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MEMORANDUM REPORT ARBRL-MR-03372

MULTIDIMENSIONAL, MULTIPHASE FLOW
ANALYSIS OF FLAMESPREADING IN A
STICK PROPELLANT CHARGE

Albert W. Horst
Frederick W. Robbins
Paul S. Gough

August 1984



US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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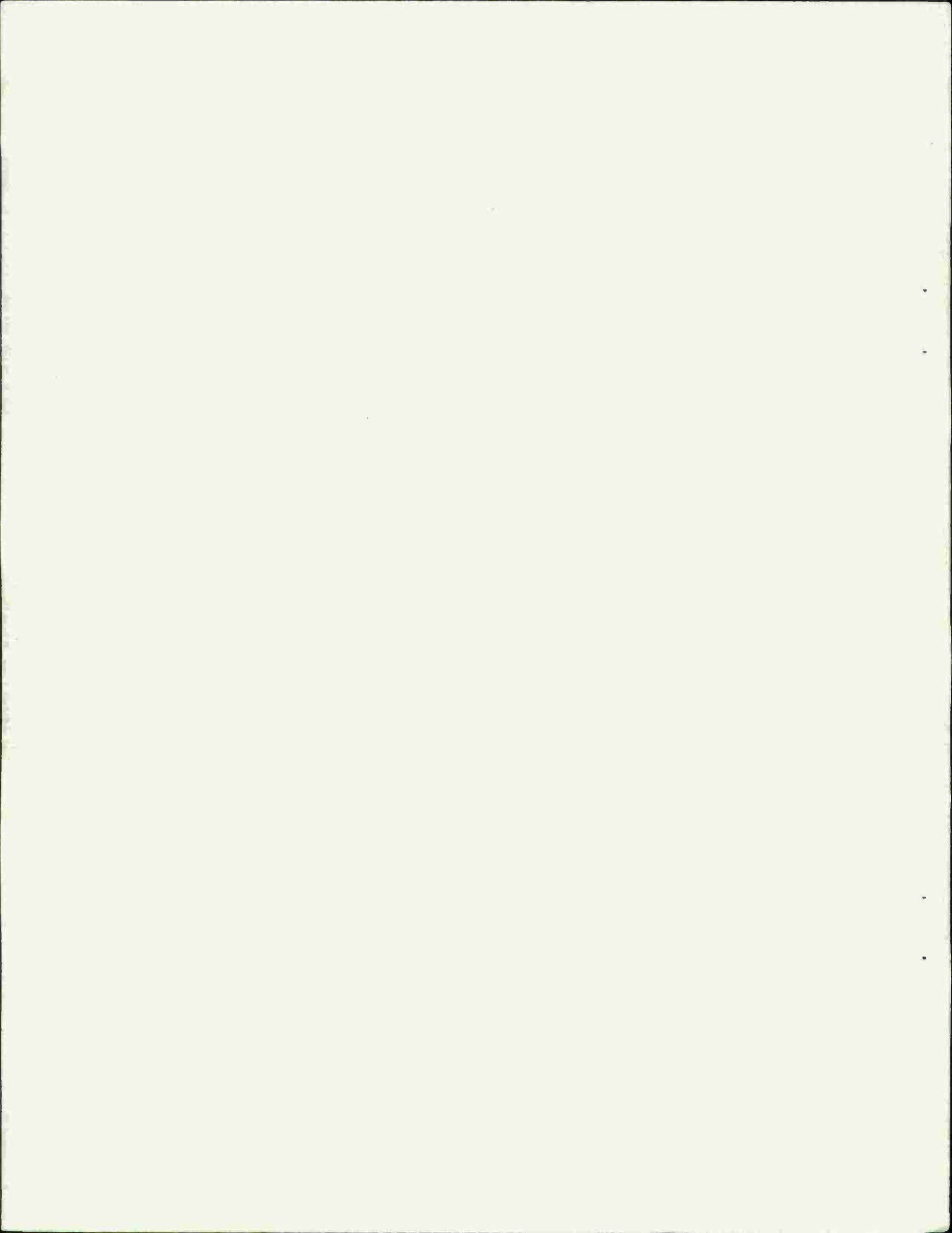
have significant impact on the acceptability of new stick propellant charges. Moreover, the mechanisms responsible for all the above behavior may well be exploitable as high-progressivity, high-density (HPD) propelling charge concepts. In this work, a state-of-the-art version of TDNOVA, a two-dimensional, two-phase flow interior ballistic code, is employed to probe the ignition and flamespreading processes in stick propellant charges. Calculations of flame propagation on exterior and interior surfaces, as well as pressurization profiles both within the perforations and in the interstices, are described for typical and simplified stick charge configurations. Reconciliation of predicted behavior with experimental observation is discussed, and further specific studies using TDNOVA are identified in order to verify a postulated explanation for stick charge ballistic data exhibiting an anomalous temperature sensitivity.

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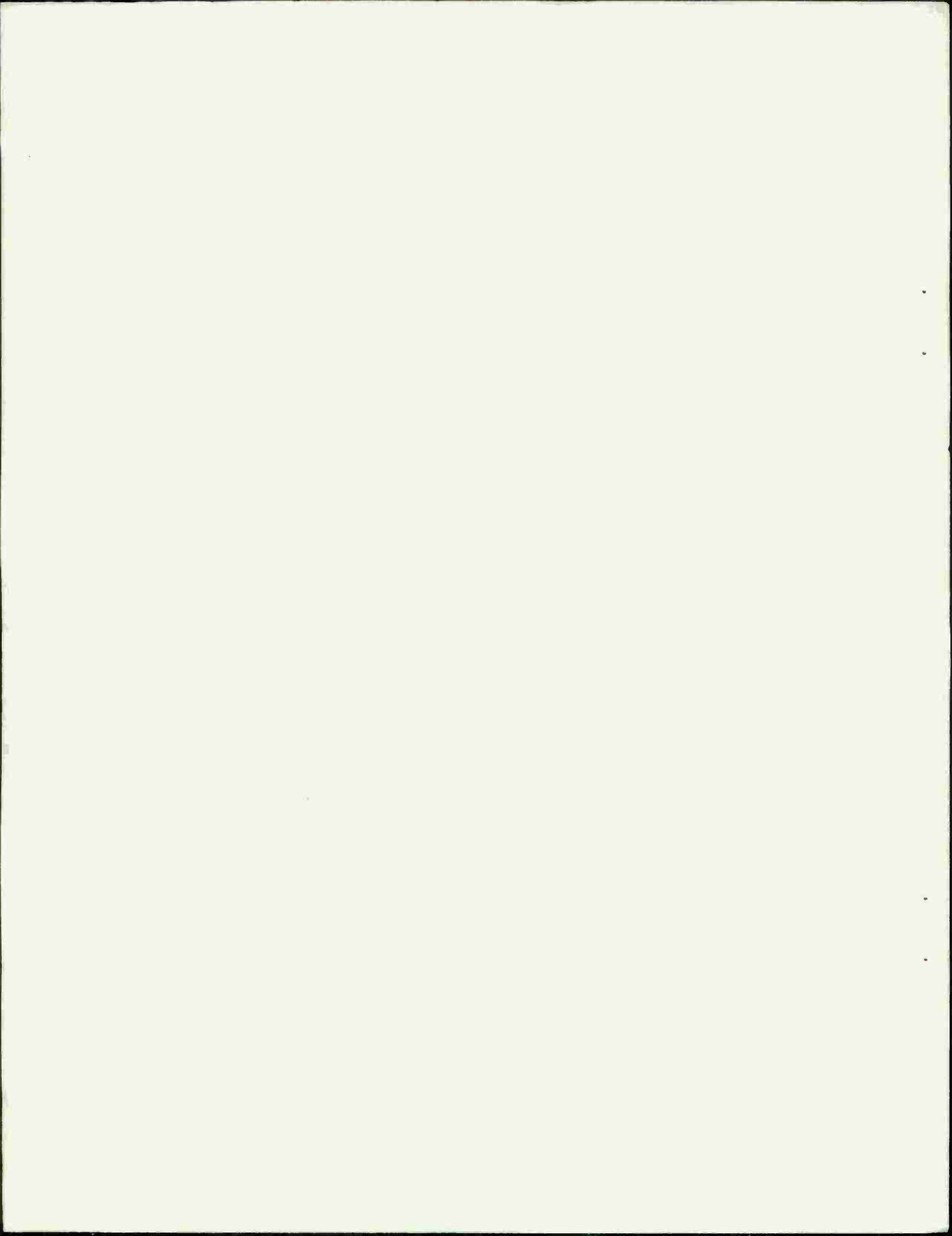
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I. BACKGROUND

A. Stick Charge Phenomenology

We have previously reported on the application of advanced interior ballistic modeling techniques to the problems of base- and centercore-ignited, granular propelling charges.^{1,2} In those studies, our interest revolved around the complex interplay between igniter, ullage, and propellant packaging and its influence on the path of flamespreading, the formation of pressure waves, and movement of the solid phase. In the current work, we shift our attention to the phenomenology of the stick propellant charge, a configuration that, by the substitution of natural flow channels for the tortuous path encountered through a bed of granular propellant, substantially reduces the problem of pressure waves -- but not without exhibiting some very interesting and yet to be totally understood features of its own.

