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FINAL REPORT

DEVELOPMENT OF NONDESTRUCTIVE TEST
TECHNIQUES FOR LARGE SOLID PROPELLANT GRAINS

Prepared by:

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National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

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aerojet solid propulsion company

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FOREWORD

The effort described herein was conducted by the Aerojet Solid Propulsion Company under the direction of Dr. B. A. Simmons, Vice President and Director, Advanced Technology Operations.

Work was accomplished under NASA Contract NAS 3-12036. Mr. H. Bankaitis, NASA-Lewis Research Center, was Project Manager.

J. M. Amaral was the Aerojet Solid Propulsion Company Program Manager. Principal investigators were B. L. Lamb and L. G. Schwieger. The 260-in.--(6.6 m) dia motor grain modes of failure analysis was performed by D. B. Syrek and E. O. Vincent.

TABLE OF CONTENTS

	<u>Page</u>
I. Summary	1
II. Introduction	3
III. Industry and Literature Survey	4
IV. Failure Mode Analysis	7
A. Case Burnthrough	8
B. Propellant Ejection	12
C. Abrupt Chamber Pressure Increase	16
D. Grain Structural Failure	18
E. Conclusions	20
V. Experimental Evaluation Program	20
A. Defect Specimens	21
B. High Energy Radiography	22
C. Through-Transmission Ultrasonic Inspection for Insulation-Propellant Separations	34
D. A Microwave Inspection System	40
VI. Quality of Inspection Results	54
A. Void Detectability Considerations	55
B. The Overall System	58
VII. Recommended Equipment and Procedures	67
A. Ultrasonic Inspection	67
B. Microwave	75
C. Radiography, Scintillation and Film	80
D. Detector Collimator Array	83
VIII. Conclusions	84

FIGURE LIST

	<u>Figure</u>
Summary of 260-in.- (6.6 m) dia Motor Program Test Firing Anomalies	1
Standard Deviations for Insulation Burnthrough Parameter	2
Summary of Insulation Burnthrough Calculation	3
Insulation Calculation Stations 1 through 13, 260-in.- (6.6 m) dia Full-Length Motor Grain Design	4
Summary of Minimum Defect Limit	5

FIGURE LIST (cont)

	<u>Figure</u>
Sketch of Grain Defect	6
End View of Defect Grain Configuration	7
Top View of Defect Grain Sample	8
Summary of Exposure Data, 260-in. Defect Specimen	9
Summary of Significant Inspection Results	10
Total Intensity and Exposure Time for ANB-3350 Propellant	11
Linear Acceleration, Propellant Penetrating Capability	12
Antivoid Test Arrangement	13
Count/Current Mode Flow Detection (Co60 Source, 2 by 2 in. (5.08 cm) NaI Detector)	14
Current Mode Flow Detection Linac Source (2 by 2 in. (5.08 cm) NaI Detector)	15
Traces of 4-in. (10.16 cm) and 2-in. (5.08 cm) Voids Through 65-in. (165.1 cm) of Propellant	16
Through-Transmission Ultrasonic Test	17
Through-Transmission Paths and Signals	18
Estimated Variation of Signal Variables on Bonded and Separated Region	19
Through Transmission Delay Times	20
Maximum Signal Amplitude vs Position Recorded Through 100-sec Gate	21
Ultrasonic Through-Transmission Received Signal Envelopes with USIP-10-W	22
Versions of the Waveguide Probe	23
Recording and Subtracting Spurious Signals	24
One-Horn Probe (2.6 to 3.9 GHz) Positioned for Inspection	25
Large Propellant Sample Signal Traces With and Without Metallic Reflector	26
Coaxial/Waveguide System Traces	27
Two Through-Transmission Test	28
Through-Transmission Traces	29
Horn Scanning Procedure	30
Fin Specimen Inspection Traces	31
Ultrasonic Flaw Detection	32
Setup for Radiography of Portion of Star Configuration	33

FIGURE LIST (cont)

