-5 fuel fire, the fire ignition was quite slow. Two thermocouples reached 538°C (1000°F) at 103 seconds. The fire spread from aft and right of the test item. Aft end failure (rupture) occurred at 130 seconds with burning noise for 16 seconds and visible fire for another 10 seconds. Post-test viewing of the remains found a number of small pieces of the extreme aft end and the nozzle plate scattered about the enclosure. These pieces gave no indication of softened metal, as would be expected from the short time to reaction (68 seconds per the MIL-STD-1648 method), and came from the tube aft of the aft ring of four holes drilled for the aluminum rivets. The aft port thermocouple (Figure 3) shows a steeply rising temperature from 126 seconds to 428°C (803°F) at 130 seconds and a negative value (broken lead) at 131 seconds, which would indicate hot gases entering the bore. This means the holes were either not venting or, perhaps, not venting enough gas to prevent unbonding or grain collapse. The aluminum rivets were not retained in any of the aft four holes (rupture location), nor in the two bottom holes, nor in two holes

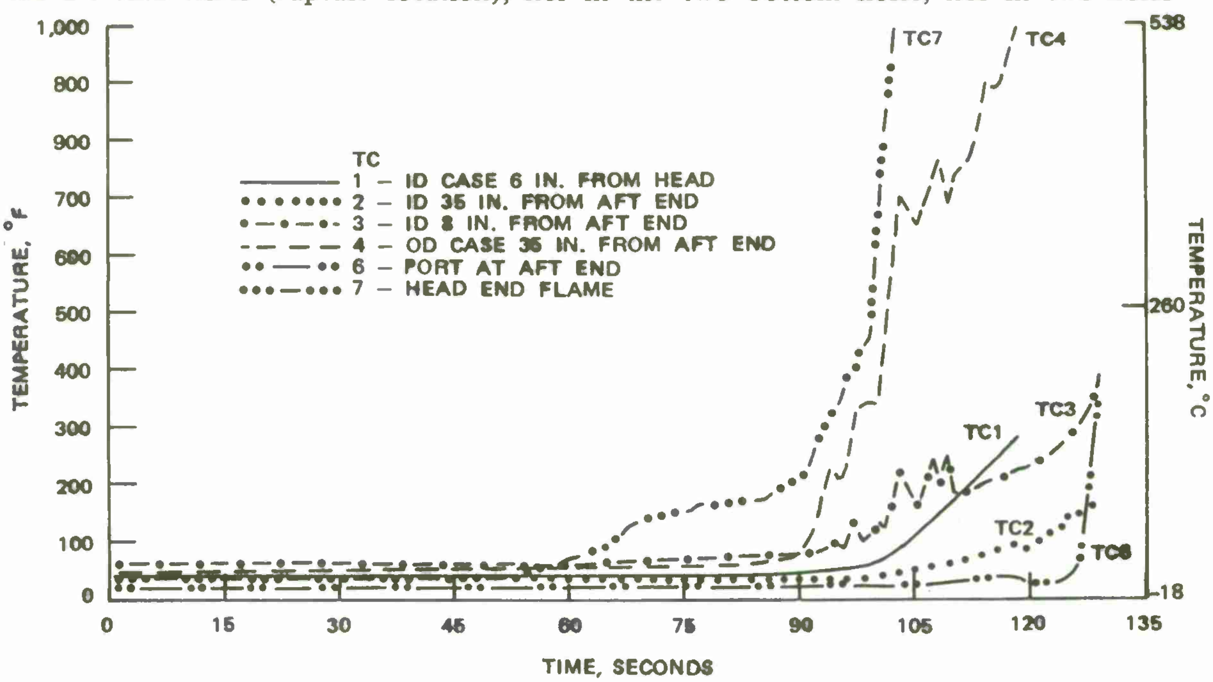

FIGURE 3. Mk 36/50 With Aluminum Rivets.

on one side. There was no enlargement or melting evident at these empty holes. The entire grain appears to have ejected when case rupture occurred. Movie coverage showed nothing except slowly building fire until rupture. The rupture caused ejection of small pieces (many burning) in a manner typical of pressure vessel failure; some of these pieces would have traveled over 15 meters (50 feet). More or larger holes might allow sufficient venting but then case weakening would worsen.

13 CM MOTOR WITH POLYETHER POLYURETHANE LINER

Reloaded Mk 36 hardware, containing an ~ 1.3 mm thick polyether polyurethane based liner (SD-723 plus 2% Kynol fibers and 10% TiO_2), was cooked on 2 April 1975. Results were much worse than anticipated. At 50 seconds there was a violent pressure rupture of the entire case with many small pieces of flaming propellant visible in the movie. Approximately 20 fragments (Figure 4) were scattered about the enclosure and judged to have been hot but not much weakened. (This was based on the approximately 45-degree-angle of the breaks, the folded and wrinkled shapes, and ID thermocouple readings of approximately 240 and 360°C (460 and 680°F). Also, the OD thermocouple was exposed to flame and had been up to saturation and back down to approximately 590°C (1100°F) at the time of rupture.) The aft port thermocouple (Figure 5) indicated temperature rise from 39 seconds to 190°C (375°F) at 50 seconds, while the head end port lagged considerably (start-up at 48 seconds and reaching 85°C (185°F) at 50 seconds). This strongly indicates gases entering the port at the aft end and igniting the bore surface. Both thermocouples were saturated (> 1315°C, 2400°F, at 51 seconds) then went negative; which may mean ignition and loss of continuity at rupture. (The previous test motor, which had the same porous propellant and nonstandard aft end configuration, lost the head end port thermocouple before the test but the aft end temperature rise was similar–it rose a bit more rapidly and reached 232°C (450°F) at 129 seconds, 428°C (803°F) at 130 seconds, and was negative (disconnected) at 131 seconds.) The decision not to use standard casting procedures and tooling (due to difficulty with thermocouple wires and not wanting to modify the tooling) apparently resulted in less pyrolysis gas confinement and propellant voids. This is evidenced by the fact that aft end bonding failed; this would not be expected in the normal configuration which has a preformed aft insulation bonded to the matching aft grain face normally formed by the casting tooling. Also, in the normal configuration, this bond is usually reinforced by a compression fit when the nozzle is inserted. The poor propellant physical properties and the extra strong nozzle closure may also have contributed to the high pressure. In summary, the sample was considered inferior but does demonstrate the importance of fore and aft bonding to seal pyrolysis products and keep them from entering the bore.

FIGURE 4. Collected Pieces of Mk 36/50 Case (LHL 187166).

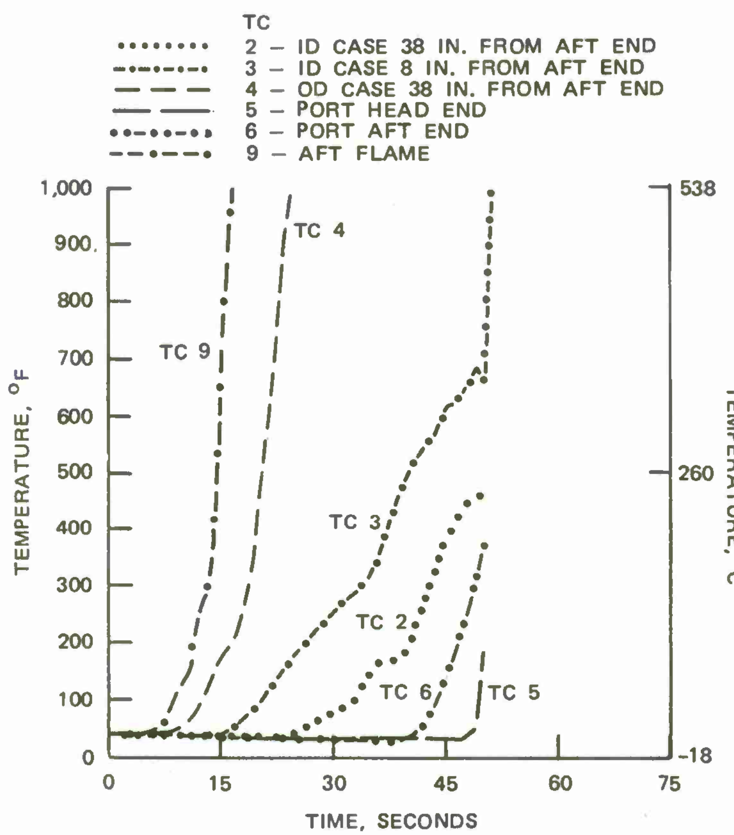

FIGURE 5. Mk 36/50 With Polyether Urethane Liner.

FIBERGLASS TUBE

A filament-wound fiberglass tube with a 0.3 cm wall thickness and 23.5 cm ID (Figure 6) was used as a baseline test motor. This fiberglass tube had six layers of glass wound 75 degrees to the axis and bonded with 31% Dow Chemical Derakane 510-A-40 (fire retardant brominated polyester-styrene) catalyzed with MEKP and cobalt naphthenate as supplied by Owens Corning Fiberglas Corporation.

The tube was primed, lined with 1.3 mm thick carbon black-filled HTPB liner (LR-13), and cast with low smoke RV-13 propellant having a large circular port. The ends were closed with steel plates after inhibiting the grain ends and applying some RTV silicone sealant/insulation. Epoxy, reinforced by glass cloth, and pipe clamp straps were used to retain the end plates. Each end was then completely coated with a layer of RTV silicone insulation so that the test was, essentially, a simulated rocket motor midsection.

The fire was good; all flame thermocouples reached 538°C (1000°F) at 17 to 21 seconds. Thermocouples located on the fiberglass tube ID (midsection and about one-fourth toward the aft end) started rising at 10-12 seconds. They showed a faster temperature rise rate at about 65 seconds and 149°C (300°F). This temperature may correspond to the unbonding of liner and increasing decomposition of the case polymer. Figure 7 shows the temperatures. It appears that the liner/propellant temperature, 155°C (312°F), at 88 seconds (about the time a loud burning noise was first heard) was much below the ignition temperature.

Ignition occurred at 70 or 78 seconds, depending on noise criteria, and did not sound like much propellant was burning until 88 seconds. The bore thermocouples indicated aft end heating at 70 seconds, which indicates aft end liner/case (?) gas leakage leading to grain ignition at 91 seconds (per the head end thermocouple). The liner/case ID thermocouples peaked at 76 and 77 seconds; this may mean that case integrity as a pressure vessel was lost at that time.

Post-test observation and photographs (Figure 8) showed that the reaction was nonviolent; both ends were on the ground directly below the initial location. The bands used to suspend the item and the thermocouple insulation material were quite undisturbed, and the remains of the fiberglass tube were generally found right under their original location. The movies showed very little beyond a fuel fire.

HTPB LINER WITH CARBON BLACK

A Mk 52 (20 cm diameter) motor case, its forward and aft stress relief boots, and core perforation were used to prepare a test motor with LR-13 liner. A 2 mm thickness of R45M-based liner was applied and the grain cast with RV-13-7198 nonaluminized propellant. The core was eccentric at the head end but this is not believed significant to the test results.

FIGURE 6. Fiberglass Test Item Before Test (LHL 188037).

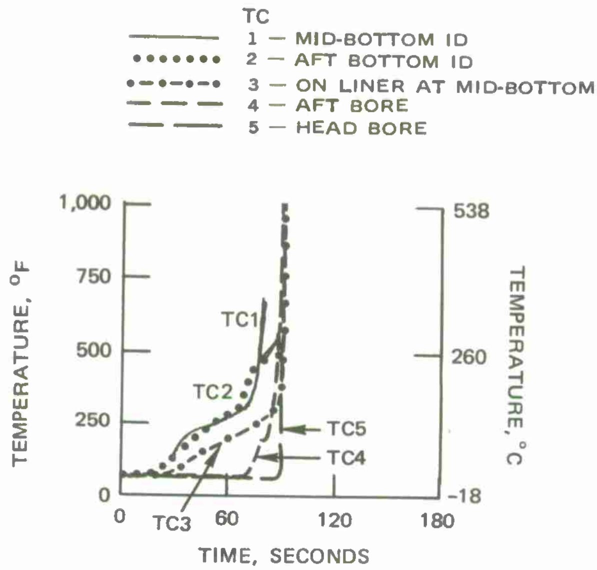

FIGURE 7. Cook-Off of 23.5 cm Diameter Fiberglass Simulated Motor.

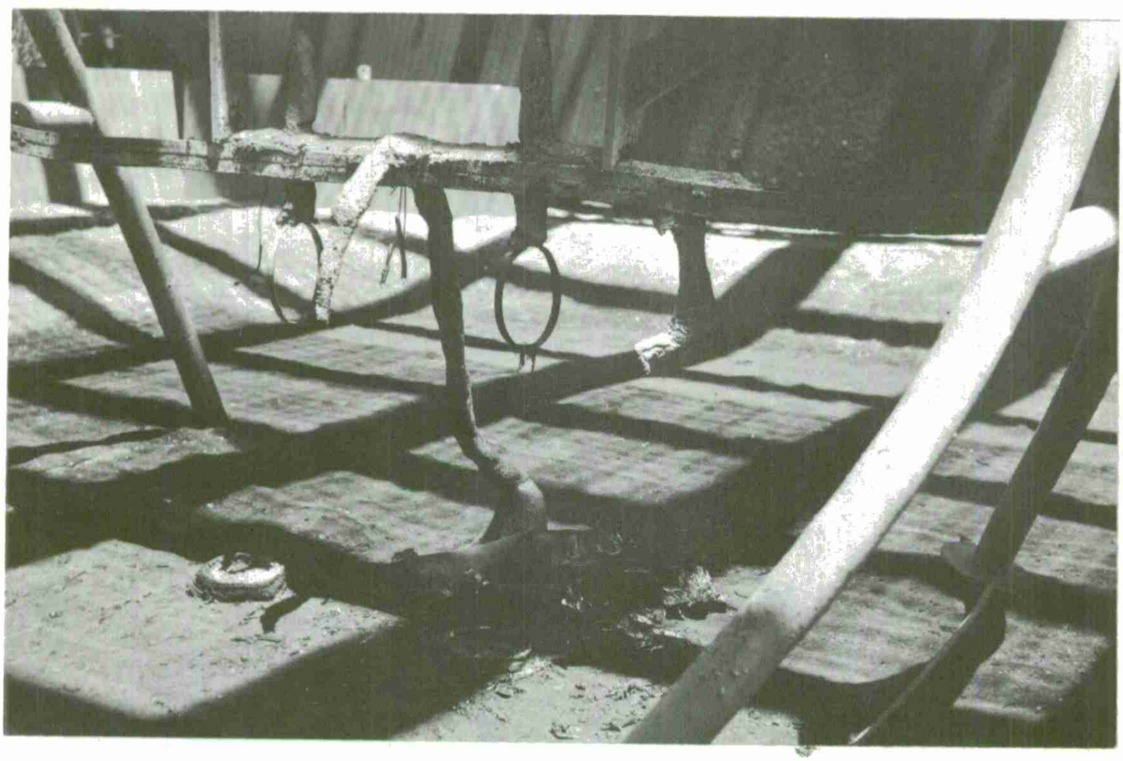

FIGURE 8. Fiberglass Cook-Off Remains (LHL 188029).

Thermocouples were the only instrumentation used. The fire appeared to have been fairly good and reached 538°C (1000°F) at 10-15 seconds. Temperatures oscillated about 980°C (1800°F) but fell off several hundred degrees after about 40 seconds, which is a little unusual.

The three thermocouples on the case wall bottom ID showed similar temperatures. All temperatures began to rise at about 9 seconds, reached 400°C (750°F) at about 50 seconds, were near 480°C (900°F) at 60 seconds, and then rose sharply (see Figure 9). All the test-item-connected thermocouples indicated fast rate changes at 62 seconds. Ignition (per sound, television and movies) apparently occurred at 56 seconds; there was a noise (pop) and burning sound at about 58 or 59 seconds with the sound level increasing soon thereafter. Thus, the probability is that the thermocouples were torn loose at approximately 61 seconds. The motor case remains were directly below the original location (Figure 10).

A bulge of heated, thinned steel on the right side of the head end may have been the initial rupture point; apparently causing the motor to jump forward and left, removing it from the small simulated "rail" and loose strap around the nozzle which

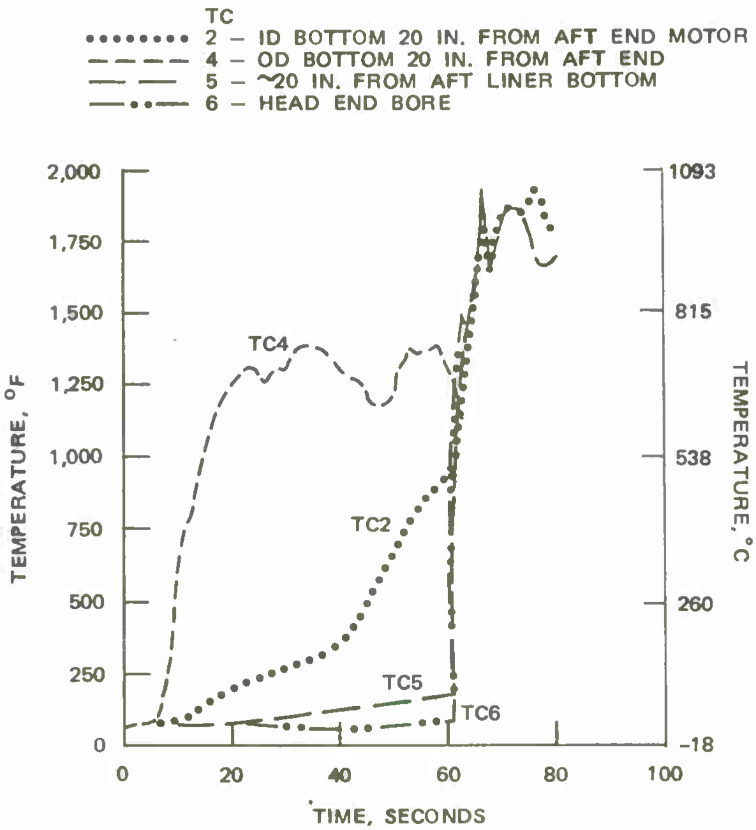

FIGURE 9. Mk 52 (LR-13 Liner/RV-13 Propellant) Temperatures During Cook-Off.