We begin by looking at a schematic representation of the interior ballistic cycle for a stick propellant charge (Figure 1). Functioning involves initiation of the basepad by the primer and subsequent transfer of ignition to the stick propellant itself. The igniter gases are expected to penetrate easily through the bundle of sticks, with flamespread proceeding rapidly in a one-dimensional fashion. Some portion of the igniter gases may be expected to flow around rather than through the charge, but to a lesser extent than might be expected with a granular propellant charge. There does exist some photographic evidence that the charge ignites essentially uniformly over its entire length after being sufficiently bathed in hot igniter gases which have previously flowed unimpeded around and through the bundle of sticks.³ However, the flow of igniter gases and the path of flamespreading within the long perforations of stick propellant, particularly if unslotted, are largely unknown and must be assumed to proceed independently of corresponding processes in the interstices. Nevertheless, the minimal resistance to axial flow and the accompanying near uniformity of

¹A.W. Horst and P.S. Gough, "Modeling Ignition and Flamespread Phenomena in Bagged Artillery Charges," ARBRL-TR-02263, USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, September 1980 (AD A091790).

²A.W. Horst, F.W. Robbins, and P.S. Gough, "A Two-Dimensional, Two-Phase Flow Simulation of Ignition, Flamespread, and Pressure-Wave Phenomena in the 155-mm Howitzer," ARBRL-TR-02414, USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1982 (AD A119148).

³T.C. Minor, "Experimental Studies of Multidimensional, Two-Phase Flow Processes in Interior Ballistics," ARBRL-MR-03248, USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, April 1983 (AD A128034).

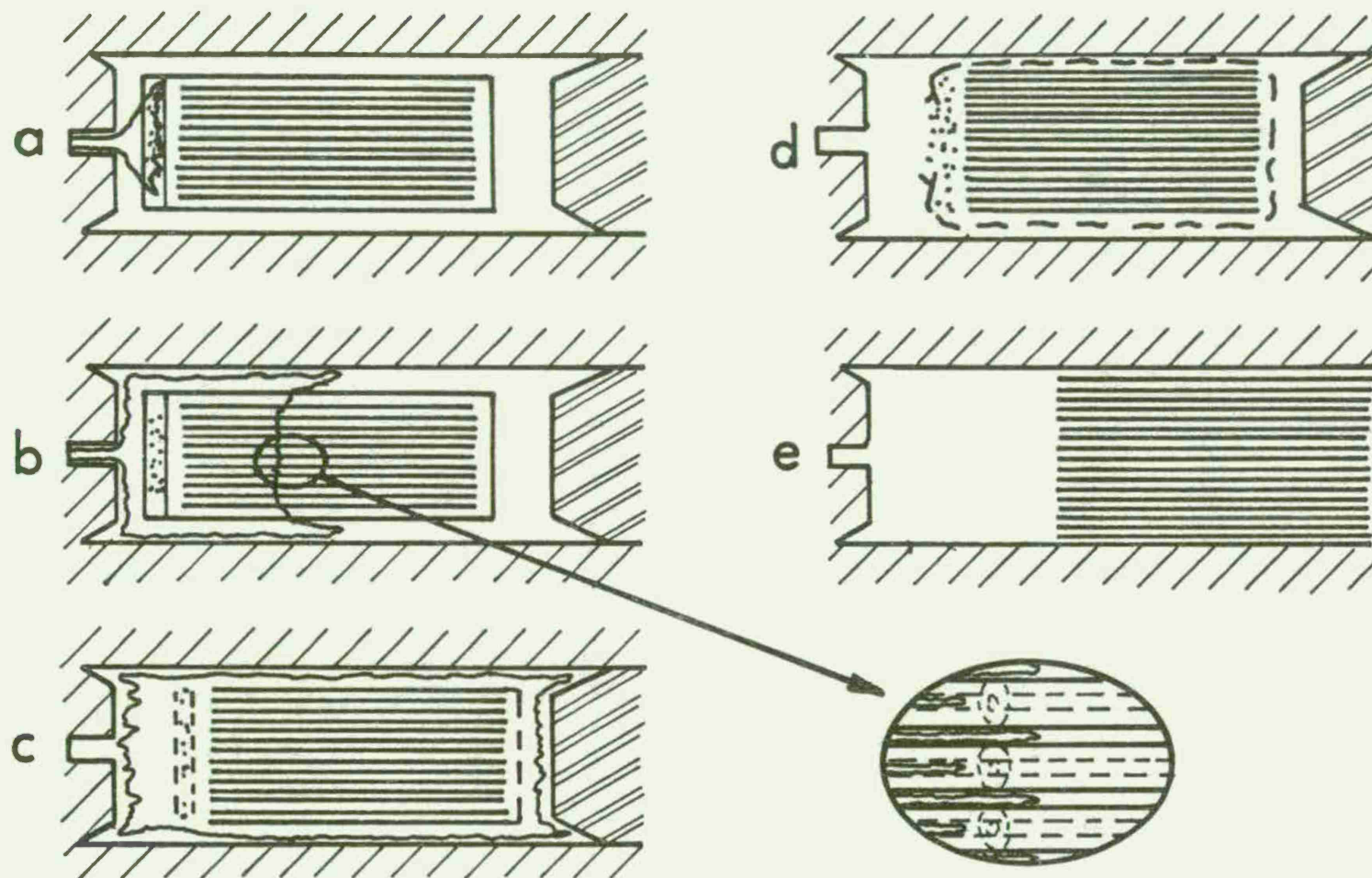


Figure 1. Stick Propellant Charge Phenomenology

pressurization over the length of the charge, at least in the interstices, is apparently responsible for the observed substantial reduction in both charge motion and pressure waves accompanying the stick propellant configuration.^{4,5}

Several other items need be mentioned before we conclude these background remarks on stick charge phenomenology. The first relates to the mechanical behavior of the stick propellant in the ignition environment. Once ignition does occur within the long perforations, rapid internal pressurization in excess of that in the interstices could lead to splitting or fracture of the sticks, yielding an unprogrammed burning surface. Slotted configurations may well reduce the pressure differential between inner and outer regions but also substantially weaken the sticks. Further, the ability of stick propellant to support reasonable tensile loads without being separated and carried downbore by interphase drag forces (as is granular propellant) is expected to result in most of the propellant charge being burned within the gun chamber itself and should be expected to impact on both gun performance and tube life. Finally, we caution the reader that the above processes are all potentially complicated by the presence of a propellant charge case, the initial impermeability, mechanical strength, and ignition and combustion characteristics of which may play major roles themselves in characterizing the above sequence of events.

B. Case in Point

The 155-mm, M203E2 Propelling Charge, shown in Figure 2, is currently undergoing development by the Large Caliber Weapon Systems Laboratory of the US Army Armament, Munitions and Chemical Command (LCWSL, USA AMCCOM) for the 155-mm, M198 Howitzer. This charge employs an M31-type stick propellant packaged in a rigid, combustible cartridge case. In June of 1982, limited testing of developmental M203E2 Charges using experimental propellant produced at LCWSL yielded higher maximum chamber pressures at cold temperatures than at ambient or hot temperatures. For example, a charge with an assessed ambient pressure of 351 MPa yielded pressures of 397 MPa at -54 degrees C and 337 MPa at 63 degrees C.

In an attempt to identify potential contributors to this observed, inverse temperature sensitivity, several M203E2 firings were conducted by Minor⁴ in the Ballistic Research Laboratory 155-mm howitzer simulator. The charges were modified to permit direct viewing of the interior of the propellant bundle, conditioned to the desired temperature, and fired in the simulator using transparent plastic chambers. High-speed cinematography was used to record the path of flamespreading and early response of the case, while flash X-rays, triggered at a pre-determined pressure, were taken to monitor the behavior of the propellant. In addition, spindle pressures and pressures and forces on the base of the projectile were recorded. Testing of

⁴T.C. Minor and A.W. Horst, "Ignition Phenomena in Developmental, Stick-Propellant, Combustible-Cased, 155-mm, M203E2 Propelling Charges," ARBRL-TR , USA AMCCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, (not yet released).

⁵T.C. Minor, "Mitigation of Ignition-Induced, Two-Phase Flow Dynamics Through the Use of Stick Propellants," ARBRL-TR-02508, USA ARADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1983 (AD A133685).