	<u>Figure</u>
Ultrasonic Scanning Fixture	34
Transducer Holding Fixture	35
260-in. Motor Ultrasonic Inspection Electronics (Conceptual Design and Signals)	36
Microwave Scanning System	37
Position Sensor for Microwave	38
Source-to-Cassette Initial Alignment	39
X-Ray Scanning Mechanism	40
Radiation Shield	41
X-Ray Film Holder	42
Scintillation Detector Mounting Platform	43
Cassette Positioning	44
Cassette Holder Retracted	45
Scintillation Detector Array	46
Accessories for Boresight Alignment of Collimators for Convergence	47
Collimator Alignment	48

APPENDIXES

	<u>Appendix</u>
Gamma and X-Ray Scanning System Analysis	A
Facilities Selected for Survey	B
Thermal Nondestructive Testing Analysis (Infrared)	C
High Energy Radiography Analysis	D
Radiographic Film Enhancement	E
Quality Control Procedure	F
Tooling Costs	G
List of References	H

ABSTRACT

A nondestructive testing (NDT) system based on a through-transmission ultrasonic technique and a combination of film and scintillation radiography is defined for large solid propellant grains. A microwave scanning technique is described for inspection of propellant during casting of the grain. Investigation was preceded by a failure mode analysis (FMA) and a survey of available NDT techniques. The most promising techniques were comparatively evaluated by application to a specimen representative of the finned section of a full-length 260-in.- (6.6 m) dia motor containing critical flaws as determined by the FMA.

I. SUMMARY

The investigation of nondestructive testing techniques for large propellant grain was concerned with determining the best methods of inspecting the propellant grain for internal flaws, and for evaluating the bonds between propellant, insulation, and case in the cast-and-cured 260-in.-(6.6 m) dia solid rocket motor. It was apparent that this problem could not be readily achieved because nondestructive testing facilities equipped to handle such a large motor do not exist. Additionally, since the standard NDT inspection procedures were considered to be inadequate, other technology capable of contributing to a useful inspection was investigated.

The ground rules for the project were that radiography, the standard in the industry, and microwave frequency domain interferometry would be used as the basis for comparison. Work accomplished under NASA Contracts NAS 7-367 and 7-544 had shown that the microwave technique had considerable potential for propellant inspection. A further guideline was that no new technology was to be developed, although extensive adaptation was to be expected. Development was considered to mean having the operating principles verified experimentally, and having been applied to some kind of NDT inspection. An extensive industry survey and literature search supported the subsequent selections. Radiography (film and scintillation), microwave frequency domain interferometry, and ultrasonic through-transmission were considered worthy of adaptation on a trial basis. For each of these methods, sufficient equipment was assembled to provide an experimental basis for extrapolating to the performance capabilities on a full-scale 260-in. motor.

Concurrent with the selection of the NDT methods to be evaluated, a failure mode analysis was made to determine the sizes and types of flaws which would have to be detected. When the failure mode analysis was complete and the candidate inspection methods were selected, a defect specimen was prepared and the inspection techniques were tested to determine if the smallest defects capable of causing failure could be detected.

I. Summary (cont)

Finally, the best available inspection system is described, along with an outline of the procedures and an estimate of the probable results and costs.

The general conclusion is that although difficult, the inspection can be performed using high-energy radiography and ultrasonic through-transmission as the basic methods with microwave inspection as a supplementary technique during casting.

For practical inspection, all of the techniques will require special equipment which is not available at this time. The construction and testing of the equipment are beyond the scope of the present project. The required equipment ranges from relatively routine recording and signal analysis equipment for the microwave and ultrasonic inspections to a 26 mev, 55,000 R(Rads)/min at 1 meter (4.2×10^{-12} j, 550 j/kg per min at one meter) (unflattened) linear accelerator. There are at least two manufacturers of linear accelerators, and the instrumentation for the scintillation radiography inspection is no more intricate than that built by Aerojet for the gamma scintillation inspection of A-3 Polaris first-stage motors. Ultrasonic and microwave inspections of cured propellant do not require equipment more complex than the signal analyzer which was developed by Aerojet and used for this study. A microwave/acoustic impact tester of comparable complexity was built for inspecting Titan skirts at Aerojet. On the basis of these data, procurement of instrumentation for cured propellant appears to be no problem.