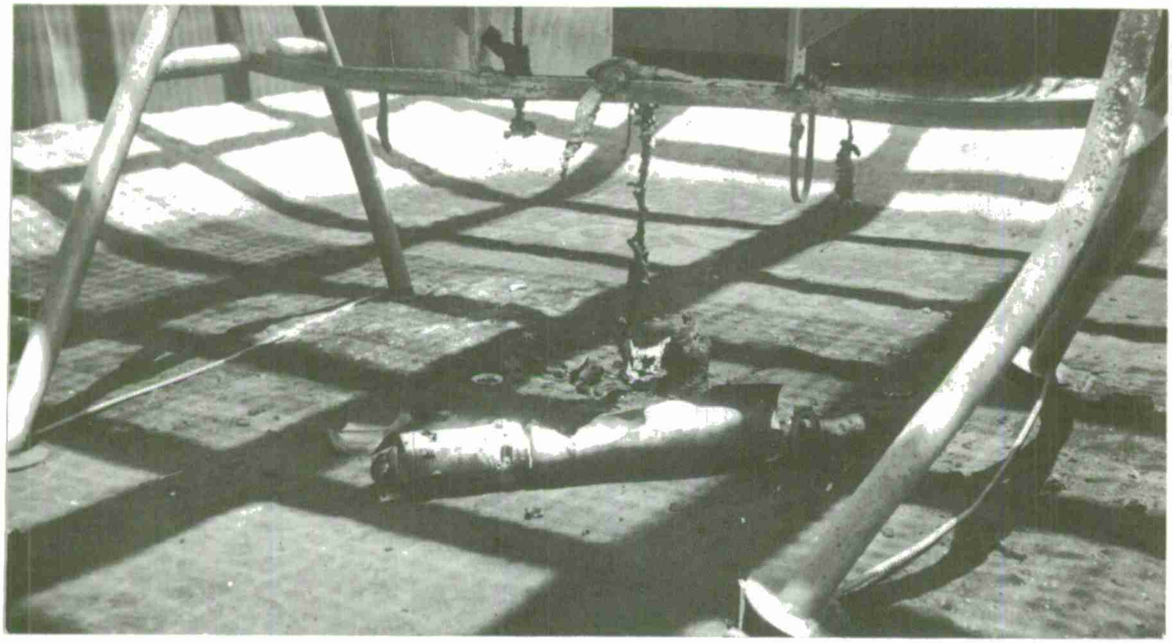

FIGURE 10. Post-Test View of Mk 52 With LR-13 Liner (LHL 188114).

suspended it from the A-frame. At any rate, when the motor fell it pulled the nozzle plug and thermocouple wires out and opened a path to the propellant bore. A single hot piece of case wall, which included some of the thinned metal, was ejected from the forward top right side of the motor and hit the horizontal beam of the A-frame causing the hot piece to deform to the shape of the beam. This could have been either when the soft area initially opened (causing the hot case wall material to be flung up to the beam, wrapped around it and held by it when the rest of the motor was pushed away by the pressure of the propellant grain and burning, expanding gas) or after the motor was on the deck.

In summary, a (mild) deflagration occurred after one minute with the grain, essentially unbonded at that time apparently due to the case temperature, ejected when the bore ignited.

CTPB LINER COOK-OFF IN 20 CM DIAMETER HARDWARE

A rehabilitated Mk 52 motor case was fitted with standard fore and aft boots (bonded to the case with polyurethane rather than epoxy) and lined with LC-2. The 2 mm (0.080-inch) thick liner consisted of Butarez CTL II, MAPO, and carbon black. The nonaluminized propellant was cast using Mk 52/53 tooling.

Thermocouples were installed on the case ID bottom with one on the liner (liner/propellant interface), one in the fore end, and one in the aft end of the bore. Although high winds were prevalent by test time, it was decided to proceed with the test. The average 9 m/s (20 mph), gusty air resulted in a slow building fire favoring the left side of the item. The flame thermocouple data show slightly more than 538°C (1000°F) after 375 seconds, when bursting reaction occurred. Figure 11 shows the unusual situation of forward and aft motor case ID temperatures being higher than the case center ID. The flame thermocouples (added to measure temperature immediately next to the motor case on each side of the motor midsection) indicated several hundred degrees higher than the head and aft case bottom ID thermocouples. We thus have a wider than usual spread of internal case temperatures, 200 to 400°C (400 to 750°F), at reaction. The primary difference for this fire was its low temperature with, consequently, a much different thermal wave into the motor. More heat energy penetrated further into the grain and reaction rates were lower than for a "normal" fire. Also, the case strength was higher at the lower steel temperature.

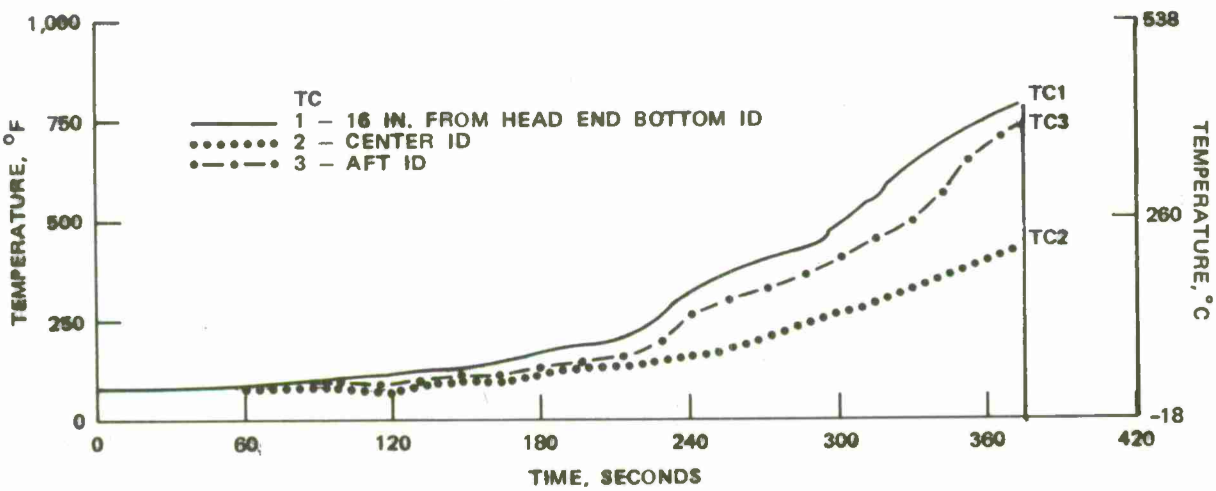

FIGURE 11. Case Inside Diameter Bottom Temperatures During Cook-Off.

Deflagration (pressure rupture) occurred at 375 seconds. The fire never reached the MIL-STD-1648 requirement since the highest peak of flame temperature was only 650°C (1200°F) per the thermocouples near the item. The case tears were full metal thickness (not stretched skin) and yielded fifteen pieces with little remaining of the head or aft domes (see Figure 12). One large chunk of propellant left the pit itself and burned near the cage wall. Propellant burned from approximately 380-400 seconds, which indicates relatively large chunks. The single liner/propellant interface thermocouple showed 133°C (272°F) at 375 seconds (Figure 13), but the center bottom was less heated than the fore and aft regions. As is often the case, the aft bore temperature rose fairly rapidly, leading to ignition. This is assumed to be hot pyrolysis product gases leaking around the aft grain end and is believed to be the proximate cause of ignition.

The postulation that CTPB liner (which produces a tarry pyrolysis with less gases but without a clean separation from the steel upon heating) would be more likely to deflagrate than the polyether or other urethanes was not tested due to the abnormal fire.

FIBER REINFORCED POLYETHER POLYURETHANE LINER

Mk 52 motor hardware was reloaded using standard tooling and fore and aft relief boots (Stoner Rubber Company). The boots were bonded into the case using polyether polyurethane, rather than the epoxy normal to Mk 52/53 motors. A 2 mm thickness of LRV-1 liner was used; this is a polyether polyurethane formulation based on Aerojet's SD746-2 (found in the Mk 78 Mod 0 Shrike) which has yielded mild cook-off reactions. The modifications were minor raw materials differences plus the inclusion of 2% Kynol (3 mm long) fibers and 9% added TiO_2, which provided much improved char retention for normal rocket motor operation. RV-13-7198 low smoke propellant was cast into this motor after thermocouples, boots, liner, and a 3 mm diameter stainless steel tube were installed. The thinwall tubing was cut on an angle and pushed through the liner to be flush on the case wall near the bottom center of the motor. Its purpose was to measure gas pressure generated during cook-off.

In addition to normal laboratory batch data on the RV-13-7198 propellant, several test motors were fabricated and static fired. All functioned normally. Two rehabilitated Mk 52 cases were fired with the LRV-1 polyether urethane liner at –40 and 57°C (–40 and 135°F). This proved the processing and propellant to be acceptable. (Another point of interest is that the LRV-1 liner bond-response-to-thermal-cycling was found to be better than expected in a small testing program conducted by another NWC group.)

The cook-off fire was good with near zero wind. Four thermocouples were located (per MIL-STD-1648(AS)) at motor height about 8 inches in each direction from the item. These thermocouples reached 870°C (1600°F) at 27 seconds and remained there, or above, past the 50 second time of first reaction. Noises monitored were a "pop" at 50 seconds, a burning sound at 51 seconds, and much flame and burning at 54 seconds. Burning continued to 77 seconds with a change in tone and lower volume also at 70 seconds.

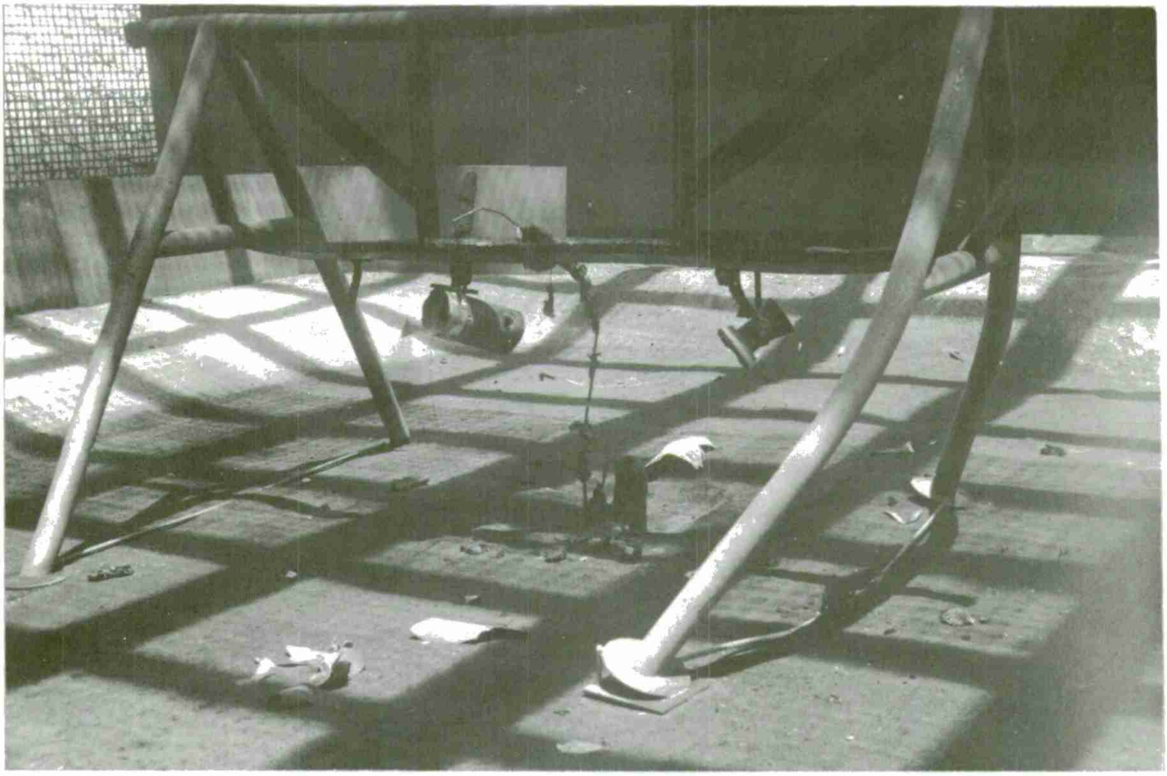

FIGURE 12. Mk 52 Case With CTPB Liner and Low Smoke Propellant After Cook-Off (LHL 188175).

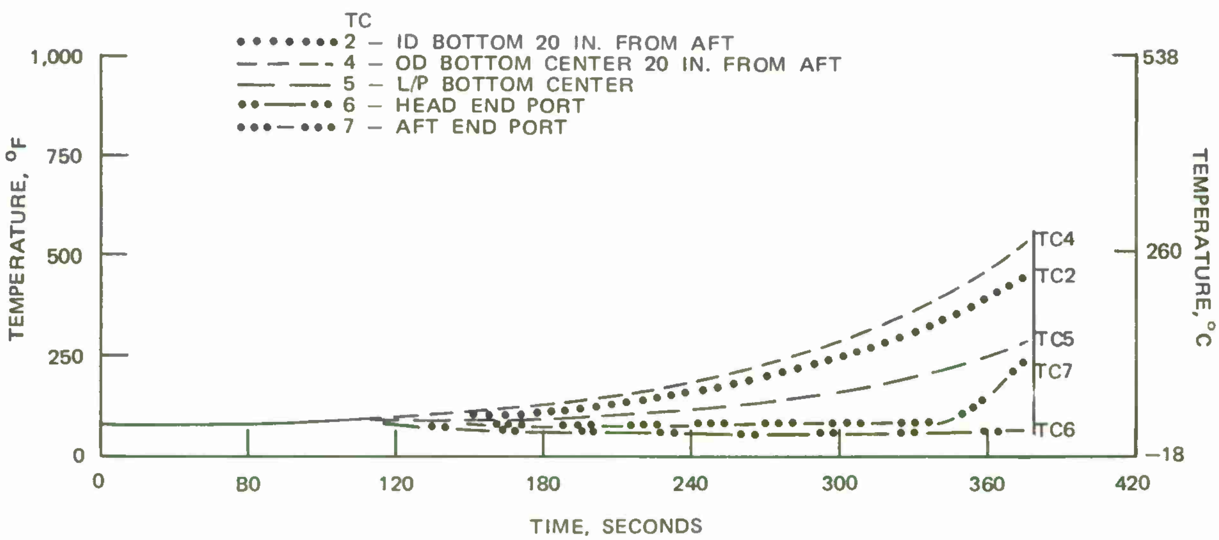

FIGURE 13. Temperature During Cook-Off of Mk 52 Case With CTPB Liner.

The case ID thermocouples at the head end and middle indicated above 427°C (800°F) (with fast increasing temperature preceding) at 49 seconds and a jump at 50 seconds. The more aft thermocouple rose rapidly from 478°C (892°F) at 49 seconds to 688°C (1270°F) at 51 seconds, 967°C (1773°F) at 52 seconds, 1226°C (2238°F) at 53 seconds, and then dropped very low. This might have been due to flame in the aft case area burning off the thermocouple wires. The case OD thermocouple at mid-bottom seemed reasonably true until 50 seconds, but was no good at 51 seconds; which might mean case motion at that time. The liner/propellant temperature at mid-bottom jumped after 54 seconds when it reached only 69°C (156°F). The head and aft ends of the bore show temperature jumps between 53 and 54 seconds, leading us to believe that the rupture of the case into three pieces occurred at about 54 seconds. However, a bulge and leak and/or ejection of the nozzle plug (silicone potting around wires and tubing) occurred at 49+ seconds when the chamber pressure peaked (545 kPa (79 psi) per oscillograph) and dropped rapidly to zero, then built up to 110 kPa (16 psi) at 54+ seconds before dropping again to zero. It is therefore conceivable that the nozzle seal broke loose (leaked) at 545 kPa due to pyrolysis gases from the liner (?) entering the aft end of the grain (see Figure 14 which shows the aft bore temperature rising from 40 seconds). The aft bore temperature hovered at about 135°C (275°F) for several seconds starting at 50 seconds (when the chamber pressure dropped) at which time we can see first activity in the forward bore temperature. Grain bore ignition occurred at 54 seconds with head end trailing aft end, corresponding to the television-visible fire spreading all around at 54 seconds.

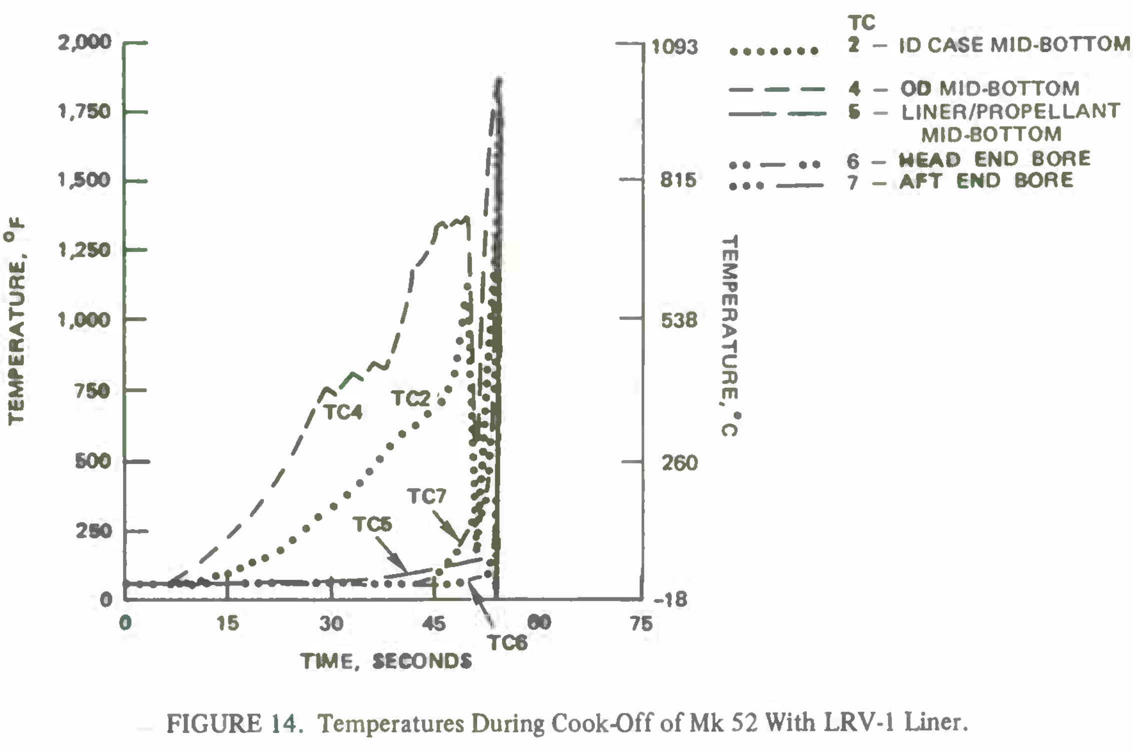

FIGURE 14. Temperatures During Cook-Off of Mk 52 With LRV-1 Liner.

It is not known whether the liner/case mid-bottom pressure probe was working properly or not. Little pressure (approximately 14 kPa) was generated. The small tube could have been plugged. It is considered unlikely that any liner bond existed after the case ID reached 260°C (500°F).

Post-test evidence (see Figure 15) showed the case opened up with tears in the steel yielding two main pieces (head and aft ends) plus a smaller piece. One side of the smaller piece and its mate on the forward motor section was thinned metal. A good deal of similarity existed between the remains of this test motor and the similarly constructed polybutadiene polyurethane (LR-13) lined motor. A large piece of grain (per movie coverage) came down on a witness plate, split (with part going down the side of the pit embankment), and then across the pit into a corner of the cage where it burned. It is difficult to explain how sufficient pressure was attained to rend the case apart since the maximum pressure recorded was 110 kPa (16 psi) when the event apparently happened.

The expectation that this liner would yield the least violent reaction was not met nor was the liner/case pressure measurement as expected. The latter may well be due to equipment and technique shortcomings. The reaction must be considered a deflagration since the grain segment could have traveled on the deck more than 15 meters (50 feet). The flight of the nozzle, case and grain thus means the test failed to meet the goal.