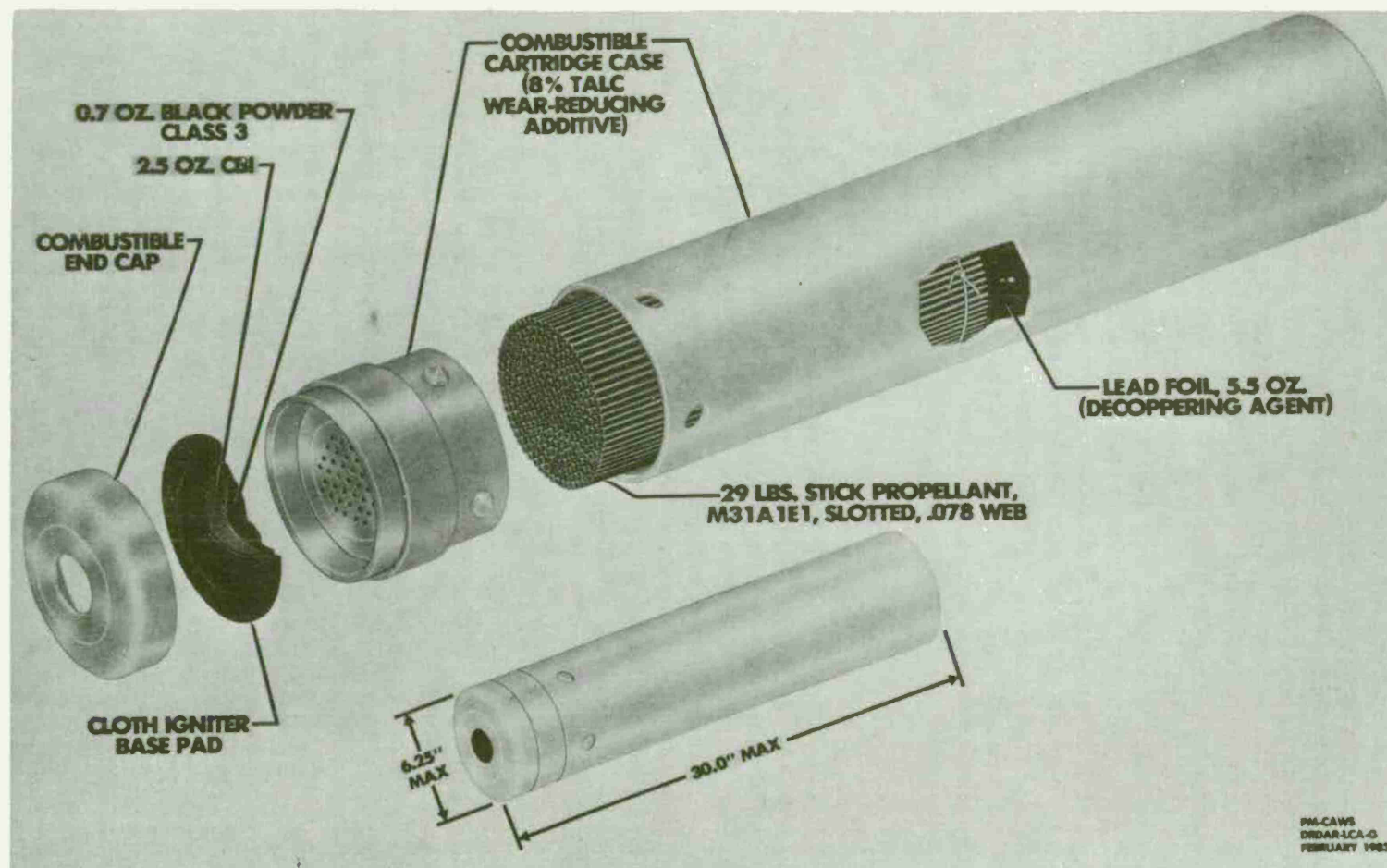


Figure 2. 155-mm, M203E2 Propelling Charge

cold, unmodified charges indicated a preferential flow of igniter gases around the outside of the charge, leading to compaction of the charge and an associated reduction in propellant bed permeability to igniter and perhaps subsequent combustion gases. A further test with the igniter charge packaged in a cloth bag rather than its original plastic cup displayed the intended mode of ignition, with igniter gases penetrating and igniting the main charge and fracturing the cartridge case from within. While subsequent charges manufactured with cloth bag igniters (and, unfortunately from a diagnostic standpoint, with different propellant lots as well) have all exhibited "normal" (i.e., not inverse) temperature sensitivities, the link between the igniter configuration and maximum chamber pressures at extreme temperatures is still unclear.

Moreover, an understanding of the mechanisms involved is of more than just academic interest. Current data for the M203E2 Charge suggest that it will necessarily operate at a higher ambient pressure than does the M203 Charge it will replace. Thus, in order to meet system constraints on the maximum chamber pressure at the hot temperature extreme, the M203E2 Charge must exhibit a low and reproducible temperature coefficient.

II. TECHNICAL DISCUSSION

A. Summary of Modeling Approach

The TDNOVA code was developed to simulate the interior ballistics of multi-increment propelling charges by means of a numerical solution of the equations of two-dimensional, two-phase flow. A major effort was just completed and reported by Gough⁶ to extend the TDNOVA code to permit simulation of rigidized, stick propellant charges. Under this representation, the charge is assumed to consist of a number of increments of similar but not necessarily identical diameters loaded end-to-end. Each increment is assumed to be separately enclosed in a container which may be either a flexible bag or a rigidized case. Each segment of each container may be characterized as having two reactive substrates on each side, permitting the simulation of combustion on each side of the container, as well as an additional component, such as a basepad, attached to the surface. Each increment may also incorporate a centercore igniter which is modeled as a quasi-one-dimensional, two-phase flow. The main charge of each increment may be either granular or stick propellant. Stick propellant may be unperforated, perforated, or perforated and slotted. A dual-voidage representation is made of perforated stick propellant; the state of the gas in the perforations is assumed to differ from that in the interstices. We similarly distinguish between the exterior and interior surface temperatures and combustion rates of perforated stick propellant. The interphase drag and heat transfer and the solid-phase stress tensor for stick charges are all posed in terms of anisotropic laws.

The ballistic consequences of heat loss to the tube may be evaluated by means of models based on steady-state pipe and plate flow correlations or by reference to an unsteady boundary layer model. Other constitutive extensions

⁶P.S. Gough, "Modeling of Rigidized Gun Propelling Charges," ARBRL-CR-00518, USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, November 1983 (AD A135860).

to the code include the influence of erosive burning, flow resistance in narrow regions of ullage, slow gas-phase kinetics with partial heat release at the surface of the solid phase, and a revision to the interphase drag correlation in a bed of granular propellant.

Each main charge increment is modeled as a two-dimensional, two-phase flow until flamespreading is complete, all containers are fully ruptured, and radial pressure gradients have subsided to within some user-selectable tolerance. Subsequently, a quasi-two-dimensional representation, in which propelling charge and circumferential ullage are treated as coupled regions of quasi-one-dimensional flow, is effected to complete the simulation of the interior ballistic cycle in an economical manner. The solution is obtained by means of an explicit two-step marching scheme for all interior mesh points together with characteristic forms at the external boundaries defined by the chamber and projectile and at the internal boundaries defined by the interfaces between the mixture and the ullage. The physical role played by the containers of the increments, including reactivity, resistance to penetration by the gas phase, and confinement of the solid phase, is reflected in the model by reference to the internal boundary conditions.

B. Application of TDNOVA to the M203E2 Charge

We now address application of the above-described TDNOVA representation to the M203E2 Propelling Charge by reference to the schematic of Figure 3. The exterior boundary depicts an axisymmetric representation of the gun chamber, including spindle face at the breech end and projectile boattail at the forward end. The centerline, breech end, and sidewall remain fixed boundaries, while projectile motion in response to the burning charge is resisted by an independently determined projectile engraving/bore resistance profile.

Internal boundaries are shown to reflect packaging of the individual increments -- in this case, the igniter region and the main charge compartment. Mechanical properties of each segment of the container are identified by a single digit number which points to an input file providing information on permeability, strength, and related parameters. Corresponding reactivity characteristics for each segment are indicated by a four-digit number, identifying files describing gasification rates and thermodynamic parameters associated with each of the inner and outer surfaces and attached components as described above. The small black powder charge in the igniter increment is seen to be treated here as an attached component described by reactivity file #1. Different reactivity pointers are associated with each of the two case increments to reflect the different nitration levels used for case components in the two regions. The many different mechanical properties pointers admit to the possibility of differing properties, though actual data are extremely limited.

Propellant input files are also required for the Clean Burning Igniter (CBI) and M31-type propellant to describe mechanical properties, dimensions, thermal properties of the solid, ignition and combustion characteristics, and thermodynamic properties of the product gases. If explicit modeling of the ignition and combustion of the container walls is desired, corresponding propellant input files are required for these materials as well.