The proposed inspection would be performed in the same facility in which the motor is cast. The handling and positioning fixtures, therefore, have been conceptually designed with this in mind. The final design and construction, although a straightforward mechanical engineering problem, may be a complex one considering the size of the motor.

II. INTRODUCTION

The web thickness of the propellant used in the 260-in.-(6.6 m) dia motor exceeds any previously produced, and practical inspection of the grain is not possible with existing facilities or techniques. Not only is the grain 88-in. (223.5 cm) thick at various locations, the steel motor case is correspondingly heavy, and the trowelled insulation is somewhat irregular in comparison with the more usual premolded insulators. It was quite apparent from inception of the program that new equipment and inspection methods would be needed to successfully inspect a 260-in.-(6.6 m) dia grain. Motor inspection for grain integrity could not be attempted at any existing facility, and inspection of a specimen representing a 30 degree (0.52 radans) of the motor circumference and 6 ft (1.8 m) of length resulted in a formidable task.

The firings of the half-length 260-in.-(6.6 m) dia subscale Motors SL-1, SL-2, and SL-3 have indicated that the 260-in. motor will require inspections similar to those of smaller motors.

To establish a plan for inspection of the 260-in. grain, it was necessary to survey the field of nondestructive testing for candidate methods, and to experimentally evaluate those that appeared to have potential. Since full-scale 260-in. motors were not available for this study, the logistics of motor inspection were not considered in specific detail. Efforts were also made to disregard impractical inspection operations. The majority of the effort was directed to the fundamentals of various inspection techniques. The details of actual inspection operations can and should be formulated after details of the final motor configuration and manufacturing procedures are firmly established. If improved performance is required of the NDT inspection facilities, the selection of the methods to be used, a valid estimation of the capability of each method, and an indication of the most potential areas of further investigation will be of primary importance.

II. Introduction (cont)

The procedures presented in this report are not step-by-step documentation of an inspection operation. The 260-in. motor is not in production, and neither are any of the major pieces of test equipment required to inspect the motor. Thus, the procedures are a general description based on current knowledge, although significant effort has been made to anticipate problems which might occur during actual inspection. Assessment of the ultimate capabilities of the various techniques presently developed and potential improvements are considered in more detail. These techniques are subject to experimental study and to reliable theoretical extrapolation, and constitute the most significant portion of this report.

III. INDUSTRY AND LITERATURE SURVEY

A survey was conducted to identify any new technology that might be of practical use for inspection of the 260-in.-(6.6 m) dia motor. The survey included a literature search which covered general publications in nondestructive testing as well as NASA scientific and technical aerospace reports. A Defense Documentation Center computer search was also conducted.

Some articles on current work in non-film radiography and articles pertaining to inspection of rubber and rubber-like materials were uncovered; however material pertaining to inspection of a large mass similar to a 88-in. (223.5 cm) thickness of propellant web was essentially nonexistent. Work currently being published appeared to be directed more to composites, honeycomb, and miniature structures.

III. Industry and Literature Survey (cont)

One exception was a radiographic technique using scintillation scanning instead of film to detect separations between insulation and propellant in rocket motors. This work was done at Naval Weapons Station, Concord, and at the Naval Ordnance Station, White Oak, Md. A model of such a system was programmed into a computer to determine theoretical performance for 260-in. motor inspection. Both the detection of voids and separations were considered, and the results are documented in Appendix A. The system for void detection was selected for further development.

In addition to the literature search, contacts were made with various facilities, and personal communications were exchanged when prospects of obtaining useful information existed. The initial contacts and the subjects discussed are shown in Appendix B. As a result of the initial contacts and the literature search, the areas of ultrasonics, infrared thermography, microwave, and radiography (film and non-film) were selected for experimental study. The experimental program for infrared thermography was performed by Automation Industries at the Aerojet Solid Propulsion Company, Sacramento. A report of this study is presented as Appendix C.