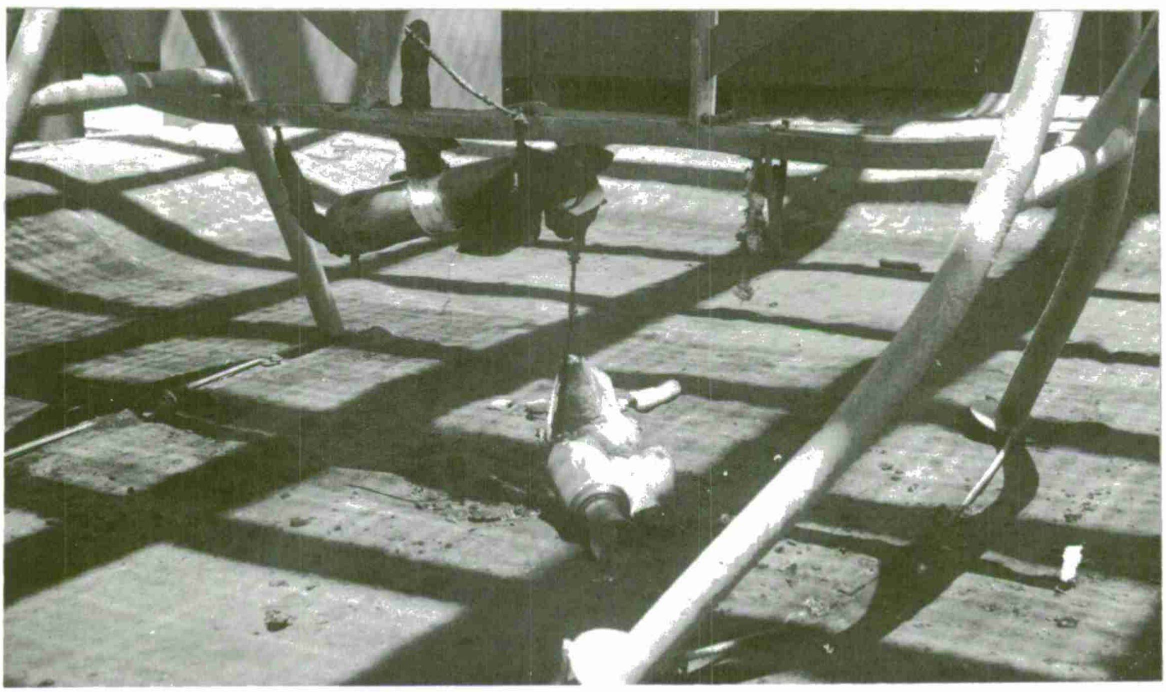

FIGURE 15. Mk 52 With LRV-1 Liner and RV-13 Propellant After Cook-Off Fire (LHL 188176).

SIDEWINDER HARDWARE USING HTPB LINER AND LOW SMOKE PROPELLANT

The Mk 36 motor has relatively thick metal and is 13 cm in diameter, which makes for a somewhat different cook-off situation than the 20 cm Shrike/Sparrow. The LR-13 liner (typical R45M basic liner) was used in this motor to compare it to the Mk 52 unit as well as to Sidewinder.

Standard Sidewinder/Chaparral processing tooling was used with thermocouple wires looped and taped at the aft end during casting. These were pulled straight after cure. Aft inhibiting was done using the regular preformed part, but a nozzle was used to retain it rather than the aluminum plug fixture. The nozzle could not be removed after inhibitor cure. It was decided to insert the lockwire as segments without installing an O-ring.

There was a mild breeze when this unit was tested. The unit was exposed to 600 gallons of burning JP-5, but the breeze had only a mild effect. However, a delay (after adding the regular gasoline (starter) to the rags with their squibs) for the purpose of recalibrating the computer led to a slow ignition. A temperature of 538°C (1000°F) was reached at 101-129 seconds and initial ordnance reaction occurred at about 160 seconds when flame temperatures were below 815°C (1500°F). The initial reaction was a low level sound increasing over several seconds to the usual low pressure propellant burning noise at 170 seconds. A visible eruption and increased burning were noted at 184 seconds with burning noise until about 200 seconds. Post-test inspection revealed that the aft end of the motor had burned through (Figure 16), then the nozzle and grain ejected. The ejection pressure was sufficient for the nozzle to make a small dent in the 3 mm witness plate, but the motor tube was propelled much more forcibly by the propellant and the dummy warhead pierced a witness plate, bent its support frame and lifted the plate around (pivoted approximately 90 degrees when hit on one end). Thermocouple data indicate the case ID was near 538°C (1000°F) at first reaction with flame exposure at 164 seconds. The liner/propellant bondline thermocouple also showed a similar response at the same time. This may mean that the initial propellant burning was in the vicinity of these thermocouple leads (considered likely) and not all along the tube ID bottom. The aft bore temperature started rising at 170 seconds (when burning noise was established) and jumped at 183 seconds while the head end bore temperature showed an increase of 17°C (30°F) at 138 seconds and went negative at 184 seconds (Figure 17). This means internal bore ignition from aft end gases and nozzle ejection occurred at 184 seconds.

The pressure gauge was attached to a fitting welded to the case OD 63 cm (25 inches) from the head end with a hole through to the liner OD. It showed a small pressure (approximately 51 kPa) from 163 to 183 seconds. At 184 seconds it went negative. The nozzle seal was gone and char was formed on a portion of the outer insulation. A small amount of metal-edge-rounding over this same quadrant indicates some hot gas leaked aft past the lockwire groove. The absence of an O-ring may, therefore, have contributed to a pyrolysis gases leak path which relieved pressure and grain deformation.

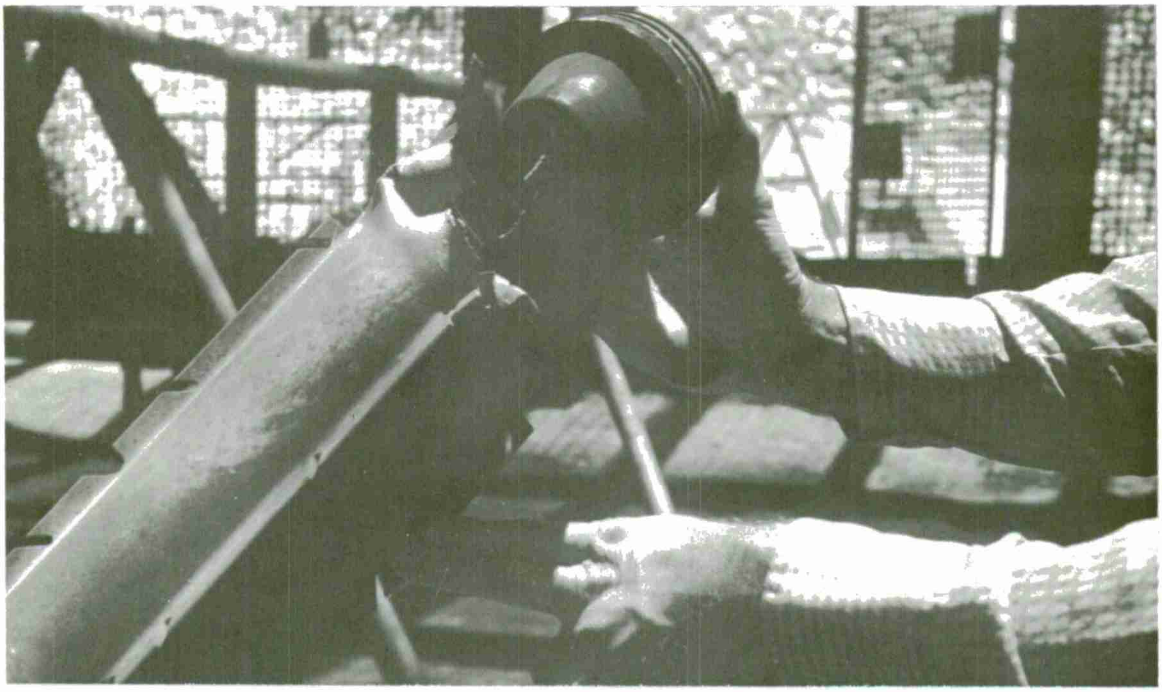

FIGURE 16. Mk 36/50 Case After Cook-Off Using HTPB Liner and Smokeless Propellant (LHL 188214).

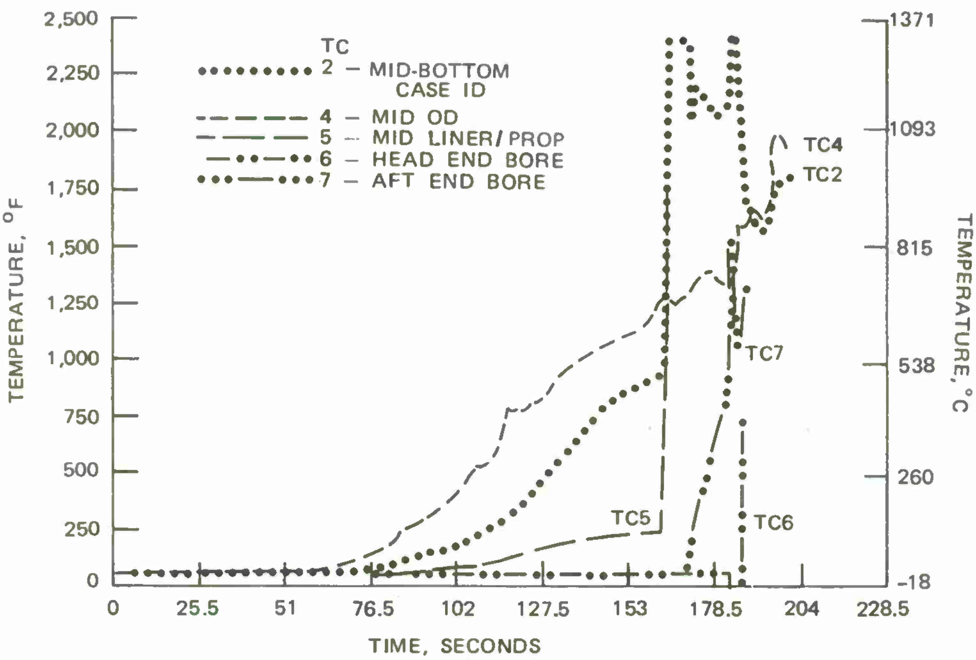

FIGURE 17. Temperatures During Cook-Off of Mk 36/50 With HTPB Liner.

POLYETHER POLYURETHANE LINER IN MK 36/50

Another motor was fabricated using the LRV-1 liner to gather additional pressure and cook-off data. Construction was very similar to standard production in dimensions, but the liner was essentially a reinforced SD746-2 composition. The propellant was RV-13, a nonaluminized R45M composition. This motor was processed at the same time as the LR-13 lined Mk 36/50 and had the same nozzle problem. This resulted in the absence of an aft end O-ring, although the aft end inhibiting liner probably sealed the unit and filled a portion of the groove.

The fire was good with 815°C (1500°F) reached at about 25 seconds, although very little happened for 15 seconds. Motor reaction occurred at 47 seconds with a loud ignition. This died out, then flared anew at 52 seconds, died down, and burned from 54 to approximately 65 seconds with television-visible jets of flame. This motor also ejected its nozzle and flew out of the straps holding it below the A-frame. The nozzle did not travel far and was in good condition. Some pieces of thermocouple wire and the nozzle's 8 mm thick phenolic weather seal were intact, except for the hole cut in its center to accept the thermocouple wires. The aft inhibitor preform came to rest in the gasoline and was cooked but still recognizable. It must have been in near-new condition at ejection. The grain must also have ejected in nearly one piece. Burned gouges in the dirt (sand) pit bottom indicated the grain had lain there and burned from both ends and the hole in the middle. The case flew forward a short distance and was quite heated but not much deformed or damaged, except that the lockwire groove had been torn nearly all around to release the nozzle. Apparently the grain was forced into the nozzle and the case parted in the lockwire groove. Not enough gas was in the bore, however, to eject the weather seal with its minor added support from silicone rubber sealant around the thermocouple wires.

Case ID temperatures were about 427°C (800°F) at reaction with liner/propellant mid-bottom being 37°C (99°F) and the fore and aft bore temperatures showing no rise at all prior to reaction. Bore pressure via head closure was monitored and there was also a pressure tap through the case wall bottom 63 cm (25 inches) aft of the head end. This hole abutted the liner, as was done with the LR-13 lined Mk 36/50 motor. More air-filled tubing was attached to this chamber wall fitting than desired; a close-coupled gauge would not have much gas plenum to be pressurized by the pyrolysis gases. The tubing was well insulated. As before, the pressure data are subject to credibility and open to interpretation. However, there was a rise on both case/liner and bore pressures at 35 seconds. This occurred on the oscillograph traces also and showed about 14 kPa (2 psi) in the chamber bore and about 138 kPa (20 psi) for the case/liner pressure tap. The pressure dropped off gradually (to zero at 42 seconds for bore pressure). At 43+ seconds, there apparently was a power supply change or stray voltage which affected both gauge outputs as a step function. The oscillograph showed no change then for either gauge until approximately 47.5 seconds when the case/liner pressure rose to 414 kPa (60 psi) over a quarter second, then dropped to below zero at 48 seconds. At this instant, both gauges jumped up simultaneously. The bore pressure jumped directly to 1930 kPa (280 psi) and continued to 2137 kPa (310 psi) over about 1/10 second, then dropped to zero and below. The case/liner pressure rose instantly to approximately 620 kPa (90 psi), more slowly to 1069 kPa (155 psi), dropped to about 172 kPa (25 psi) before jumping back up to 1103 kPa (160 psi) instantaneously as a spike, then down and back up abruptly to 1344 kPa (195 psi). It then descended relatively slowly to 862 kPa (125 psi) at about 48.3 seconds when it dropped rapidly and bore pressure jumped. The motor may have physically left the A-frame at this time, or before, and disconnected the gauges.

One can speculate on the credibility of the values or the mechanisms which created these pressures. However, bore thermocouple data overlays show the case/liner pressure spike to correspond to bore ignition temperature spike. Data after this are very suspect. The case ID temperatures at midpoint and forward end show dips over the 35-47 second time span when the case/liner pressure rose, which might mean gases or grain, or both, were moving. If the casewall is about 260°C (500°F), the liner will "fry" generating gases when contact is made with the casewall. After the grain liner is released all around by this frying, gravity will tend to pull it into contact at the bottom. Thermal dimensional changes will also cause motion of the various materials and pieces.

Again, the results of the test did not meet the goal of a very low pressure case opening and burning of the grain in place at low pressure such that negligible thrust is developed. However, the resulting mild deflagration is much better than violent case rupture with many case and propellant fragments thrown about.

PROPANE BURNER COOK-OFF TESTING

INERT PROPELLANT TRIAL TEST

A 10 cm diameter simulated motor test device and fixture for flame heating was designed. Three test items were fabricated as metal parts. One of these was loaded with thermocouples, liner, and inert propellant. The propane burner fire system developed for fuze and booster testing was used to heat this test item so that better visibility and instant stop capability were obtained. Better post-test evidence is another benefit in that no more heat is added after the propane is shut off, and pieces do not fall into gasoline.

Nothing visible occurred to the item during this test and fire on and off was rapid. Video monitoring showed opaque flame for much of the test time. Test item positioning was somewhat high above the burners and flame temperature just below the item was about 1038°C (1900°F) with about 15 seconds buildup time. The propane was shut off at 2.5 minutes, when the forward bottom ID thermocouple showed about 650°C (1200°F). The case ID reached 663°C at the hottest thermocouple with 552°C maximum on the next hottest location (also on the bottom). The flame temperature just below the item was 1093°C. No metal deformation occurred.

Pressure measurements were made in the bore and at the wall (midbottom). The case/liner interface pressure tap registered a step pressure of about 13.8 kPa (2 psi) from 1.1 to 1.7 minutes. At this time both pressure gauges started a rise to ~ 517 kPa (~ 75 psi) which lasted until the fire was terminated at 2.5 minutes. The case/liner pressures then dropped before increasing; both went over 1035 kPa (150 psi). The bore thermocouples showed a temperature rise starting at 1.2 minutes, indicating a "gas" leak at the time when case/liner pressure is initially seen.

Post-test disassembly revealed decomposed liner (sticky liquid) in the bore. The end was machined off and the grain pushed out to allow further inspection. It was found that most of the polyether polyurethane liner was liquified. The liner on the aft end (which was not exposed to flame; and protected by massive steel heat sink) and a small patch of liner on the top of the other end were intact, though largely unbonded from the steel. The absence of liner along this path provides definite evidence that liner gases and liquids flowed along the thermocouple leads and into the bore. The mechanical compression seal did not maintain much pressure because of these thermocouple leads.

The inert propellant bottom sector was found to be blackened to a depth of ~ 0.2 cm in worst areas. The inadvertent failure to install the desired grain/liner interface thermocouple renders it totally conjectural whether the grain/liner interface heating (charring of grain) occurred during or after the flame heating. We do know the case wall ID temperatures ranged from 260 to 330°C at 4.7 minutes and cooled rather slowly. Liner and binder decomposition rates at this temperature are significant.

POLYETHER POLYURETHANE LINER

Two live propellant items were fabricated to route the thermocouple wires differently in order to provide a better seal. The propellant batch appeared normal and the 10-cm-diameter "model motor," with SD-723 liner, was trimmed and assembled with thermocouples in the bore. The unit was mounted on the test fixture and two pressure gauges were attached along with the flame thermocouples. The propane/air burner bank was ignited and produced a 538°C flame at about 5 seconds with about 955°C average from 15 seconds through 1 minute, when reaction occurred. Inside diameter case bottom temperatures rose immediately from propane ignition with a maximum temperature of 482°C on the hottest and 360°C on the next hottest thermocouples at 58 seconds (Figure 18). At about 38 seconds, pressure began to be measured (Figure 19) at the liner/case juncture; several of the thermocouple traces show "wiggles" and changes in temperature rise rate. These temperatures exceeded the values where liner bond release occurred on laboratory test heating of steel plates, and depolymerization must have begun. At 57 seconds, the case/liner pressure was about 179 kPa (25 psig) and the bore pressure was zero. The case/liner pressure then rose to 1048 kPa (152 psig) peak just before 58 seconds and dropped off quickly about one-half second later. The bore pressure started to indicate at ~ 57.5 seconds and shows an abrupt spike just after 58 seconds. The bore thermocouples (head and aft) indicated a slight change at 58.5 seconds and a temperature rise at 59.0 seconds. Physical and television/audio evidence show that the welded end closure (flat plate) of the model motor failed near the weld at ~ 58 seconds allowing the grain to eject. The sound indicated propellant was burning, and it continued to burn and consumed itself on the ground in about 15 seconds. The pressure gauges apparently are not responsive enough to high rise rates since only 1449 kPa (210 psig) peak was recorded and this is low even for a poor weld when the steel was only 482°C or less. The desired reaction (slow pressure buildup until case softening and venting before ignition of propellant) was not obtained.