A number of degenerate forms of this data base are also addressed in this

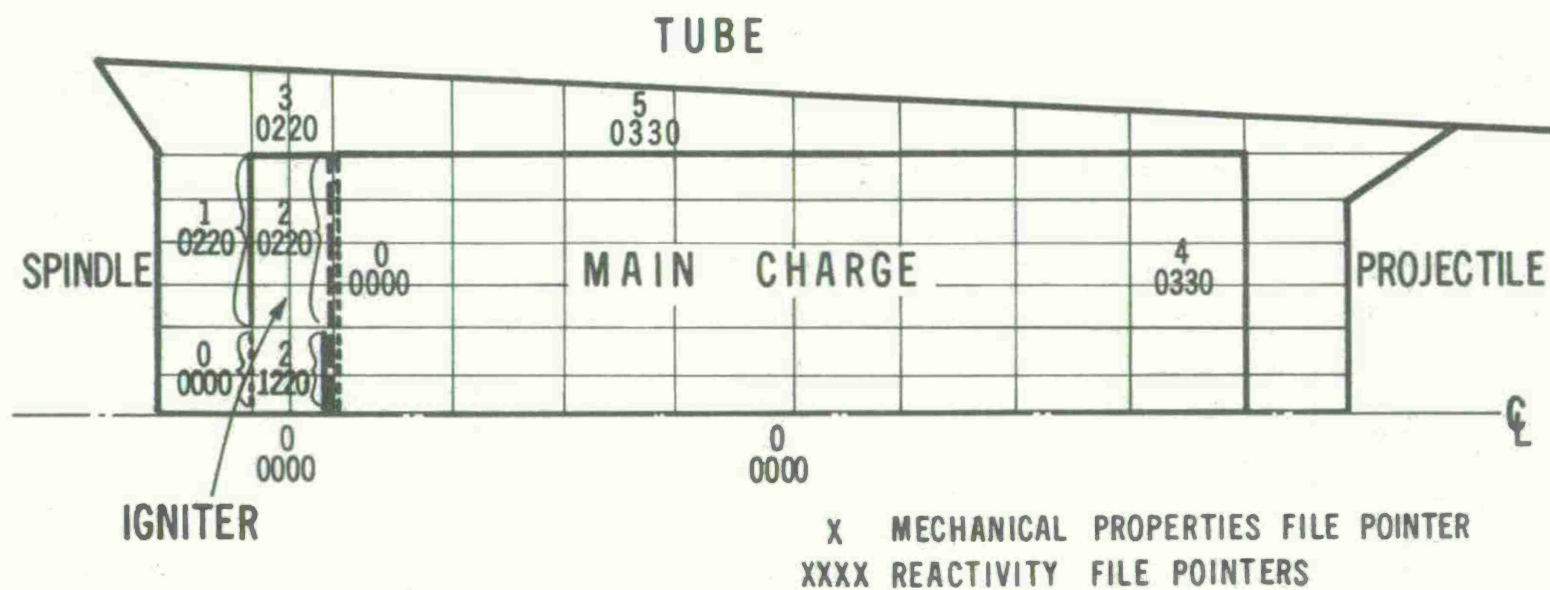


Figure 3. TDNOVA Representation of the M203E2 Propelling Charge

paper, various simplifications of the representation having been adopted in an attempt to circumvent computational difficulties encountered during the course of the investigation. The first of these entailed a simplification of the level of modeling of the rigid combustible case modules, as an insufficient treatment of boundary values associated with the rupture of two adjacent increment sidewalls led rapidly to an instability which prevented further study of the problem. While the source of this difficulty is under study, immediate interest in the problem of flamespreading in the M203E2 Charge motivated a temporary, more elementary treatment of the sidewall. Rather than the rigidized sidewall model with failure based on an equivalent stress calculated using a linear elastic model, a previously developed flexible sidewall representation with rupture based simply on a predetermined overpressure criterion was employed to allow continuation of the calculation.

Using this representation, some limited but very interesting insight was gained into the problem. Figure 4 displays the pressure field at various times very early in the ballistic cycle. We note first features of the pressurization event associated with the localized burning of the black powder spot within the igniter increment, the more extended region of CBI (assumed here to fill the igniter increment), and the energetic case material itself. We need to keep in mind here that, while flamespreading through the CBI and the M31-type stick propellant is driven in the calculation by convective heat transfer as deduced from the two-phase flow, combustion of the case, like that of the black powder spot, has been given a tabular representation with a small but finite contribution occurring right from time zero. This perhaps premature contribution to the pressure from the case was examined briefly in a subsequent calculation; however, a more meaningful analysis of this effect within the framework of TDNOVA awaits both activation of the explicit case ignition and combustion submodels within the code and useful ignition, burning rate, and heat release data for the case material. Nevertheless, by about 0.8 ms into the cycle, substantial pressurization is seen within the rear portion of the charge, the progression of which through the charge is seen to dominate the picture from that time forward.

Normalized flow field plots of the gas phase for this calculation are provided in Figure 5. (Flow vectors originate at the centers of the cells and are normalized with respect to the largest value of velocity for that phase at that particular time in the calculation. Further, the expanded width-to-length ratio depicted in these views similarly increases the apparent radial components of flow.) A substantial portion of early igniter output is seen to flow rearward and around the case, contributing to pressurization of the ullage, rather than forward into the bundle of stick propellant. However, a major contribution to the early flow of gas, both into the ullage and into the bundle of propellant, results from the case reactivity, as mentioned above. As the calculation progresses, we note significant distortion of the igniter element mesh, associated with the high drag forces exerted on the finely granulated CBI, leading to a prediction of substantial rearward motion of the igniter increment. While we emphasize the inaccuracies associated with the very coarse axial mesh which, in fact, may have led to the premature termination of the calculation, the reader is also reminded of the experimental results of Minor⁴ in which the igniter cup was apparently observed, via high-speed cinematography, to be propelled rearward towards the spindle face. The calculation will be attempted once again after some restructuring of the code has been made to allow a greater pre-allocation of axial mesh points preferentially to the fine-grained igniter region.

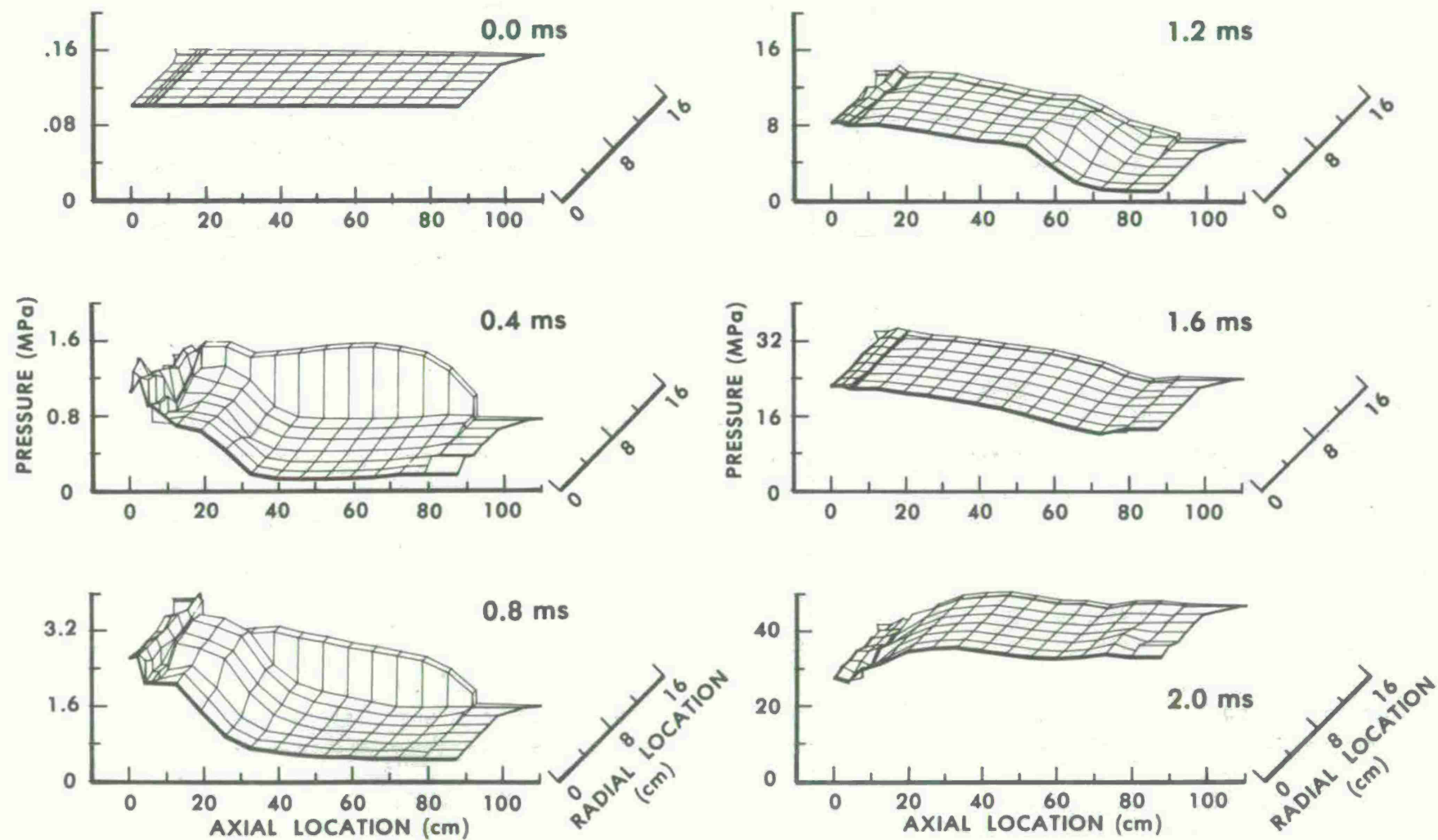


Figure 4. Predicted Pressure Fields for the M203E2 Propelling Charge

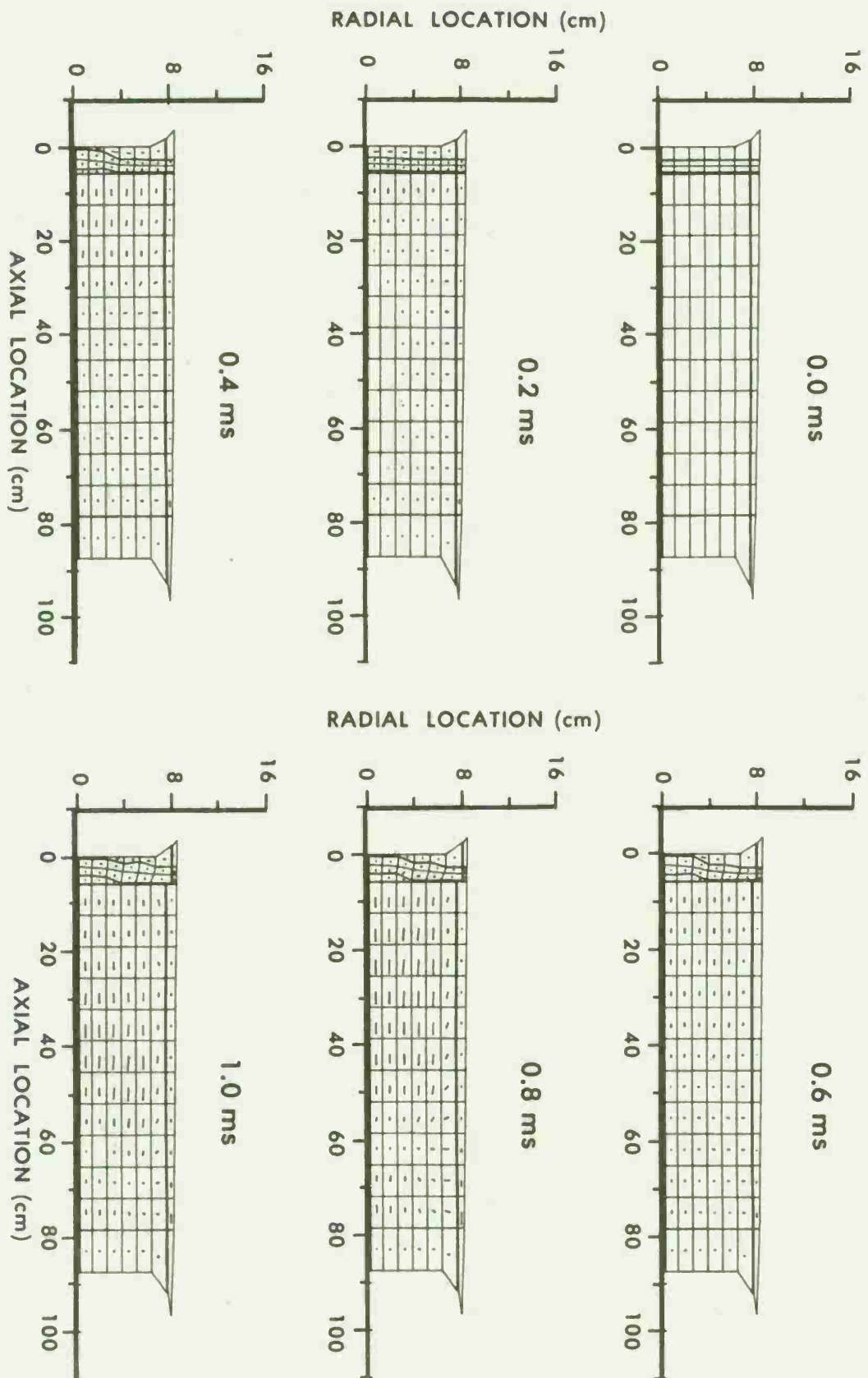


Figure 5. Predicted Gas-Phase Flow Fields for the M203E2 Propelling Charge

A second, and this time major, simplification to the representation was then effected to circumvent numerical difficulties associated with separation of the coarsely described igniter increment from the main charge and stagnation against the spindle face. Figure 6 depicts a single-increment version of the M203E2 data base, with the entire igniter charge (black powder, CBI, and combustible case material) described as attributes of the rear boundary of the charge. Hence, while separation of the igniter charge from the bundle of sticks was not possible, the partitioning of the flow of igniter gases forward into the bundle of sticks and rearward into the ullage, as influenced by the permeability of the boundary itself, was still amenable to treatment. In order to describe a problem of some interest, the black powder and CBI were lumped together and treated as an added energetic component external to the semi-permeable rear boundary, while igniter-increment case energetics (both rear and forward endwalls) were released at the surfaces of the now single rear boundary. Finally, in the same spirit, the physical attribute of case thickness was temporarily eliminated in order to circumvent a related computational difficulty. With this substantially simplified data base, we were then able to complete calculations through the completion of flamespreading and transformation of the problem to the quasi-two-dimensional representation.

We note first in Figure 7 early pressurization of the ullage, again a result of both igniter functioning and early case combustion. Some pressurization at both ends of the charge then takes place, but pressurization within the rear portion of the charge is seen to dominate the picture, with ignition first predicted to occur adjacent to the igniter shortly before 0.5 ms into the cycle. Some additional insight into the process can be gained from the gas- and solid-phase flow field plots of Figures 8 and 9, the latter suggesting radial compaction of the stick bundle at 0.5 ms, as observed experimentally by Minor.⁴ Accompanying flamespreading contours for the first 1.0 ms of the event are displayed in Figure 10, revealing a largely one-dimensional event, both inside the perforations and on the outside surfaces of the sticks.

Additional runs were made with the permeability of the boundary between the igniter and the bundle of propellant substantially decreased (to as low as 10% of the total boundary area devoted to ventholes), with surprisingly little noticeable impact on the results. We will return to this result in a moment.

Several calculations were made with case reactivity turned off in order to determine its impact on the above observations. Early pressurization in the external ullage was predicted to be substantially reduced, slowing the charge pressurization and flamespreading events as well. Perhaps most significantly, the influence of the permeability of the boundary between igniter and propellant then became evident (Figure 11). Though preliminary, this result may be a first indication of the importance of packaging properties to the path of flamespreading for stick as well as granular propellant charges.

Finally, calculations were also performed with the propellant slots initially closed (i.e., no mass transfer between perforations and interstices), leading to an expected increase in pressurization rates within the perforations (Figure 12). As the slots were allowed to open, in the simulation, when internal pressures exceeded external by only 10 MPa, very little subsequent effect was observed.