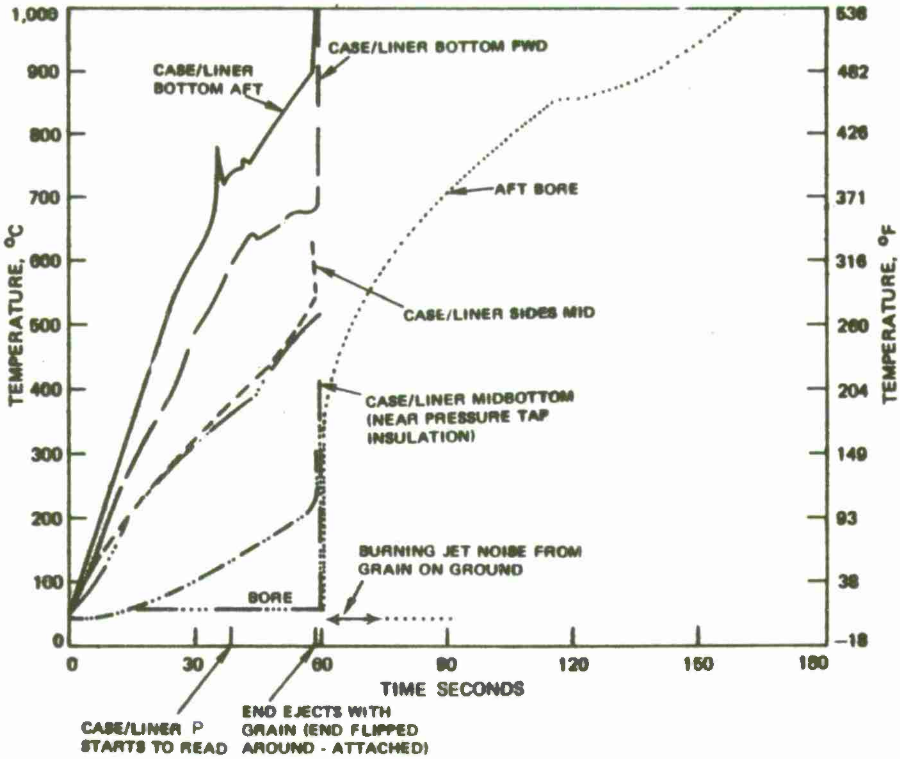

FIGURE 18. Temperatures During Cook-Off of 10 cm Diameter Model Motor.

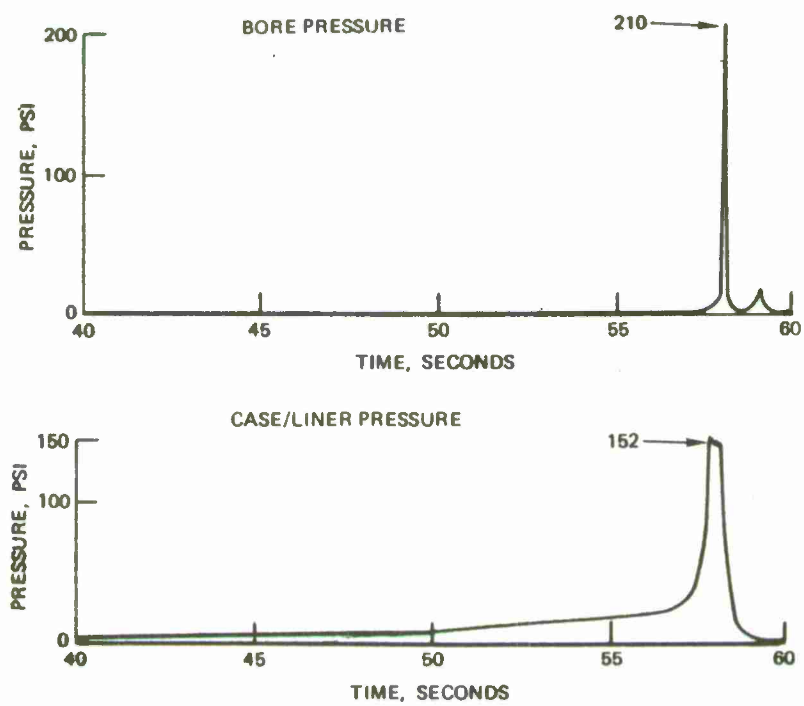

FIGURE 19. Bore and Case/Liner Pressure Versus Time.

STEEL SHIM LAMINATE MOTOR TEST

Test of 0.25 mm by 10-cm-wide spiral wrapped bonded steel shim (Rapier type) 13 cm diameter "motor" resulted in mild deflagration, as expected; i.e., the unit burned in place with low pressure and no pressure vessel burst. Thermocouple data are shown in Figure 20. A high speed movie shows the formation of smoke jets from numerous places as the case adhesive decomposed. Eventually, propellant ignition occurred on the grain outside diameter. This resulted in gas that cut the shimstock and enlarged holes, as well as causing unraveling of the shimstock on [ne end. The bore, reached by burning through the web, was then ignited and the case soon separated from one end closure. Two motor end pieces plus a dozen pieces of unwrapped shimstock were all that remained (see Figure 21). This test, using the unique construction in a closed vessel configuration, indicates that this motor case fabrication method can provide ordnance which will "burn" per MIL-STD-1648(AS) in a fuel fire.

HTPB/OXAMIDE LINED MODEL MOTOR TEST

A 10-cm-diameter model motor, lined with HTPB based liner containing oxamide and cast with low smoke HTPB propellant, was tested in the propane/air burner facility. Figure 22 shows the thermocouple data obtained and Figure 23 shows the bore and liner/case midbottom casewall pressures monitored during the cook-off. The vagaries of the thermocouple readings are believed due to eventual thermal flow to junctions in some of the thermocouples. These junctions were necessary due to severing during lining operations. No movie coverage was obtained because the film broke; however, video tape records were obtained. The failure mode was again structural loss of the flat end of the model motor and ejection of the grain. The oxamide/HTPB liner showed gas pressure at 25 seconds with a maximum thermocouple temperature of 232°C on the case ID. The polyether liner gas pressure rose a bit at 38 seconds when 343°C was seen by one case ID thermocouple. There was much more pressure (more gas formed) from the oxamide filled liner. Case rupture (end plate ejection) occurred at 104 seconds for the oxamide filled liner at 2.1 MPa, per the slow response gauges. (The polyether-polyurethane-lined unit had a maximum pressure of 1.4 MPa and failed at 58 seconds.) Neither case showed steel stretching although the oxamide-HTPB-lined case ID maximum thermocouple temperature was 660°C. Figure 24 is the oscillograph pressure traces at rupture.

It is difficult to do more than conjecture that some propellant surface area ignited at about 101 seconds (see Figure 23) and that the movement of the grain (allowed by failure of the closed end) toward the rupturing end allowed gas to enter the bore. Pressure on the grain OD caused it to deform inward and against the aft (open bore) end taper. Failure of the closed end then would vent the forward end pressure, providing the force to hold the grain against the aft closure. This means that the case failed before the gases leaked into the bore, i.e., the bore was not ignited prior to failure.

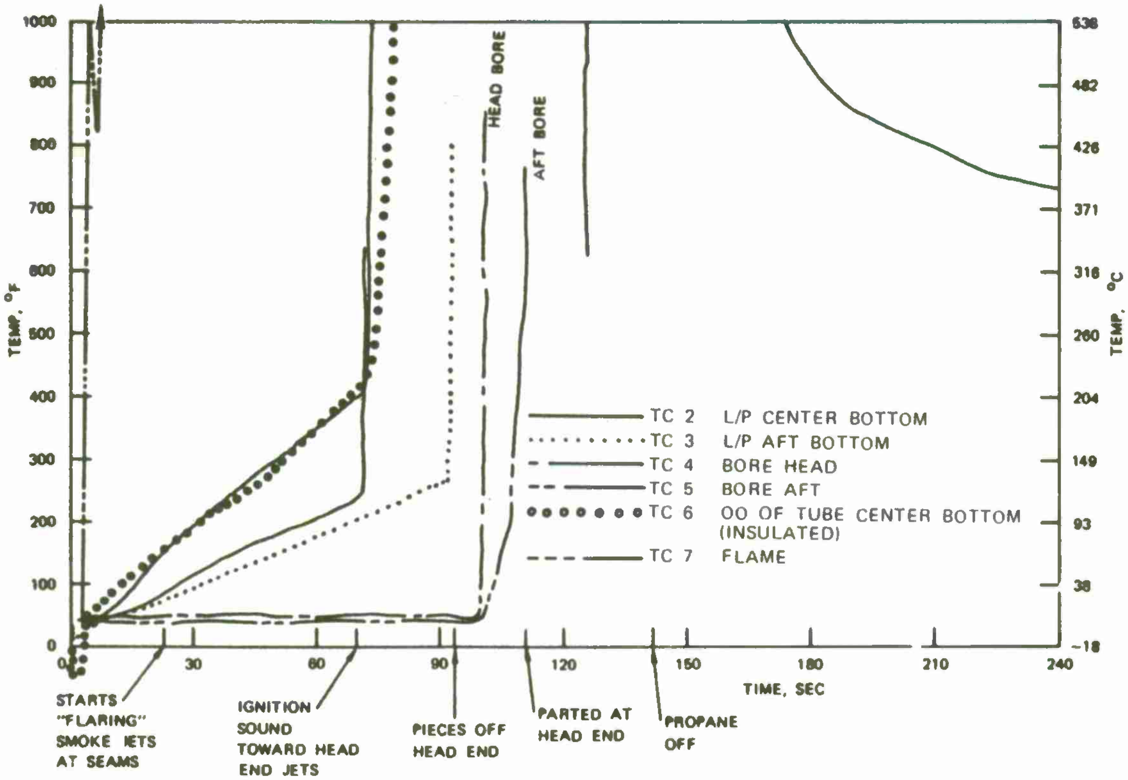

FIGURE 20. Temperatures During Cook-Off of HTPB Lined Low Smoke Propellant Loaded Steel Shim Spiral Laminated Rocket Motor.

FIGURE 21. Remains of Laminated Steel Spiral Wrapped Tube Cook-Off Test No. 1 (LHL 192362).

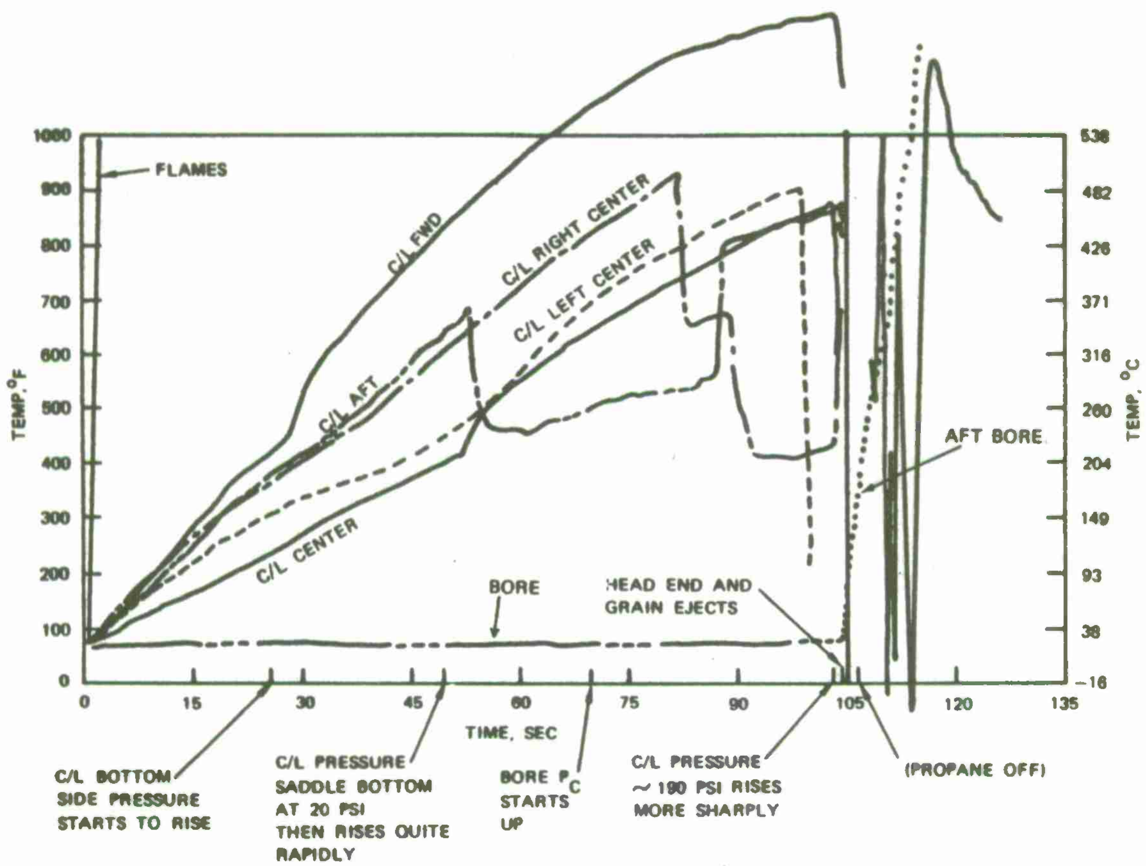

FIGURE 22. Temperatures During Cook-Off of LRV-11 HTPB-Lined RV-7-298 Low Smoke Propellant Loaded 10 cm Diameter Model Motor.

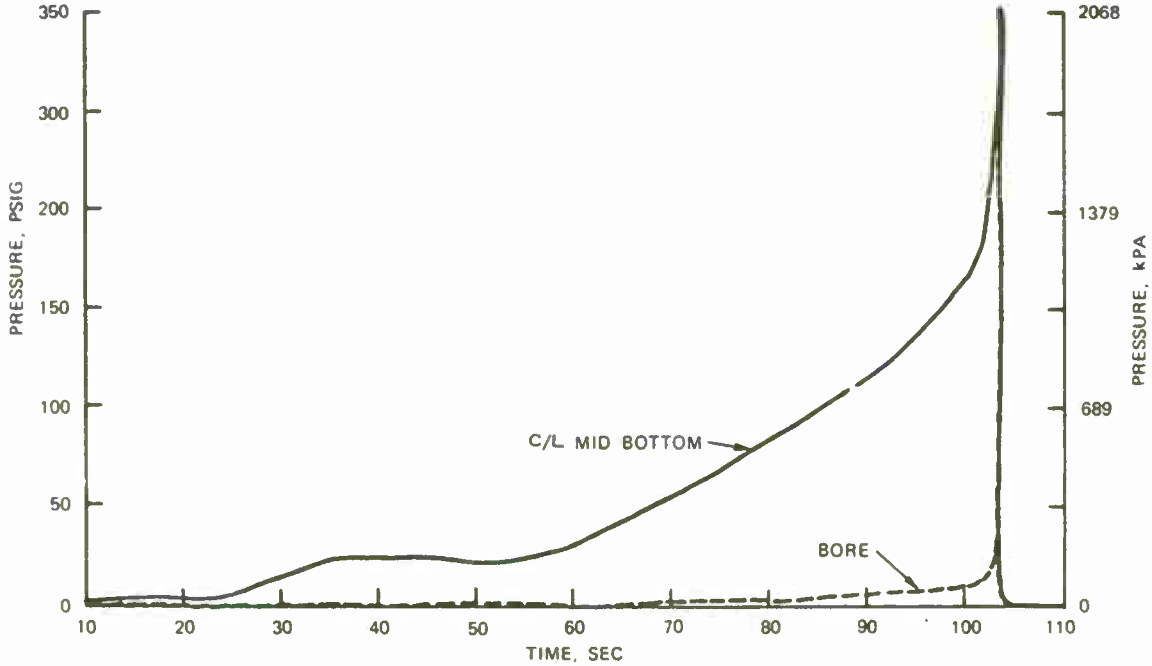

FIGURE 23. Pressures of Bore and Liner/Case Mid-Bottom During Cook-Off.

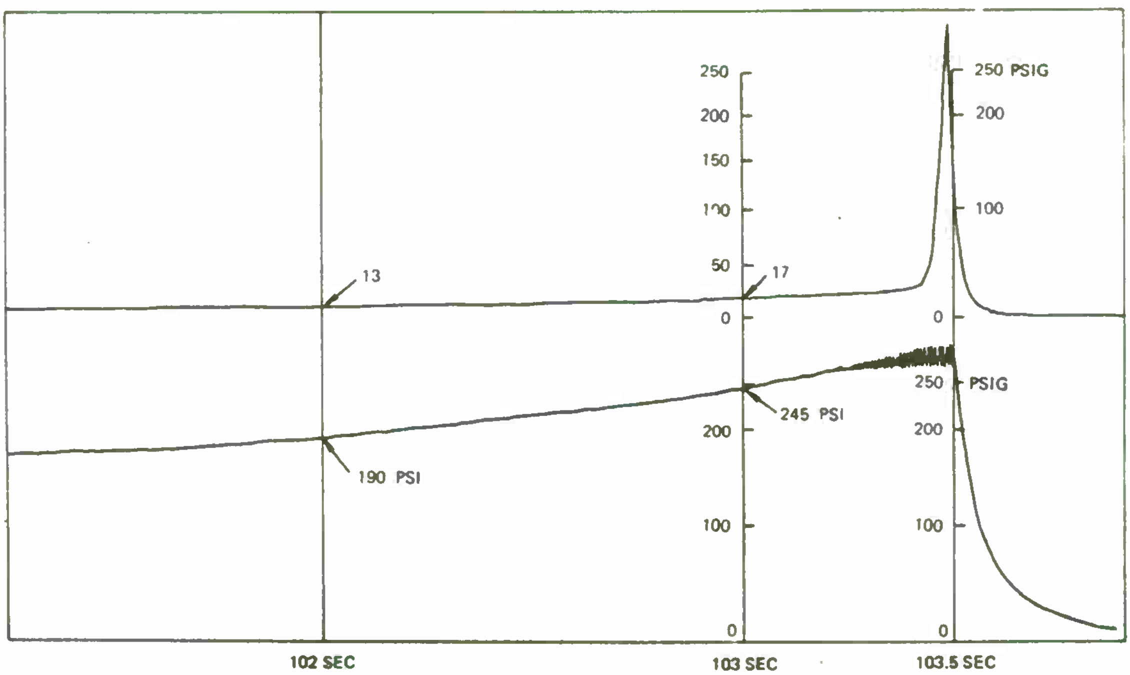

FIGURE 24. Oscillograph Pressure Records at "Reaction Time."

STEEL SHIM LAMINATE MOTOR COOK-OFF TEST NO. 2

A second 92-cm-long, 13-cm-diameter simulated rocket motor case, purchased from Hercules, was tested. The HTPB liner was coated with fresh HTPB liner (LRV-11) and the tube loaded with 11 kg of RV-7 (batch 7445) propellant. One change from the earlier construction was a further "overtest": steel pipe clamp straps were attached over the ends of the wrapped steel shim such that the ends could not unwrap.

The propane/air burner fire was normal; both flame temperature thermocouples recorded over 871°C for the duration of the test after about 6 seconds. Three thermocouples at the inner layer of liner along the bottom of the motor showed steady temperature rise until 118.5 seconds, at which time (propellant flame) temperature started to rise for two of the three thermocouples. The third began to rise about one second later. Liner/propellant temperature was 120-150°C at the time of reaction. Television replay sets the times of visible effects as follows: 15 seconds–first indication of gassing between shims; 115 seconds–jetting between shims at head end; 118 seconds–jetting and unwrapping at aft end leading to more burning and eventual unwrapping of all shim steel except the ends.

These visual results were also apparent in the 100 fps film coverage, although timing cannot be confirmed. The grain OD burned for quite a few seconds before the ID (bore) caught fire. This was confirmed by the thermocouples in the ends of the bore. These showed no change until 142 seconds in the aft end and 144.5 seconds in the head end. Abrupt rise to thermocouple saturation occurred at these times.