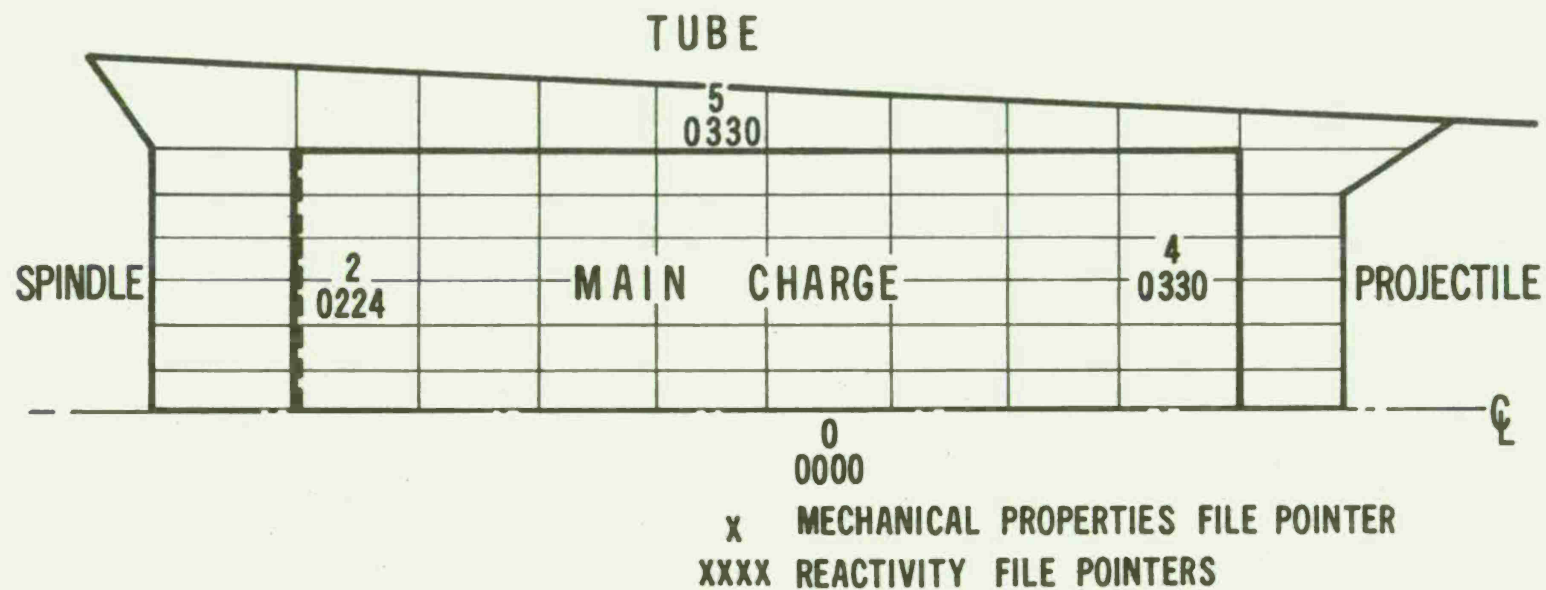


Figure 6. Simplified TDNOVA Representation of the M203E2 Propelling Charge

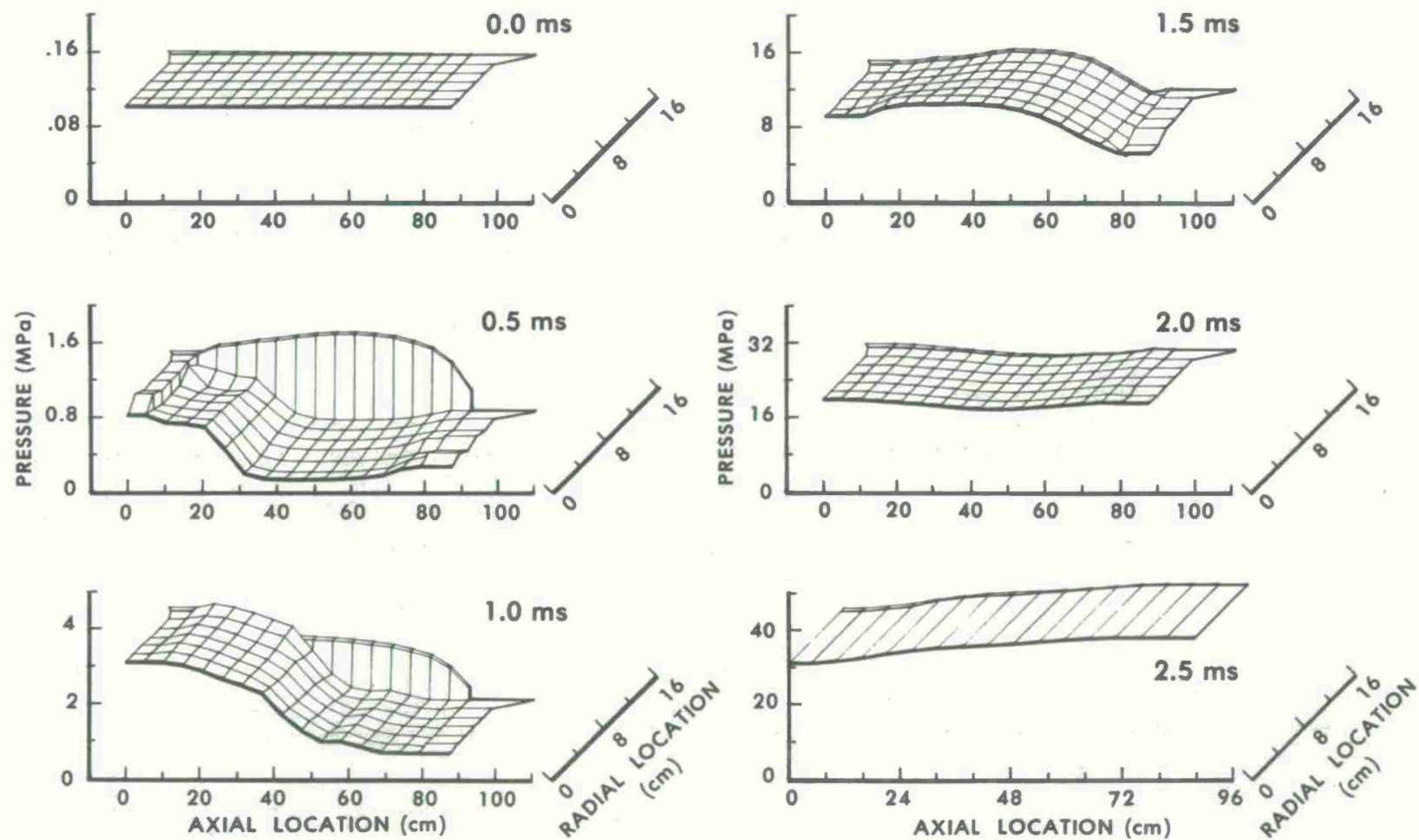


Figure 7. Predicted Pressure Fields - Simplified Representation

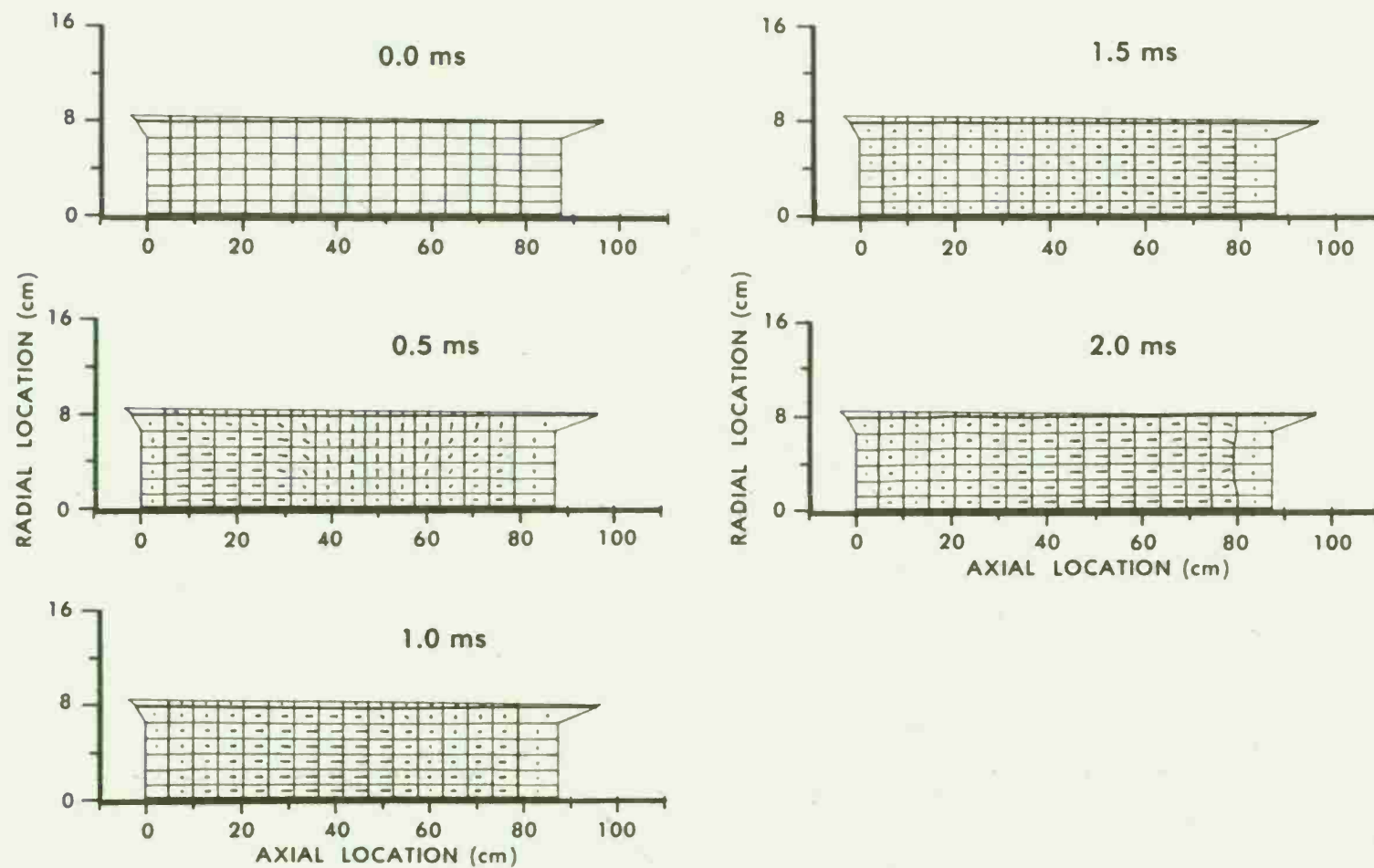


Figure 8. Predicted Gas-Phase Flow Fields - Simplified Representation

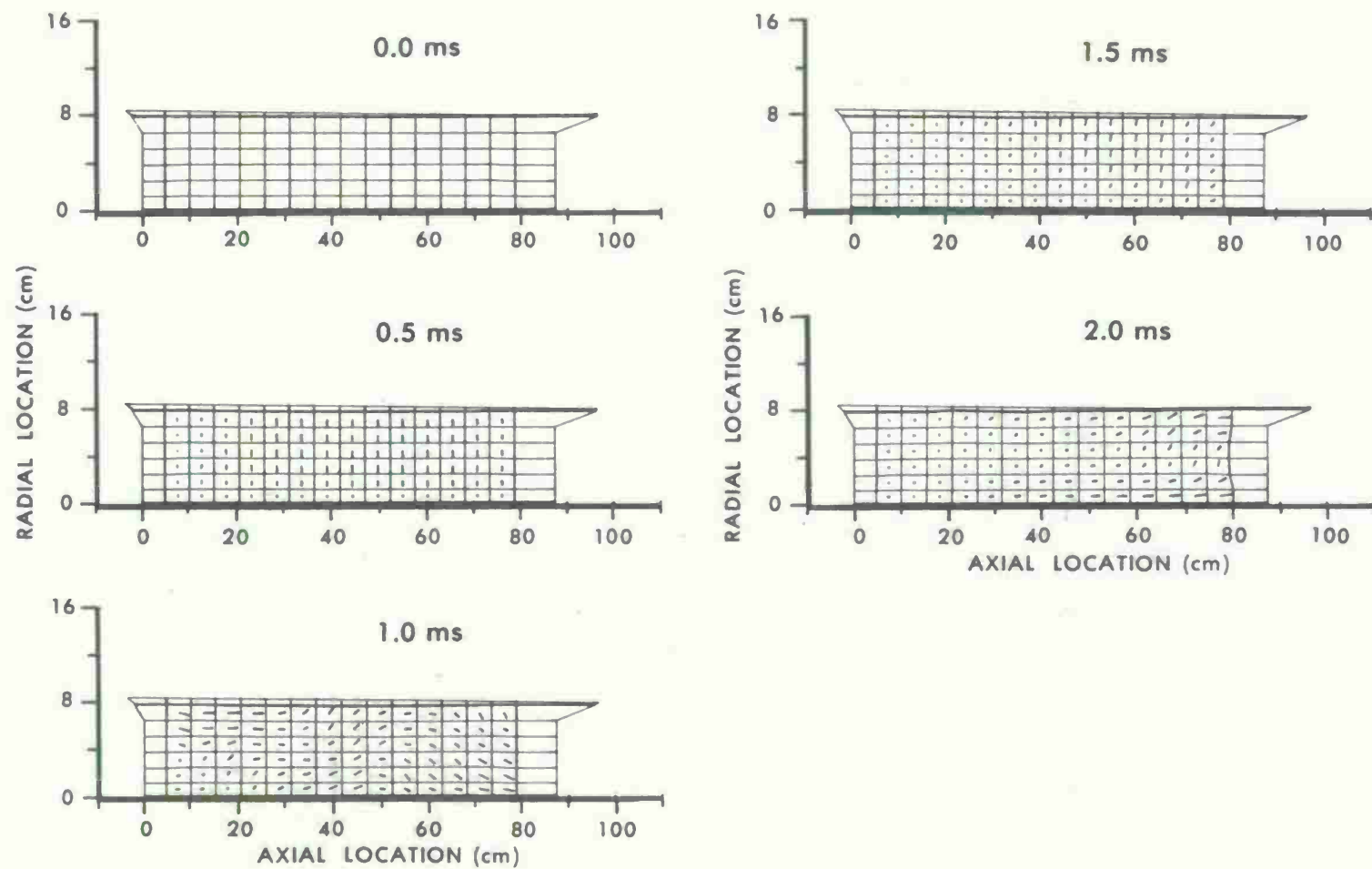