Although bore pressure was also monitored during the test, nothing much was recorded except for a very brief 70 kPa (10 psi) blip at about 117 seconds. The test item was sealed. At about 124 seconds, the pressure gauge and the linear potentiometer showed zero shifts. The linear potentiometer was mounted in one end of the bore to measure vertical displacement (bore diameter increase or decrease). From about 116 to 117 seconds, a deflection of 1 mm was recorded which remained constant except for an approximately one second electrical shift at about 122 seconds. It is believed that little deflection or internal bore pressure was created per these data and the video and movie records. The propellant ignited at 115 seconds and a larger hole was "cut" at 118 seconds, but there was no evidence of high pressures. Review of the test movie showed that, after the case had burned, unwrapped and fallen away, the grain OD continued burning until some holes appeared in the grain wall and the unsupported end dropped from the test fixture. This means little or no internal pressure existed since a thin tube of propellant would bulge or rupture. We know the internal bore started burning 23.5 seconds after the case ruptured and the grain OD started burning. Figure 25 depicts the hardware remains after this test.

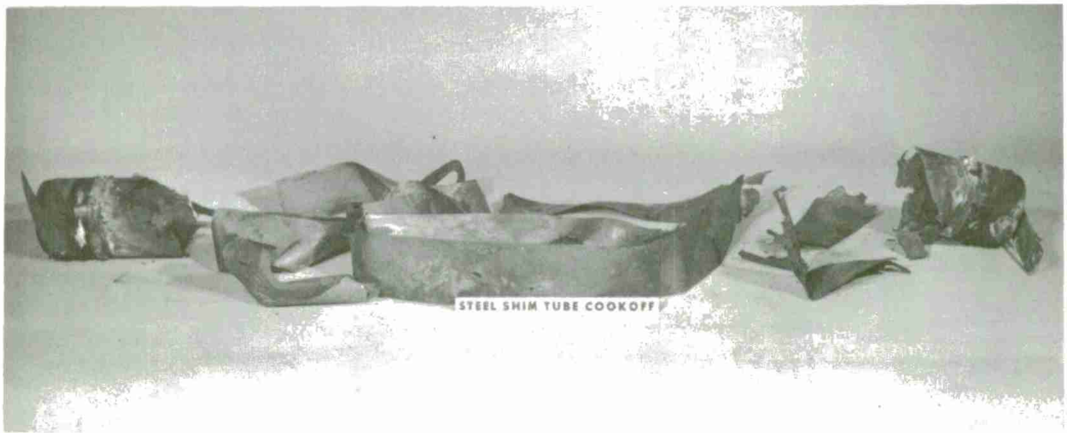

FIGURE 25. Remains of Laminated Steel Spiral Wrapped Tube Cook-Off Test No. 2 (LHL 192361).

In summary, a very mild burning reaction was obtained from this steel shim wrapped motor. This was due to the fire having softened and ignited the adhesive which, in turn, led to pressure vessel integrity disintegration prior to propellant ignition. Strong consideration should be given to using this type of construction for all rocket motors and perhaps bombs and warheads as well. Reduced damage and hazard in fire environments would be expected from using this type construction.

EXTENDED MODEL MOTOR COOK-OFF TESTS

Oxamide-Filled HTPB Liner Test

The first of the new design model motors (Figure 26) had an oxamide-filled HTPB liner with 2% Kynol fibers. The propellant was the low smoke RV-7 (batch 7445) formulation and weighed 6.9 kg. This model motor had a 33 cm center test section which was centered above the propane/air burner flames. The ends, made of heavier metal pipe, were welded to this test section. The ends remained cooler, as would normally occur for the nozzle area and head end attachment of a missile.

The videotape test records indicated loud noise and case separation at the aft joint, etc., at 89 seconds after propane ignition. Thermocouple data (Figure 27) showed some activity at 88.5 seconds or soon thereafter. The bottom ID (fore, center and aft) thermocouples showed a jump at 89 seconds while the liner/propellant temperatures near those same locations increased at 90.5, 91.5 and 89.5 seconds, respectively. Bore thermocouples showed minor rises at 88.5 and 89 seconds; these may have been due to adiabatic compression or electrical signal cross-over. Aft bore temperature rise occurred after 92 seconds, while forward bore temperature rise occurred at 94 seconds. The unit was burning well on the grain OD and separated into two pieces at that time. Unexplained temperature excursions of the case ID thermocouple data occurred after 70 seconds.

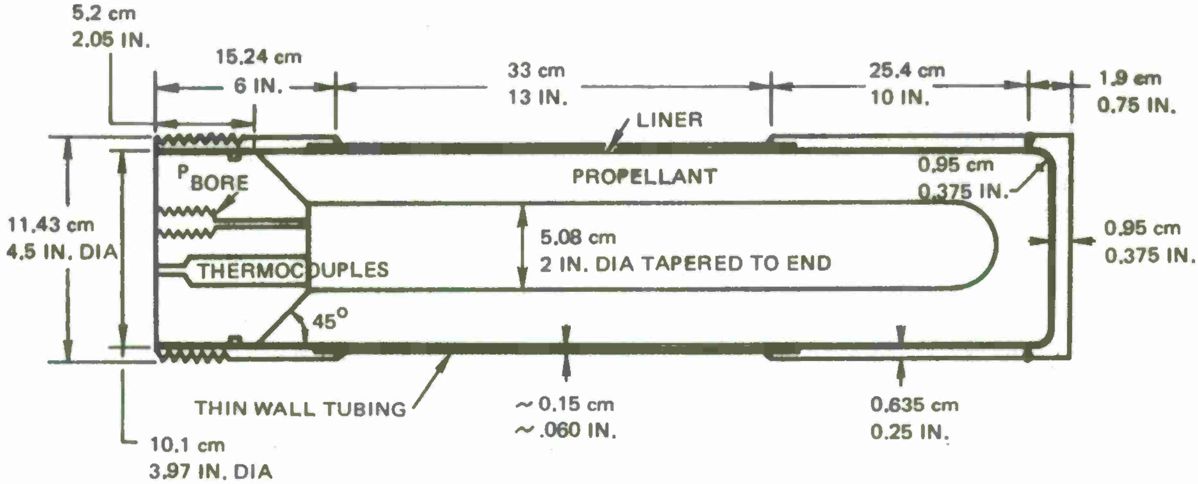

FIGURE 26. Extended 10 cm Diameter Cook-Off Model Motor.

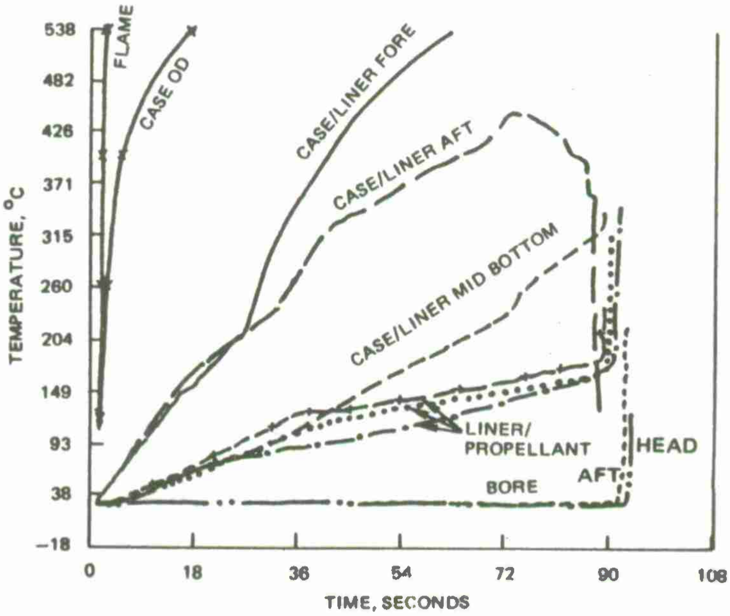

FIGURE 27. Thermocouple Temperatures During Cook-Off With LR-29M Liner and RV-7 Propellant.

The center bottom case/liner pressure tap and aft end bore pressure measurements provided some interesting data (Figure 28). Case/liner pressure started to rise very quickly, with a little jump from 124 kPa (18 psig) at 57 seconds to 276 kPa (40 psi) at 60 seconds. A knee, where the rate of rise jumps up, occurred at 88.9 seconds with the case/liner pressure at 1324 kPa (192 psig). Bore pressure was first indicated at 28 seconds, then reached 41 kPa (6 psig) at 60 seconds and 138 (20 psig) at 88.9 seconds. Bore pressure then jumped to a peak of 4 MPa (580 psig) at 89.7 seconds after the case/liner pressure peaked off-scale at 89.6 seconds.

The 36.8% oxamide in the liner apparently generates quite a lot of gas (pressure) but does not insulate the case well enough to allow the metal to soften prior to propellant ignition. It is assumed that the 138 kPa (20 psig) bore pressure was due to compression of the air in the bore, caused by collapse of the propellant "bladder" by the decomposition gases and vapors from the liner. Over 0.7 MPa (100 psig) case/liner gas pressure could be expected to cause large stresses and strains in the liner, leading to exposure of propellant surface to the hot gases and subsequent ignition. The absence of flame temperatures on the bore thermocouples denotes that cracking of the grain did not occur at case rupture.

Polyether Polyurethane Liner Test

An extended model motor, lined with modified SD-723 liner with 2% added Kynol fibers, was cast with low smoke HTPB propellant and cook-off tested over the propane/air burners. The first visible reaction was at 63 seconds. At that time about half the forward (~ 0.15 cm thick) steel test section ejected; the heavywall head end may have moved forward somewhat and then bent the propellant down (gravity). Propellant burned on the bottom and back side (a few square inches) of the exposed grain and progressed around as the liner (restrictor) burned away. The flame progressed through the propellant web to the inside bore in about 14 seconds. Jetting noise intensity increased at 80 seconds. The head end metal and propellant fell down soon thereafter (86 seconds) as the propellant supporting the cantilever burned away. Burning in the bore continued until all propellant was consumed at 104 seconds.

The case/liner midbottom and bore pressures measured during the test corresponded to the visual observations. Case/liner pressure started to rise at 24.5 seconds and had a jump and higher rise rate at 44 seconds when 170 kPa (25 psi) was reached. This caused the bore pressure to start rising. At 60 seconds, pressures started to rise more rapidly (Figure 29) and the case/liner pressure reached a peak of 2.9 MPa (422 psig) at 61.9 seconds. The case/liner pressure then dropped somewhat while the bore pressure rose more rapidly. This corresponds to the postulation that the liner was releasing from the hot case and the propellant was being deformed inward by the gases (which probably included propellant combustion products from a small ignited area after 60 seconds); i.e., an air-filled "rubber" bladder, externally pressurized, collapses and raises the pressure inside the bladder.

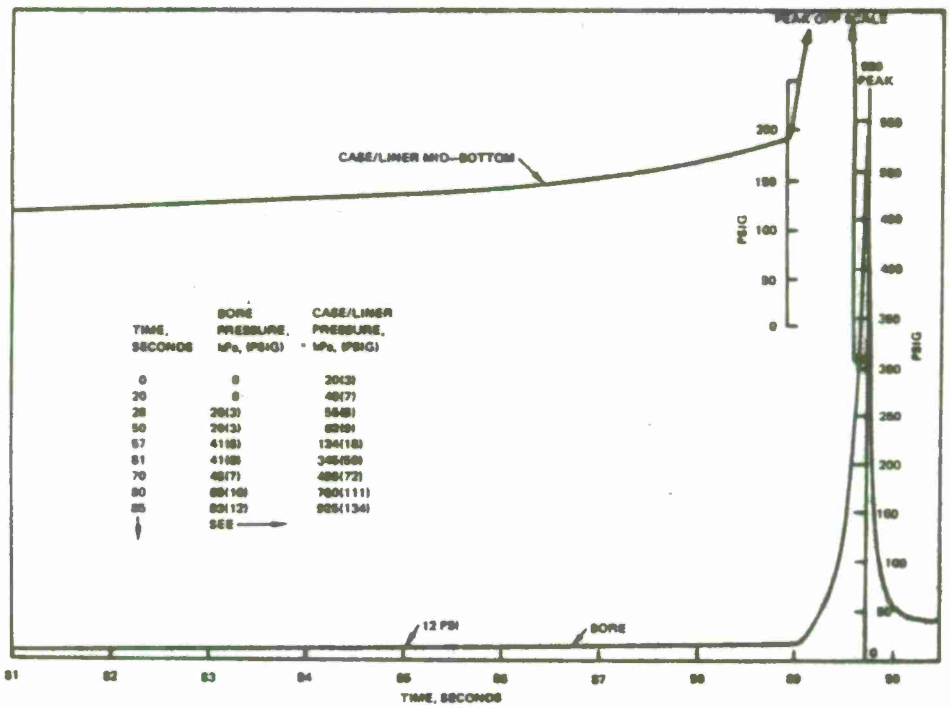

FIGURE 28. Pressures During Cook-Off.

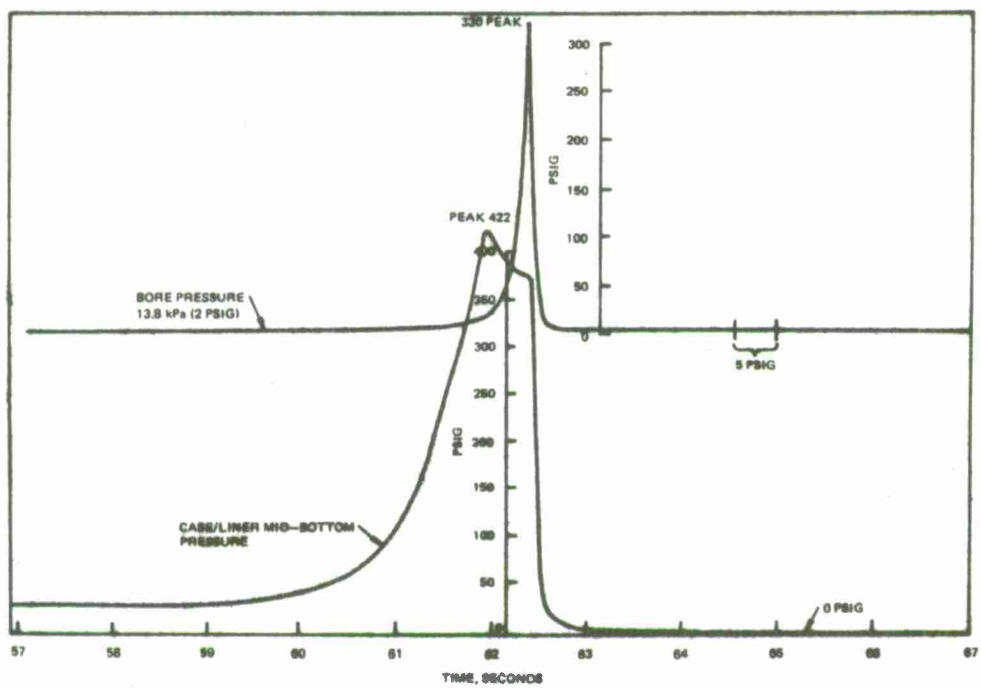

FIGURE 29. Case/Liner Bottom and Bore Pressures at Case Rupture.

At about 62.4 seconds, both pressures very rapidly collapsed to zero and near zero; which must correspond to the case rupture. The pressure was 2.58 MPa (375 psi) at the case/liner measuring location and 2.28 MPa (330 psi) in the bore. The bore pressure went from 34 kPa (5 psig) at 63 seconds (after rupture) to 21 kPa (3 psig) at 80 seconds; which corresponds to the time the jetting-noise-of-burning increase was recorded on the videotape. The pressure then came up to 76 kPa (~ 11 psi) at 80.7 seconds and dropped slowly to 14 kPa (2 psi) at 86 seconds (Figure 30). The case/liner pressure dropped to −34 kPa (−5 psig) at 86.3 seconds. This corresponds in time to the observed dropping off of the grain segment and case head end (cantilevered from the case aft end which was mounted to the test support).

Post-test hardware observations included the retrieval of two pieces of the test section case wall which had ejected from the test item and fire site at the time of rupture. These pieces fit to each other as well as to the heavy head end weld plus the remainder of the test section attached by weld to the aft closure. Small pieces of the thermocouples on the case ID and OD were still present and this, plus the presence of a portion of the hole where the case/liner pressure tap fitting was attached, made orientation definite. The bottom head end of the test section failed with high heat and metal thinning (Figure 31). The case/liner pressure was high enough to cause rupture with tearing of metal which propagated to the pressure tap hole and changed direction there. The tear extended longitudinally in the other direction (forward) to the heavywall weld joint and changed direction there also. As a result, unpeeling up both sides simultaneously gave a tearing load from inertia of the separating sides. Thus the piece of test section case wall separated on ejection. Movie coverage at 100 fps does not definitely show a case bulge before the rupture. No inhibitor (liner) was attached to these pieces; indeed, the videotape shows the grain still inhibited over most of the exposed portion. There was "virgin" Seaguard blue primer paint on the top sides of both pieces of ejecta as well as (a small amount) around the pressure tap hole. Heat discoloration and distortion spread from the thinned metal area to areas having no evidence of heating at the still primed sections. (Unfortunately, the photograph, Figure 31, does not have the pieces oriented as they were originally attached.)

Thermocouple data (Figure 32) show the forward bottom case ID, and bottom case OD just forward of center, were both quite hot, reaching 538°C at 45.5 and 48.5 seconds, respectively. The forward ID reached a peak of 598°C at 57.5 seconds, then dropped a few degrees to 580°C at 60.5 seconds. At this time there was a very rapid rise to propellant flame temperature (thermocouple saturation at 62 seconds) which would indicate ignition of some propellant near the thermocouple. The thermocouple on the liner (about 2.5 cm from the case ID thermocouple) showed a jump from 120°C at 62 seconds to 1304°C (saturation) at 62.5 seconds. Recall that the case/liner pressure showed an increasing rate rise from 60 seconds to a peak at almost 62 seconds with case rupture at about 62.5 seconds. The bore thermocouples both jumped about 11°C at 62.5 seconds, which probably indicates some gas was leaking into the bore. The aft rise was actually 14°C while the fore end rise was 9°C. These are probably more than would be expected from adiabatic air compression when the propellant "balloon" is compressed, but perhaps not. The bore did cool until 79.5

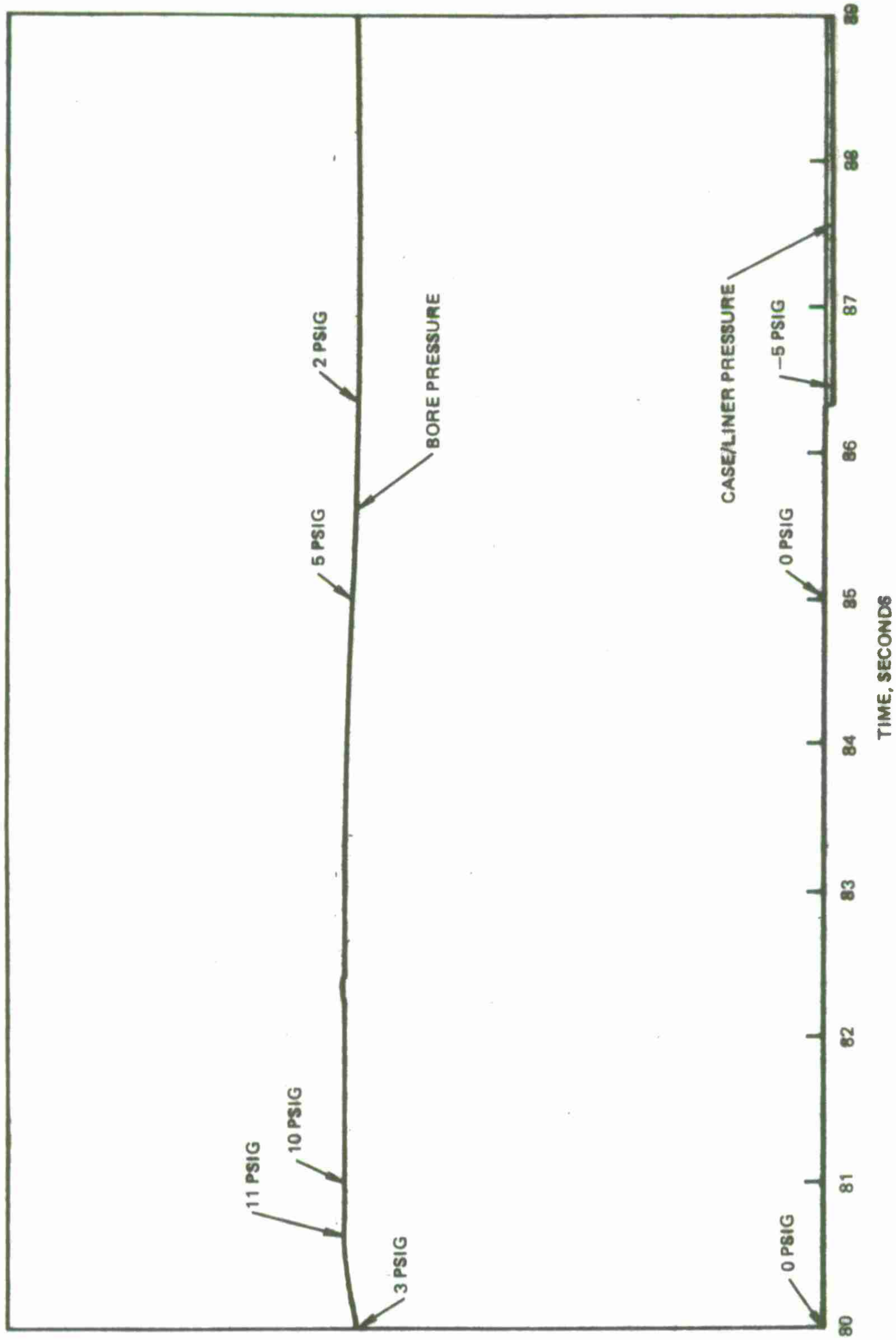

FIGURE 30. Case/Liner Bottom and Bore Pressures at Bore Ignition.

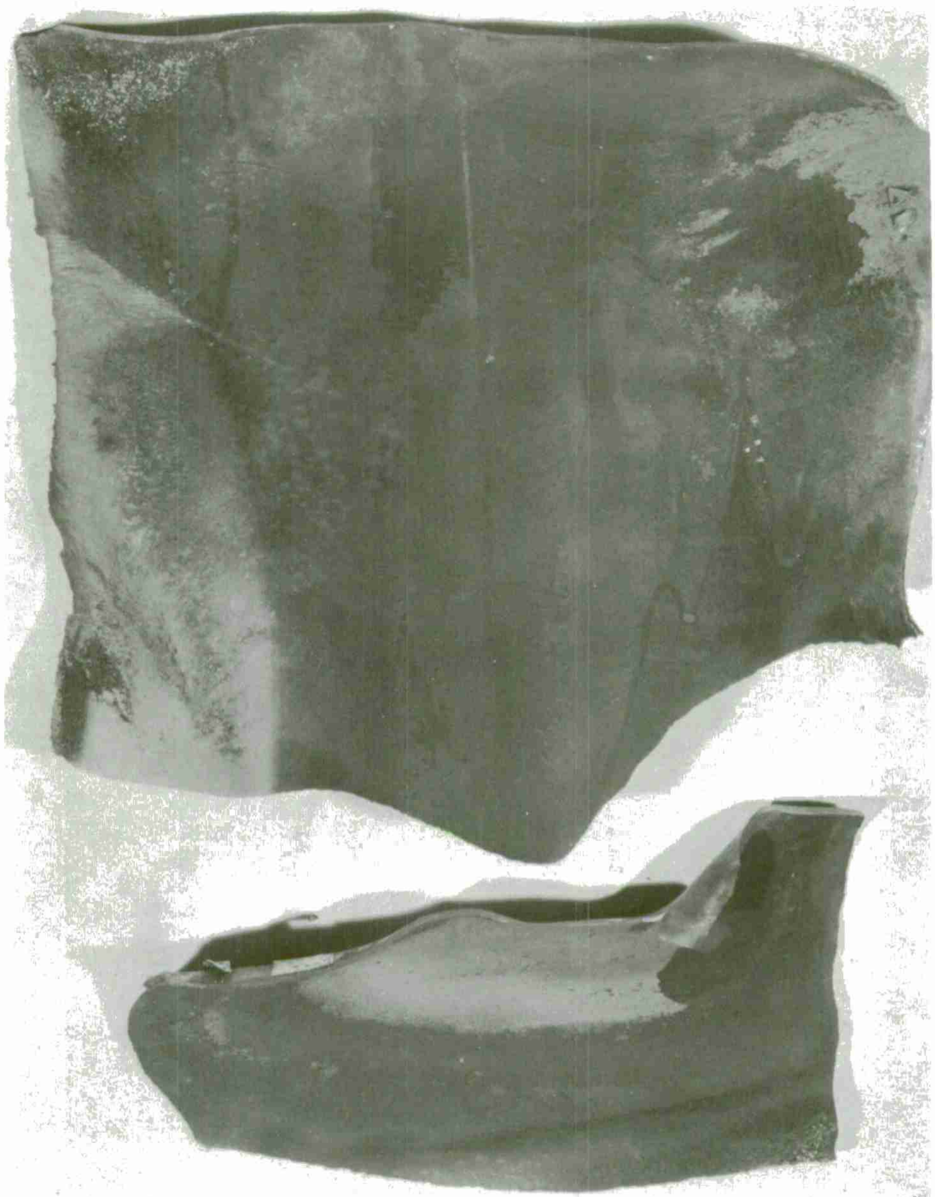

FIGURE 31. Test Section Case Well Ejecta (LHL 192377).

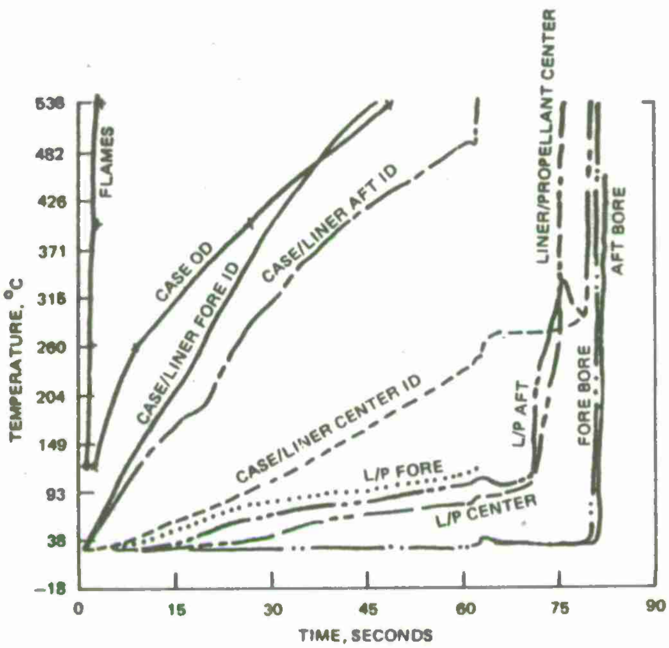

FIGURE 32. Temperatures During Cook-Off of Polyether Polyurethane Lined Model Motor.

seconds, at which time the forward bore thermocouple started to rise. The aft thermocouple started up at 81 seconds and both reached saturation at 82.5 seconds. Bore pressure showed a rise at 80 seconds. The aft bottom liner/propellant thermocouple indicated that flame reached it at 76 seconds while the center bottom liner/propellant thermocouple was saturated at 81 seconds.

In summary, the reaction was mild deflagration with early liner separation from the case. Metal thinning occurred, but the 2.59 MPa (375 psig) gas at failure did accelerate the metal, causing pieces to tear off and fly some distance. This polyether polyurethane liner appears to provide some "mild deflagration" and "burning" reaction per the MIL-STD-1648(AS) definitions. This is certainly one of the least expensive cook-off improvements in that no cost, weight, volume or drag changes are imposed on the rocket or missile.

High Energy Smokeless Propellant Test

A baseline cook-off test of HMX-containing propellant with nitroplasticizers was conducted using the extended model motor hardware. The hardware was lined with LR-29 (oxamide-filled HTPB) low-smoke liner and cast with 6.9 kg of NPCL-11-7437 propellant.

Audio-visual data showed rupture at 37 seconds which exposed the inhibited grain over most of the test section. The head and aft ends (cooler, thicker metal walls and less heat) remained bonded. The grain then ignited and increased in burning area with whistling (resonant) from 54 to 70 seconds, at which time the grain separated (burning from both ends until about 2 minutes) and then the thicker head end web corners burned out.

The 100 fps movie revealed some better detail. After the frame in which the case was seen to burst (a very quick unpeeling and tearing), there was no fire and the burner flame was blown away. The inhibited grain flexed some and then cantilevered with the torn metal providing some support. A tiny flame on the bottom started to burn (propellant) after 83 frames (0.83 second) and built to several square inches after 130 frames. The flame then enveloped the grain after 210 frames. (It is possible that the grain would not have burned if the propane had been turned off at the instant of case rupture instead of at 46 seconds.) The burning became more vigorous and the grain started bending down about 14 seconds after rupture. It and the heavy head end were nearly vertical with the end near the propane burner heads after another 15 seconds (about 65 seconds after cook-off start).

Midbottom case/liner and bore pressure data were taken as before (Figure 33). The case/liner pressure data do not appear to be accurate; pressure rose very quickly but then stayed flat at about 131 kPa (19 psi) from 18 to about 36 seconds when an abrupt rise (off-scale) above 2.1 MPa (300 psi) occurred. The bore pressure showed no pressure rise until 35 seconds, then rose relatively slowly to 138 kPa (20 psi) at a faster rate (from the time case/liner pressure spiked upward) to about 483 kPa (70 psig), then faster yet until saturation and gauge failure 0.1 second or more after the case/liner pressure spiked.

Thermocouple data (Figure 34) show case ID bottom temperatures of 315-370°C at rupture. One thermocouple shows a decrease for 1 second before 37.5 seconds, which apparently was the rupture time. The data at the 38 second time show jumps and discontinuities although two thermocouples jumped at the 37.5 second datum. Thermocouple saturation (equivalent to propellant burning about the thermocouple) was first reached at 40.5 seconds on the two thermocouples that had been attached to the case ID. Of the three propellant/liner thermocouples, one reached saturation at 42.5 seconds and the other two reached saturation at 44.5 seconds. This agrees with the movie observations of no propellant burning for a brief time after case rupture and gradual ignition of the propellant as the liner burned away. The bore thermocouples showed an 11°C jump at 38 seconds for the aft end only and rose at

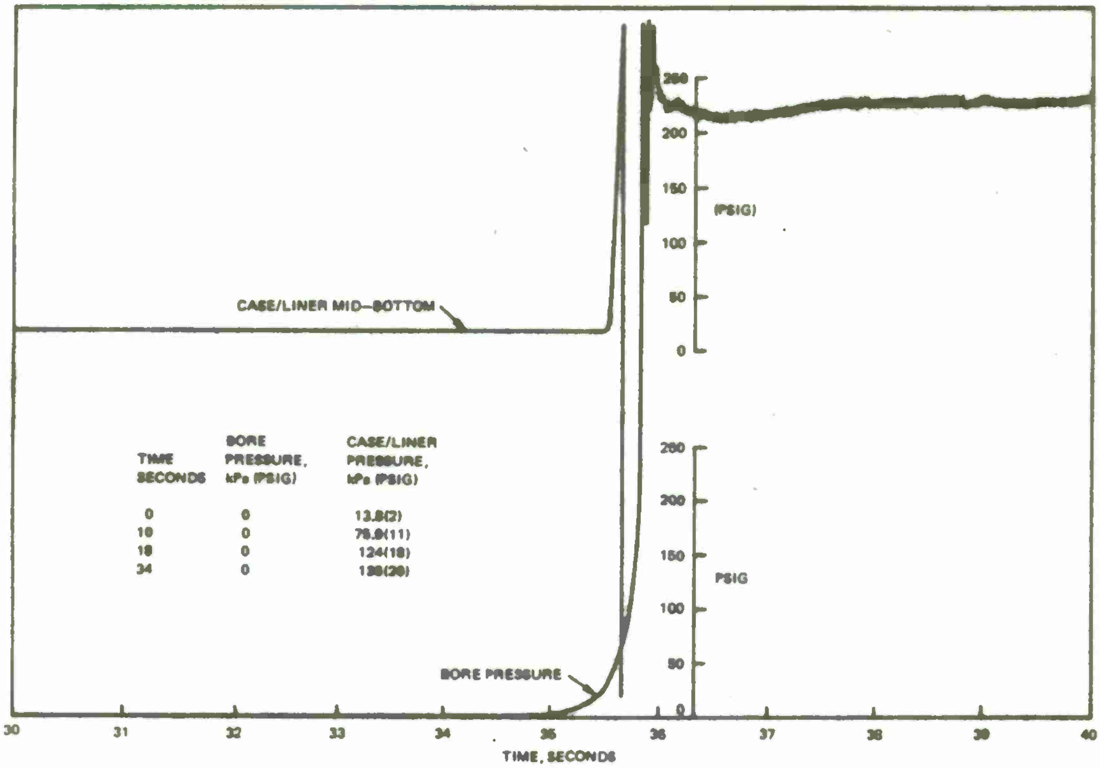

FIGURE 33. Pressures at Case Rupture.

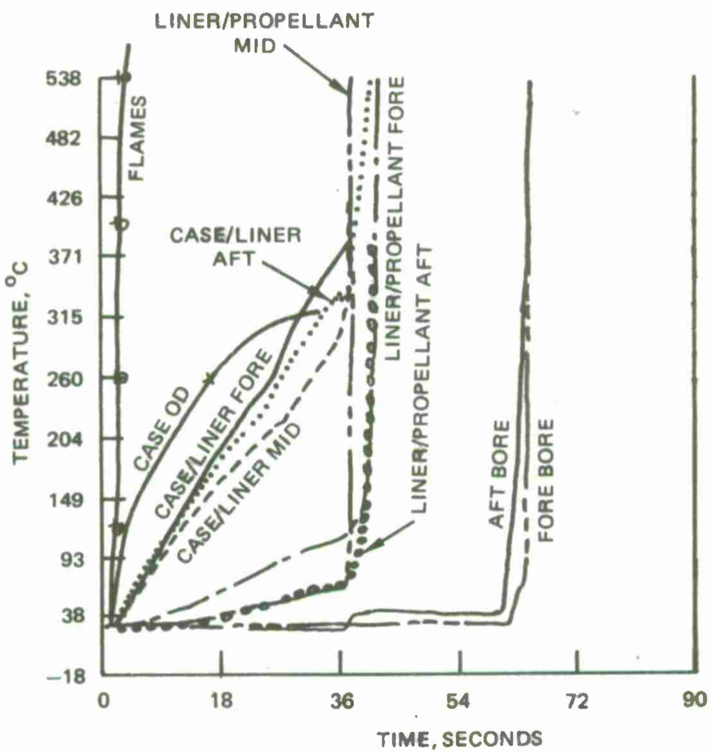

FIGURE 34. Temperatures During Cook-Off of HMX Propellant Model Motor.

61.5 and 62.5 seconds for the aft and fore ends, respectively. The head end showed flame temperature at 65 seconds, followed by the aft end at 69.5 seconds. These times correspond to the grain bending nearly 90 degrees, as was seen in the movie and video films, and then burning from both ends.

The near absence of flame in the rupture frame does not necessarily mean that the propellant did not ignite. It would be extinguished by the high negative rate of change in pressure (dp/dt). Case strength was not much degraded because the temperatures were low, therefore, pressure was high. The high spikes indicate propellant burning, and this propellant has a high burning rate pressure exponent which would tend to exaggerate the spike. The high bore pressure, without any appreciable (if any at all) gas entering the bore, means the grain was very compressed and deformed but did not crack. Movie and thermocouple data corroborate the integrity of the grain after case rupture. (The end and thermocouple seals were excellent in all three extended model motor tests.)

We conclude that not much liner gassing occurred prior to ignition of propellant. The case/liner pressure port must have been partially plugged or was not contiguous to a gas pocket which started deforming the grain and created bore pressure since the case/liner pressure did not rise for about 1 second before the case/liner gauge showed a spike. It is conjectured that the gases from the oxamide in the liner pushed the grain away from the case. This possibly led to an unbond at one of the case/liner thermocouples and provided a premature (instrumentation induced) ignition site. (This may have been the situation during cook-off of the lower burning rate, lower pressure exponent RV-7 propellant with the same class of liner. There was some fiber reinforcement of that liner which may have been partially to blame for its having reached a higher temperature, pressure, and time before propellant ignition and pressure spike to rupture.)

Dual Liner

A steel model motor lined with thin painted coatings of SD-723 polyether polyurethane and then HTPB-based liner and cast with low smoke HTPB propellant was "cooked" over the propane burners. Figure 35 is a post-test photograph showing the split along the entire bottom of the test item. A small area of the metal was stretched (thinned) at the initial failure site. The rupture occurred at 73 seconds with bottom forward case/liner pressure exceeding 3.4 MPa (500 psig) just prior to the bore reaching 3.25 MPa (472 psig). At 72 seconds, a higher rate of pressure rise started and was postulated as due to a small area of propellant igniting with a much higher rate of gas production. The bore was collapsed by this external pressure on the propellant cylinder which continued until the case ruptured. This round-bore test item is not typical of rocket motors in the sense that there is no stress concentration upon bore collapse such as that involved with a typical star-shaped grain perforation. This means that the model motor has mechanical strength failure modes that are different from a tactical rocket: (1) stronger intrinsic grain as elaborated, (2) excellent fore and aft sealing on the grain OD, and (3) a solid closure rather than a weather seal closure in the nozzle. The nozzle closure will normally fail at a nominal bore pressure of perhaps 1.2 MPa (200 psi) and thus reduce the grain support by removing the internal bore pressure. This means that some tactical motors would react more violently than the

FIGURE 35. Dual-Lined Extended Model Motor Case After Cook-Off Test (RV-7 Propellant)(LHL193542).

model motor because the propellant grain wall (web) would tear, thereby allowing internal bore ignition which would tend to throw propellant and case fragments much more violently.

The thermocouple data for this test (Figure 36) show internal case wall temperatures above 538°C (1000°F) with some cooling before rupture. The cooling may have been due to material movement and pyrolysis gases flowing. The highest temperature of three liner/propellant locations at time of reaction was 149°C (300°F). Some disturbance of bore temperature occurred at reaction, but burning of the bore did not initiate until 88 seconds (15 seconds after case rupture). The video and movie coverage verify the web burning through from the OD at that time.