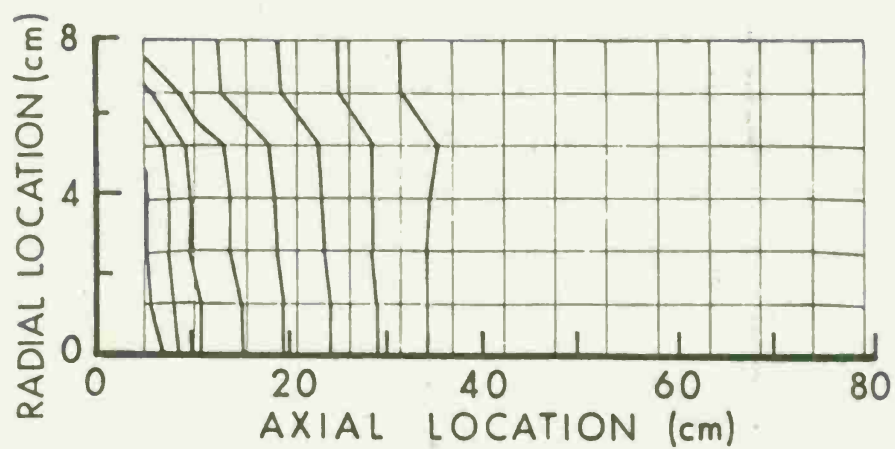


Figure 9. Predicted Solid-Phase Flow Fields - Simplified Representation

OUTSIDE SURFACES



INSIDE PERFORATION



Figure 10. Predicted Flamespreading Contours - Simplified Representation

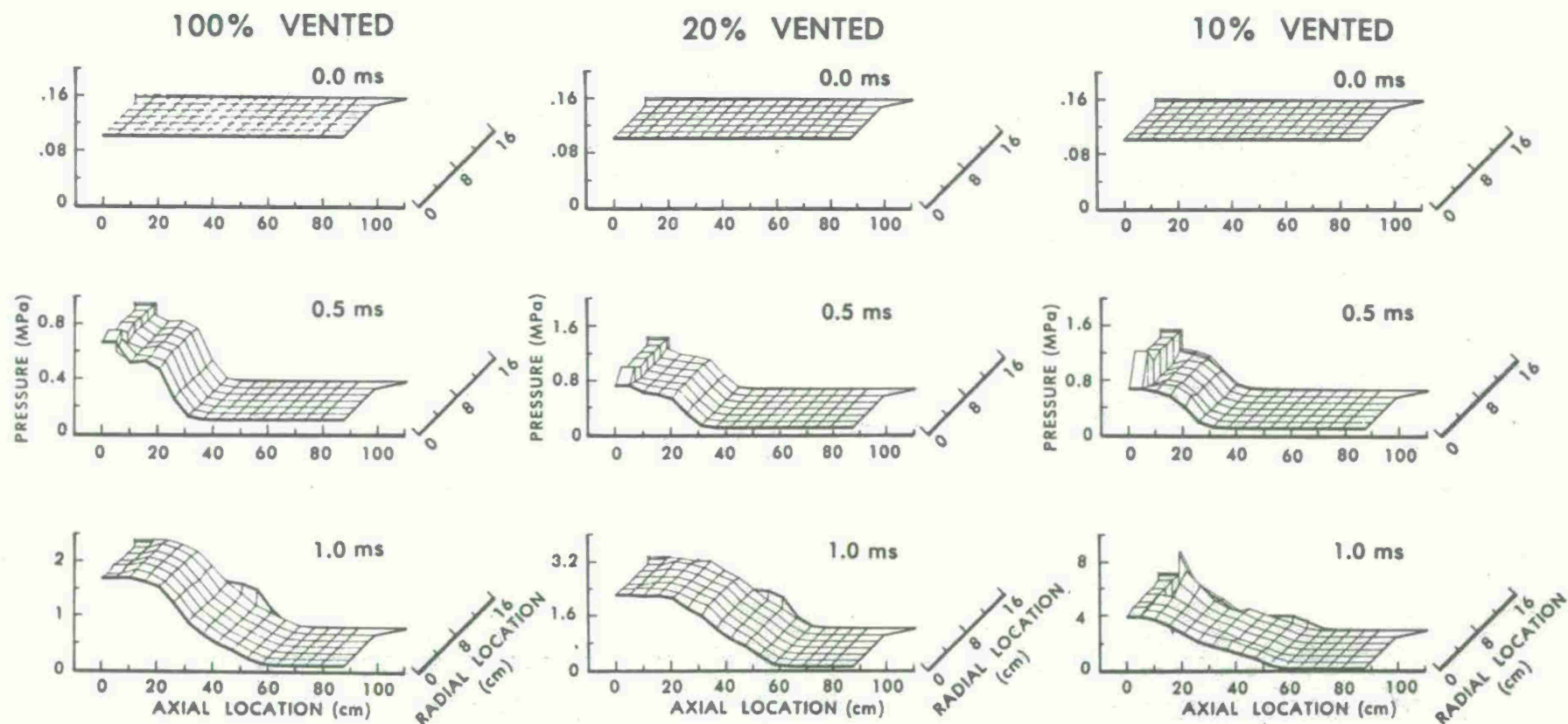


Figure 11. Predicted Pressure Fields - Simplified Representation; No Case Reactivity