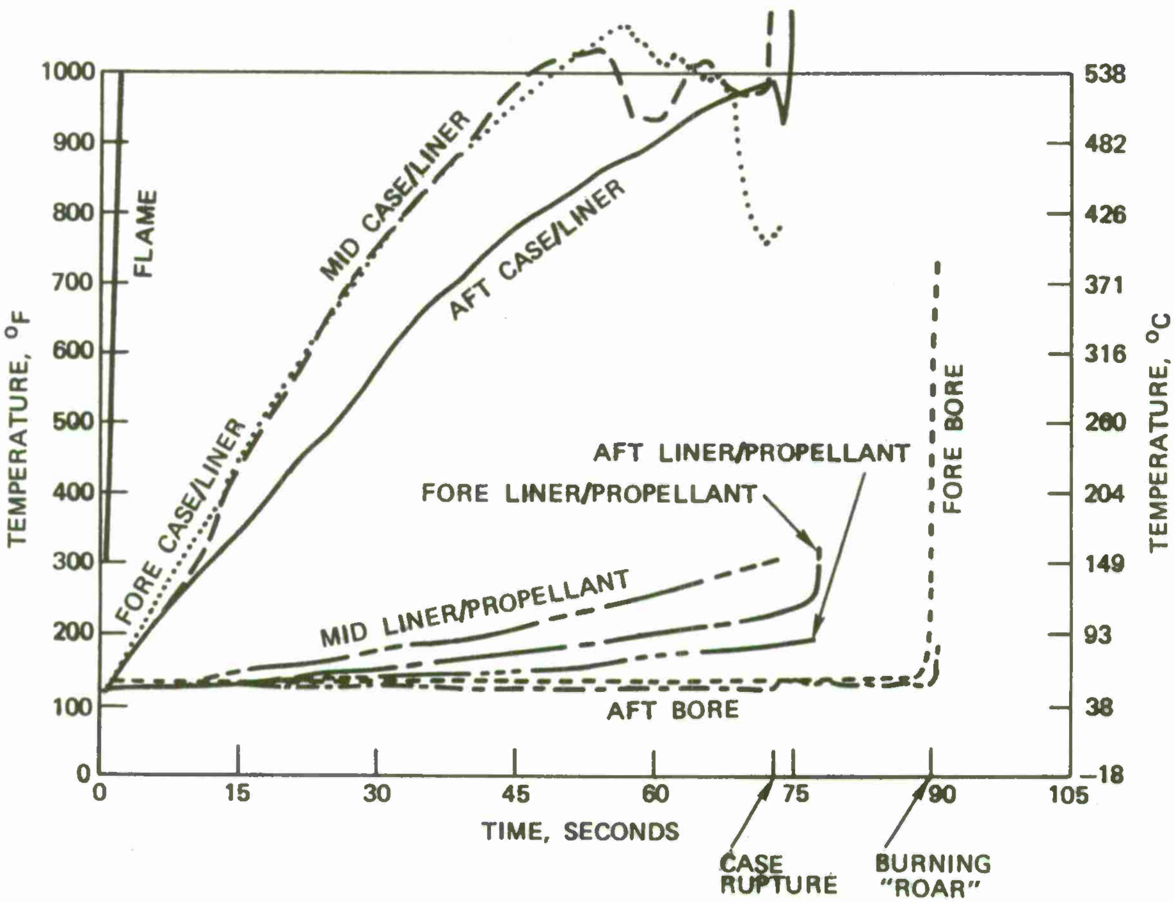

FIGURE 36. Temperatures During Cook-Off of SD-723/LR-29/RV-7 Model Motor Test.

As can be seen in Figure 35, the case/liner pressure tap location was changed to the forward instead of the midbottom location as previously done. Figure 37 presents the pressure data, which follow the typical pattern of case/liner pressure rising quite rapidly just prior to rupture and bore peak pressure occurring just after "rupture."

Fiber Reinforced Plastic

PRD-49 (now Kevlar) style 181 cloth was used with Dow DEN-431 epoxy novolac/nadic methyl anhydride curing agent/dimethyl amino methylphenol catalyst to fabricate a 13.7 cm diameter by 91 cm long simulated rocket motor. Seven layers of cloth were used. Metal end fixtures were epoxied in place. After priming, the tube was lined with LR-13 HTPB liner and cast with low-smoke HTPB propellant. The configuration was the same as that previously reported for two spiral steel shim laminate motors. Cook-off in the propane/air facility resulted in smoking of the resin quite soon after fire start. Shedding (flaking) of small pieces of the case OD started at about 20 seconds and propellant flame was visible at 93 seconds. The hottest case/liner thermocouple showed 405°C (760°F) at this time. Temperature rises typical of flame reaching the thermocouple occurred from 100 to 120 seconds; bore temperature showed flame at 126 seconds. Measured bore diameter change and bore pressures were quite small during the test. This test resulted in mild-burning, as expected and desired. Figure 38 is a photograph of the two ends of the test item after the test; burned layers of cloth are visible.

There was little pressure measured in the bore during the test. About 7 kPa existed at fire initiation and about 35 kPa was detected from 20 seconds through 66 seconds with 41 kPa noted from then until 135 seconds when some oscillation occurred and about 27 kPa was measured although the grain and case were opened to the atmosphere at that time.

A linear potentiometer was mounted vertically in the grain bore not far from one end of the test item to measure deflection during the test. Diameter change in the 5.08 cm (2 inch) bore showed a smooth increase of 2.0 mm at 35 seconds and slightly further increase from 35 seconds to 70 seconds where the value was 2.8 mm. The diameter then decreased smoothly by 110 seconds to 0.5 mm larger than at ignition. No change was noted until 127.5 seconds when the potentiometer output oscillated from zero to maximum. This is the time when the fore bore thermocouple showed flame. These data correspond to the expansion of the case when heated–the grain is pulled outward with it and returns when the case has softened.

Figure 39 depicts the thermocouple data and indicates the visible activities (marked at times of occurrence). The first visible flame did not emanate from the bottom of the test item. It occurred at 93 seconds and the forward liner/propellant thermocouple was the first to indicate flame (fast rise to saturation) at 103 seconds.

This plastic reinforced construction gave very satisfactory results— mild burning.

TIME, SECONDS	FORWARD CASE/LINER PRESSURE		BORE PRESSURE	
	kPa	PSIG	kPa	PSIG
20	0	0	0	0
23	0	0	14	2
30	0	0	21	3
50	0	0	34	5
52	0	0	34	5
53	179	26	34	5
60	296	43	34	5
70	586	85	69	10
71	620	90	69	10
72	793	115	83	12
72 ½	1931	280	207	30
73	>3500	>500	1448	210
73 ¼	−138	−20	3245	472
74	−138	−20	14	2

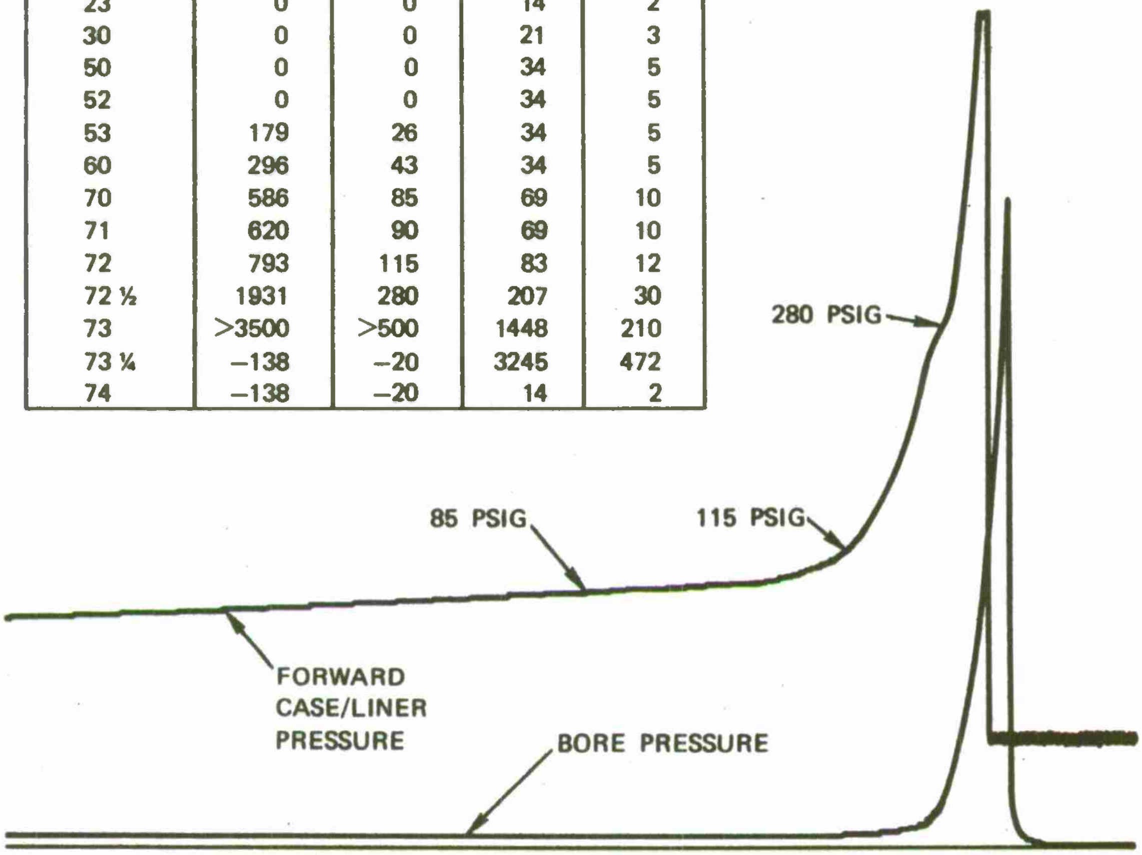

FIGURE 37. Pressure Measurements Near Reaction of Dual-Liner Model Motor Cook-Off Test.

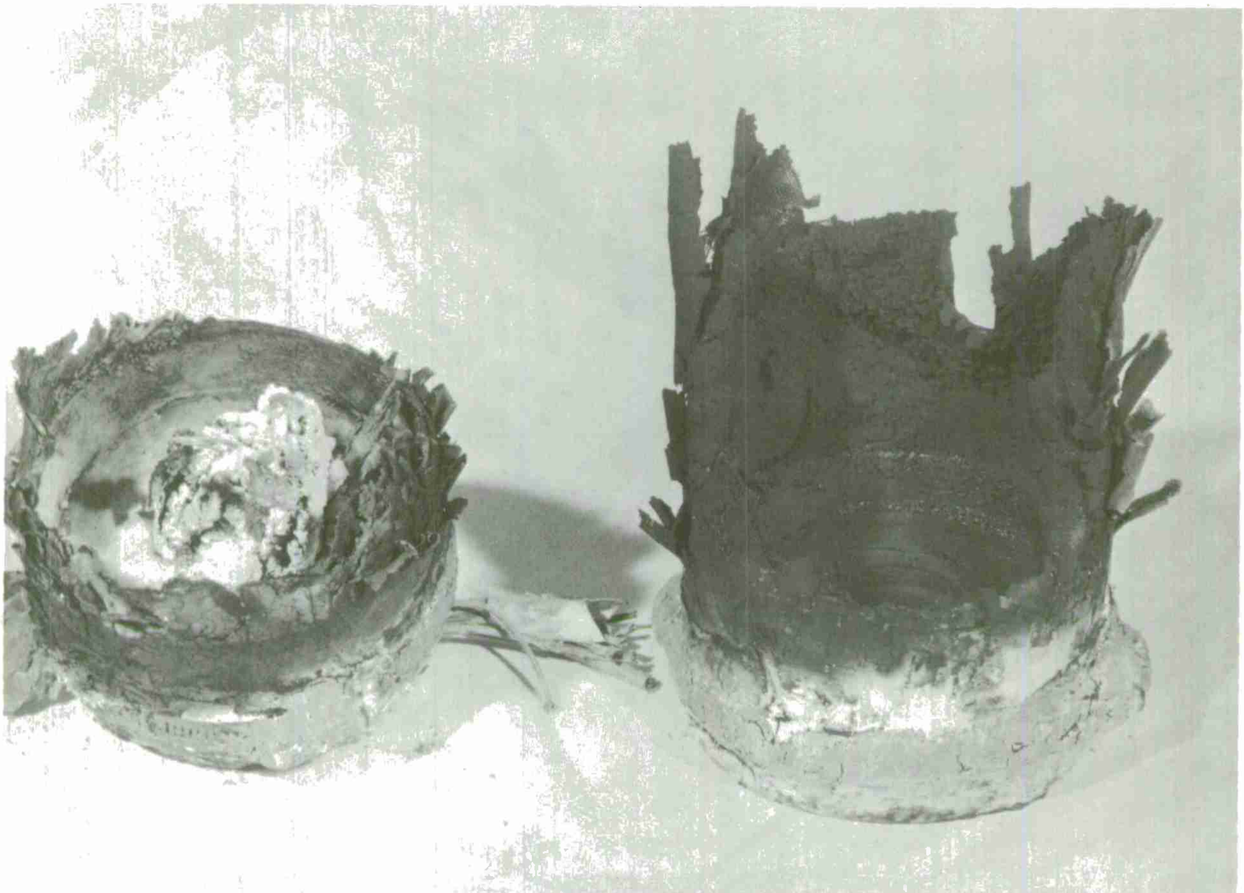

FIGURE 38. Post-Test Remains of Kevlar-Cloth-Reinforced Plastic Motor Tube (LHL 193541).

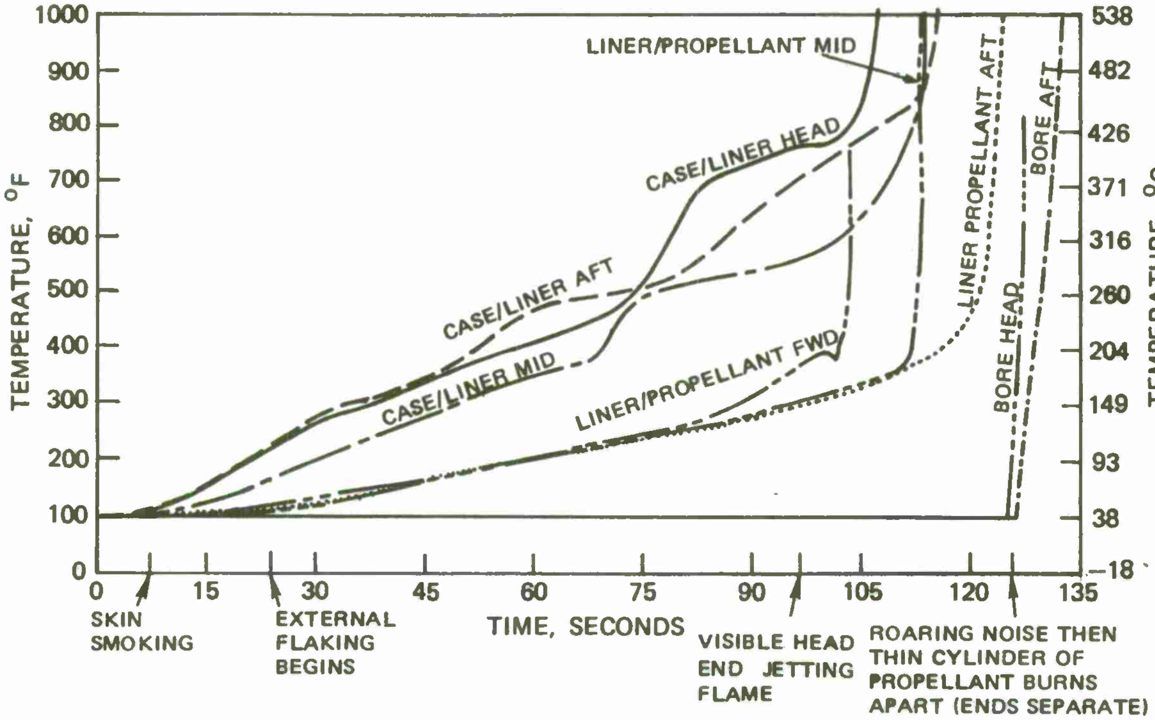

FIGURE 39. Temperatures During Cook-Off.

Dual Liner/High Energy Propellant Test

A second test using nitroplasticized polycaprolactone (NPCL) binder propellant in the extended model motor hardware was conducted. The smokeless NPCL-13-7557 propellant was cast onto LR-29 liner with this liner having an undercoat of polyether polyurethane liner. Cook-off over the propane burners facility resulted in case rupture occurring at 37 seconds. This exactly duplicated the previous test with this type of propellant. The thermocouple data (Figure 40) show the bottom forward test section case ID temperature to be 478°C (893°F) at reaction time with center and aft temperatures being much lower, which is somewhat atypical. Maximum liner/propellant temperature was 109°C (229°F) (at the forward end of the test section). The aft bore temperature jumped at reaction time (37.4 seconds) but then continued to drift upward to about 51.5 seconds when rapid rise started. The forward bore temperature also jumped at 37.4 seconds, but then drifted downward (cooled) until 48.7 seconds when rapid rise (flame) was indicated. This probably means gas leaked into the bore at the aft seal, which correlates with the abnormal, soft liner observed before assembly. The reaction occurred early and, again, this must correspond to the lower thermal stability of the propellant. The case temperature was lower; thus, the pressure required to rupture the case was higher.

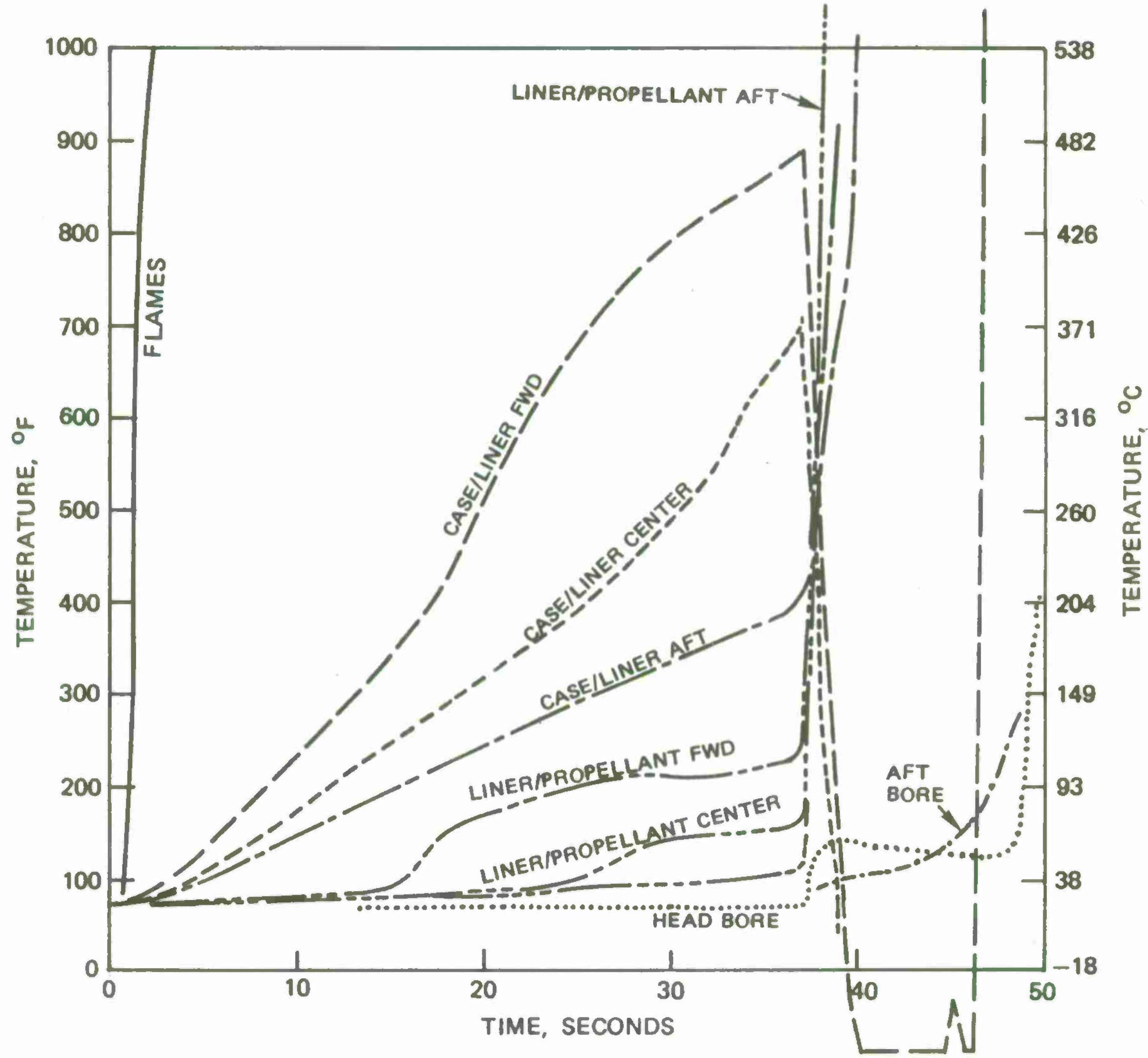

FIGURE 40. Temperatures During Cook-Off of NPCL-13 Model Motor.