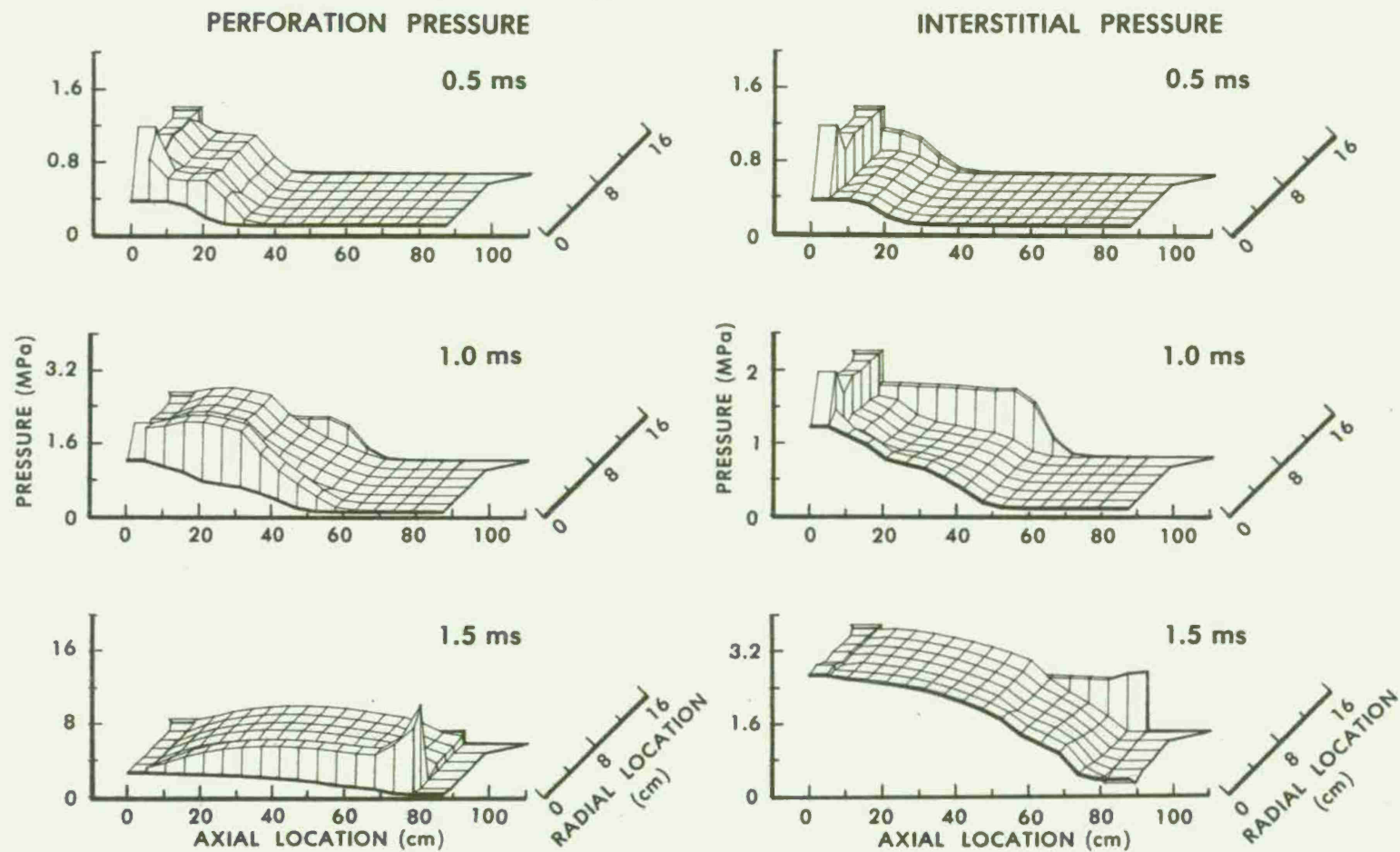


Figure 12. Predicted Pressure Fields - Simplified Representation; No Case Reactivity; Initially Closed Slots

III. CONCLUDING REMARKS

At this point, it should be stated that, above all else, the M203E2 Propelling Charge has shown itself to be an excellent vehicle for shaking down the new capabilities of the TDNOVA code. A number of minor coding errors were located and corrected, and several problems were encountered that require further work before additional progress can be made with the M203E2 study. While most of these are considered to be simple coding "glitches," it remains to be seen whether or not the preferential allocation of additional axial mesh points to the igniter increment will then allow completion of the unadulterated data base. Further, it seems reasonable to activate the explicit ignition and combustion submodels for the case material, based on the above results, before proceeding too much further with the problem. Useful exploitation of this feature will, however, be dependent on the availability of required case ignition and combustion data.

Indeed, we have yet to provide a complete explanation for the reverse temperature sensitivity experienced with an early version of the M203E2 Charge. However, one possible sequence of events consistent with the apparent influence of the path of flamespreading on maximum chamber pressures has been postulated. This mechanism, which indeed seems more likely with cold-conditioned propellant, involves splitting of the sticks upon ignition and rapid overpressurization within the perforations while the bundle of sticks is still tightly compacted from early flow exterior to the charge. The additional, unplanned burning surface then leads to the observed increase in maximum chamber pressure. With the preferred mode of flamespreading, early igniter products flow into the bundle of sticks, pressurizing and rupturing the case and dispersing the sticks radially. Ignition and pressurization within the perforations can then readily lead to a slight opening of the slots and rapid equilibration of pressures inside and outside the sticks, preventing any significant splitting. Complete verification of this hypothesis was unfortunately outside the scope of Minor's limited experimental investigation.

It is not unreasonable to expect that we might be able to examine the feasibility of this sequence of events as the source of the problem with TDNOVA in the not-too-distant future. In addition to the above improvements, however, we plan first to upgrade the stick splitting/opening submodel to be based perhaps on the Lamé equation and, necessarily, to include the influence on radial bed compaction as a resisting force. A complete investigation of the proposed mechanism is then anticipated.

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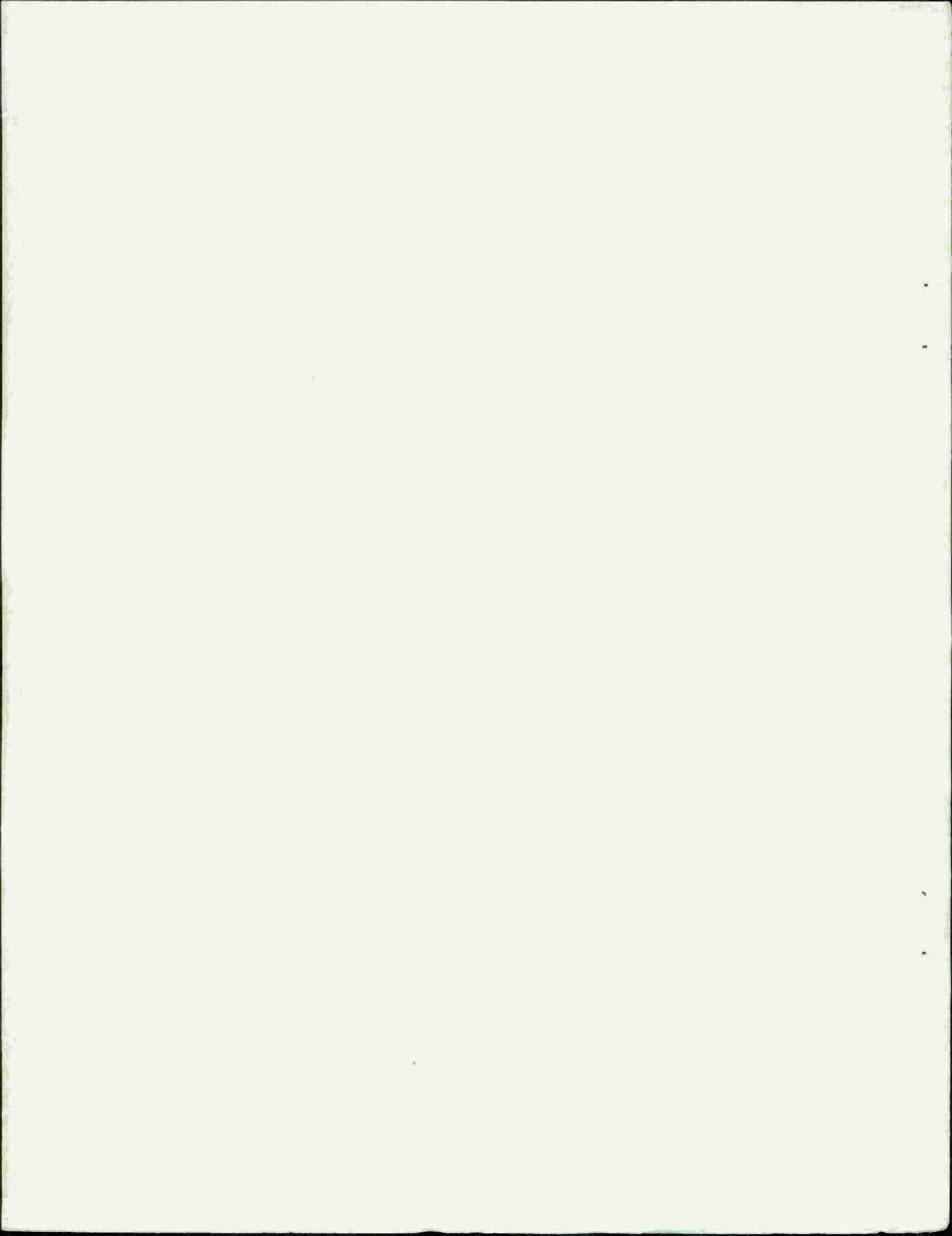
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