The high speed movie showed slight grain slippage from the aft end at rupture. Grain deformation "at" rupture of the case was extreme–sort of resembled an inchworm. A small area on the bottom started burning about one second after rupture and spread slowly. The head end, with much propellant still unburned therein, fell off about 20 seconds after rupture. Whistling started at 50 seconds, corresponding to the bore ignition (thermocouple data), and was due to acoustic resonance driven by combustion energy.

APPENDIX A

COMPUTATIONS OF DEFORMATION DUE TO PYROLYSIS GASES

Mr. Ken Bischel of NWC used stress analysis computer codes to determine those deformations likely to occur under conditions where pyrolysis gases exist along with unbonds. Such deformations were calculated for 8-inch-diameter hardware with HTPB propellant properties. The pressure rise profile and values were arbitrary but resemble the data from the instrumented motors. A calculation assuming 345 kPa (50 psi) in 5 seconds, followed by 3450 kPa (500 psi) in 0.5 second, entirely collapses the star perforation. Such deformations would require appreciable gas volume, but it is easy to visualize that high peeling and tension loads are created at the edges of gas pockets and particularly at the motor ends. If propellant is thereby exposed to the heated fuel vapors, the propellant could ignite.

Figures A-1 through A-5 portray the plane strain deformations produced by one-quarter or one-half perimeter unbonding and assumed gas generation to produce a pressure of 345 kPa (50 psi) smoothly over 5 seconds time (during which time, the propellant has a modulus of 400 psi/in/in and the liner a modulus of 130 psi/in/in) followed by further pressure rise to 1033 kPa (150 psi) (during which rise time of 0.5 second the propellant and liner moduli are raised to 650 and 200 psi/in/in, respectively). The cylinder and star grain perforations were used in 20 cm (8-inch) diameter motor size.

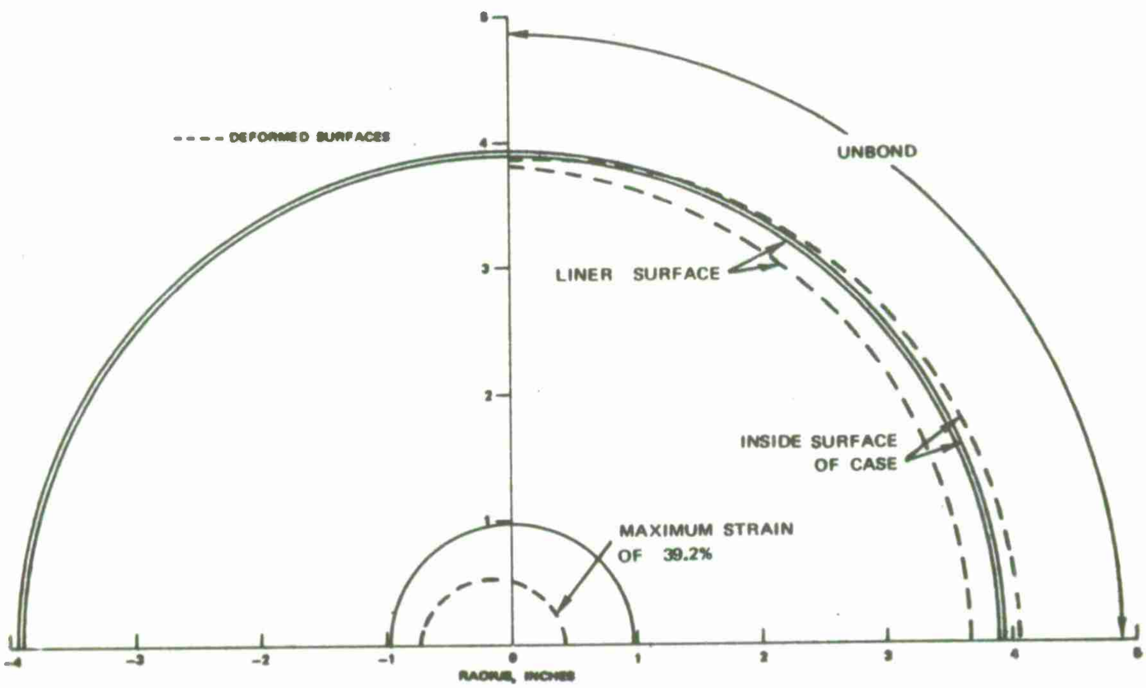

FIGURE A-1. Deformation of Propellant Grain Half-Section Due to Pyrolysis Gases Pressurization at the Case/Liner Interface.

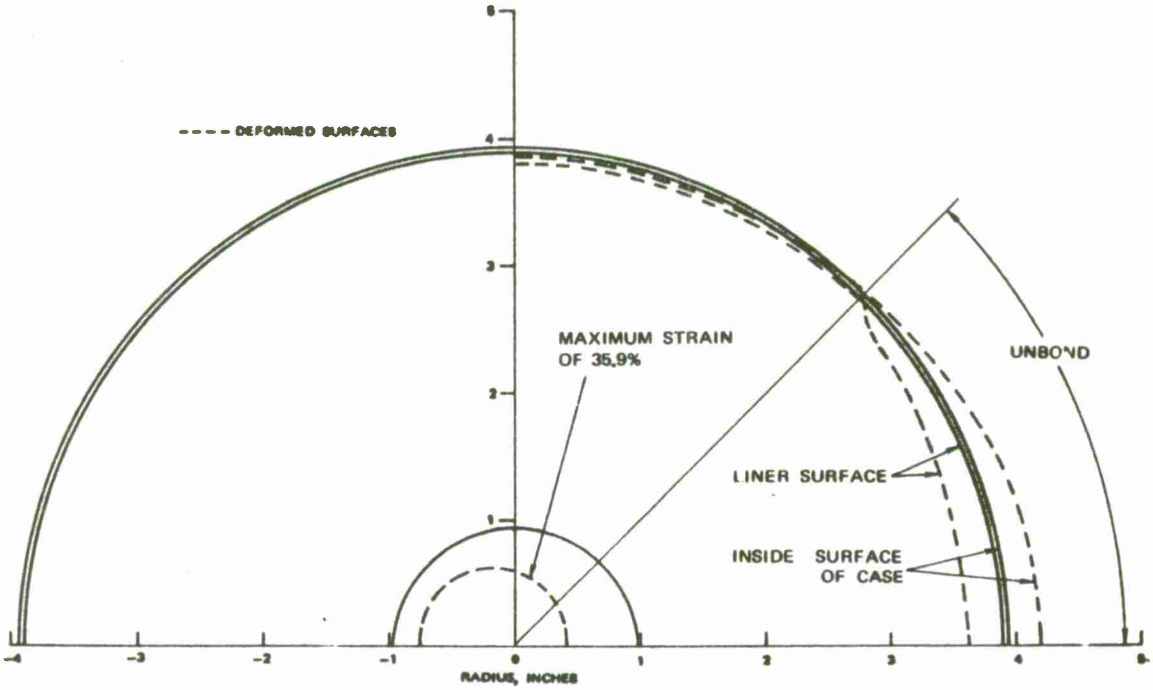

FIGURE A-2. Deformation of Propellant Grain Half-Section Due to Pyrolysis Gases Pressurization at the Case/Liner Interface.

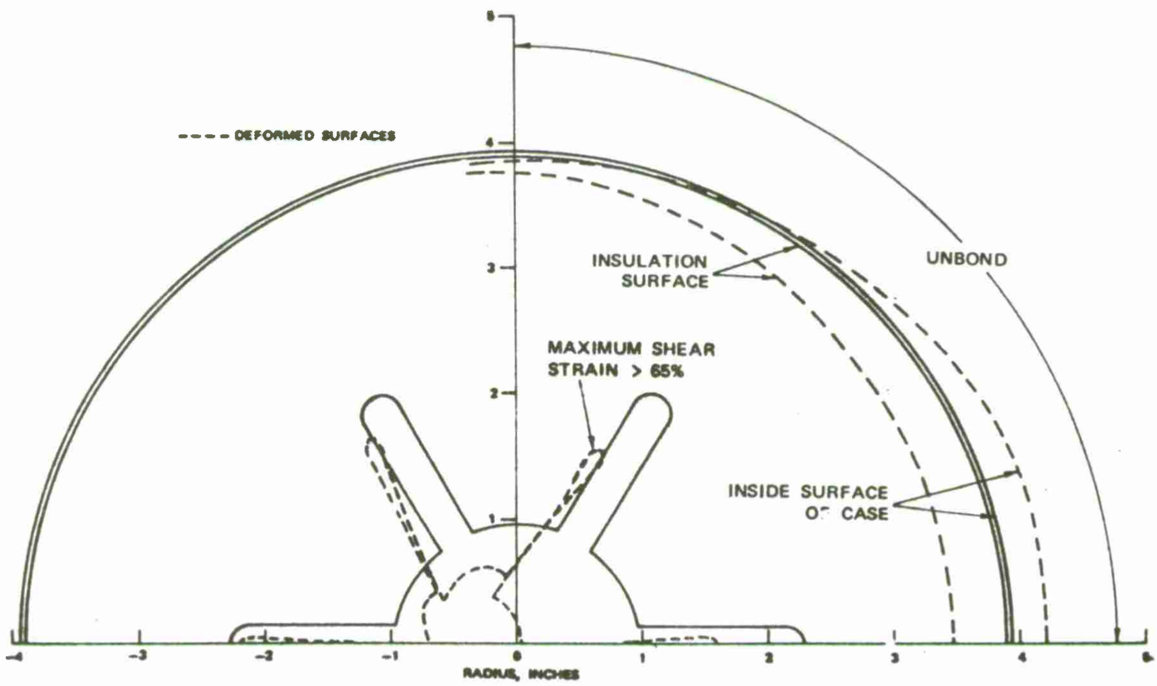

FIGURE A-3. Deformation of Propellant Grain Half-Section Due to Pyrolysis Gases Pressurization at the Case/Liner Interface.

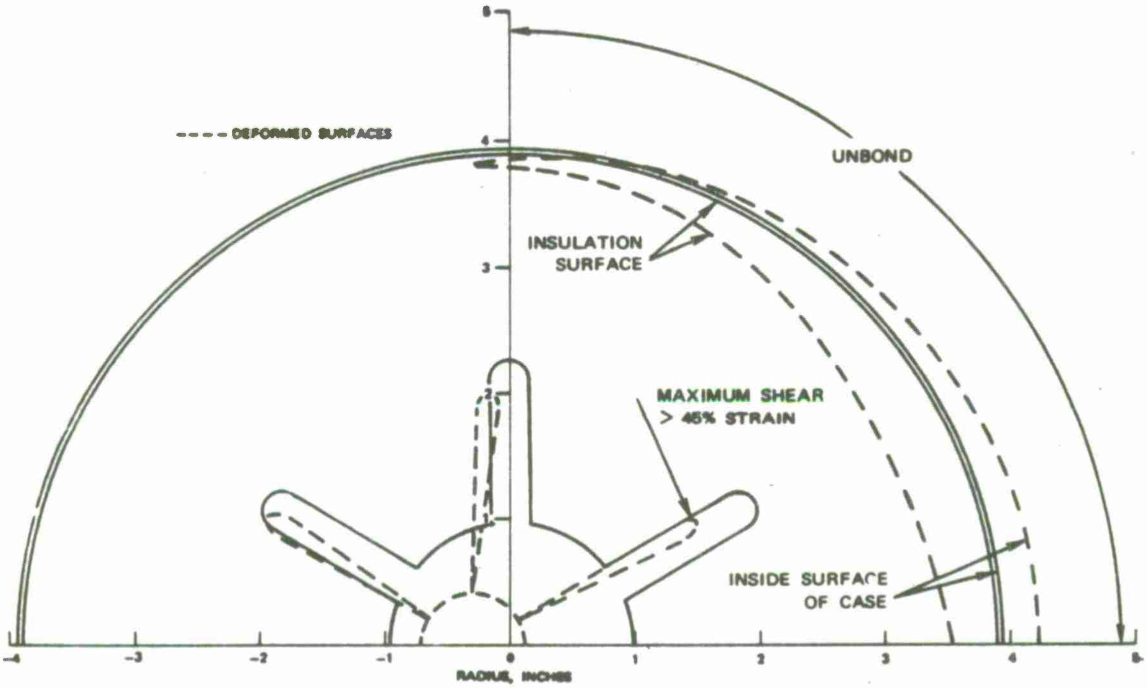

FIGURE A-4. Deformation of Propellant Grain Half-Section Due to Pyrolysis Gases Pressurization at the Case/Liner Interface.

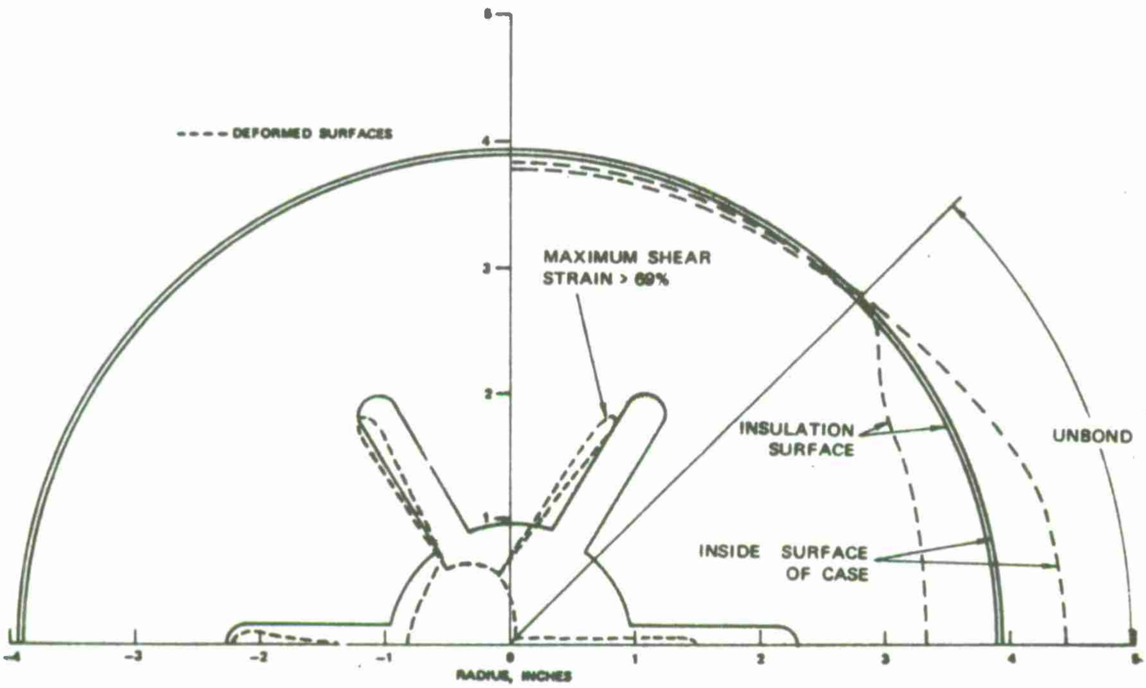

FIGURE A-5. Deformation of Propellant Grain Half-Section Due to Pyrolysis Gases Pressurization at the Case/Liner Interface.

NOMENCLATURE

Butarez CTL II	Carboxyl-terminated polybutadiene (Phillips Petroleum Company)
CA	Cellulose acetate polymer
Cab-o-sil	Fine silica (Cabot Chemical Company)
CaF	Calcium formate
Chemlok 205	Adhesive primer and adhesive
Chemlok 234B	Adhesive primer and adhesive
CTPB	Carboxyl-terminated polybutadiene
DC 93-104	High temperature silicone (Dow Corning)
DC Q3-6548	Experimental silicone foam (Dow Corning)
ERLA0510	Epoxy resin (Union Carbide Corporation)
FeAA	Ferric acetyl acetonate catalyst
HTPB	Hydroxyl-terminated polybutadiene
IPDI	Isophorone diisocyanate
Kynol	High temperature fiber
LC-2	Adhesive rocket motor liner made from Butarez CTL II, MAPO and carbon black
LC-4	Liner material made from Butarez CTL II, MAPO, ERLA0510, CA and carbon black
LC-48	Liner material made from R45M, IPDI and oxamide
LC-50	Liner material made from R45M, IPDI and 40% oxamide
LR-13	Liner material made from R45M, TEA, TDI, Cab-o-sil, and carbon black
LRV-5	Liner material made from R45M, TEA, TDI, oxamide, carbon black and FeAA
LRV-7	Liner material made from SD-723 plus added TiO_2 and 1/8-inch long Kynol fibers
MAPO	Tris(1,2-methyl)aziridinyl phosphine oxide
MTDA	Monohydroxyethyl trihydroxypropyl ethylene diamine
PBNA	Phenyl beta naphthyl amine
PPG	Polypropylene glycol
R45M	Prepolymer HTPB (Arco Chemical)
RPD-150	Phenolic/asbestos insulation
RTV-615	Silicone (General Electric)
RV-7	Reduced smoke, HTPB-containing propellant
Seaguard (blue primer)	Wash primer per MIL-P-15328C
SD-723	Liner material made from PPG, TDI, MTDA, PBNA, TiO_2 and FeAA
SD-746	Liner material made from PPG, TDI, FeAA, Polymer 2000, plasticizer and fillers

SP40X415	Primer (Stanley Chemical)
SP66X5457	Primer (Stanley Chemical)
SS-4155	Silicone primer (General Electric)
TDI	Tolylene diisocyanate
TEA	Triethanol amine
TiO_2	Titanium dioxide
UF-2158	Liner (Thiokol Chemical)
VP-2757	Vinyl plastisol wash primer (Union Carbide)
VP-2849	Vinyl plastisol wash primer (Union Carbide)
VP-2894	Vinyl plastisol wash primer (Union Carbide)
VP-2983	Vinyl plastisol wash primer (Union Carbide)

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