Ultrasonics, as used here includes audio-frequencies. Improved penetration at low frequencies between 50 KHz and 500 KHz provided the best results. The decision was made to experiment with a through-transmission test developed at Aerojet, Sacramento, under Contract NAS 7-367, Phase II, Development of Ultrasonic Nondestructive Test Technique for Large Solid Rocket Motors, Final Report, May 1966. These experiments are described in Section V of this document. The current development of ultrasonic-holography technology was determined to be inadequate.

The microwave frequency domain interferometer developed at Aerojet, Sacramento, under Contracts NAS 7-544 and NAS 7-367 was selected as the principal microwave technique; no other potential techniques were discovered. Electro-Physics Co. participated in some of the experimental studies of the microwave technique.

III. Industry and Literature Survey (cont)

Radiography is a standard method for examining solid-propellant-rocket grains. Both isotope and accelerator sources are in use, and both film and non-film detectors have been used successfully. Because of the similarity of previous work to the present application, the groups at Aerojet Nuclear Division, Applied Radiation Co., and Naval Weapons Station, Concord, Calif., were consulted during the experimental evaluation program. The Naval Weapons Station, Concord, contributed to the analysis of non-film techniques presented in Appendix A.

The Applied Radiation Co. contributed to the analysis of radiographic quality and X-ray source requirements presented in Appendix D.

As a result of the theoretical studies and the infrared experiments, the decision was made to proceed only with evaluation tests of microwave, ultrasonic, and radiographic techniques. Several of the rejected techniques are discussed briefly in the following paragraph.

Infrared rays penetrate only a few solid materials, and do not penetrate steel or propellant. The infrared technique discussed is based on heat transfer and uses infrared radiation to map surface temperature. A temperature gradient is set up from interior to surface so that heat losses by radiation from the surface are made up by conduction from within. Flaws which interrupt the flow result in cold spots on the surface. The equipment is not sufficiently developed to handle a 260-in. motor because of the size, thickness, and highly conductive characteristics of the case.

The most familiar holographic technique discussed consists merely of using holograms to detect small displacements of the surface of an object. The holograms act as an optical transducer and are capable of detecting either vibration or static-load deflections. Unfortunately, this technique is not readily adaptable for use on a 260-in. motor. Positioning fixtures with sufficient rigidity and a

III. Industry and Literature Survey (cont)

capability of handling such a large object are unavailable. Holography with ultrasound and microwaves has also been investigated, and there has been at least one effort to apply microwave holography to nondestructive testing^{(1)*}. The use of holography in ultrasonics is more extensive, although the technique is usually restricted to immersion testing of relatively small parts. The development of ultrasonic and microwave holography technology is not as advanced as other techniques, although both have a grain penetration capability and hence, more ultimate potential than optical holography, which can only study surface displacements, at least for objects opaque to light.

Several other nondestructive testing techniques such as sonic-impact, stress-wave analysis, and neutron-radiography were investigated although none were considered to be practical for 260-in.-motor grain inspection application.

IV. FAILURE MODE ANALYSIS

The analysis of defects required to initiate failure was based on consideration of abrupt pressure rise, case burnthrough, nozzle damage, or obstruction by propellant ejection and gross grain structural failure. The term failure, as used here, means a probability of 10^{-6} or greater that the motor will not perform within acceptable limits. In the case of chamber overpressure, this is 1% above nominal. Calculations are based on the full-length 260-in.-grain configuration and the case and insulation described in the 260 Motor Reliability Study⁽²⁾. Test firing results were also utilized from Motors 120-SS-1, 260-SL-1, 260-SL-2, and 260-SL-3. A summary of the 260-in. motor program firing anomalies is presented in Figure 1. The calculations are for flight configuration, and the failure modes are analyzed separately.

*Numbers in superscript refer to List of References in Appendix H.

IV. Failure Mode Analysis (cont)

A. CASE BURNTHROUGH

1. Failure Mode Identification and Criteria

The failure mode involving case burnthrough was originally defined as case burnthrough prior to the end of action time. However, since even a defect-free motor can have a small probability of failure caused by random variabilities of thickness and erosion rates of the propellant, insulation, and case, it was decided that the best method in establishing a case burnthrough failure criteria for this study was to define failure to mean an unacceptable increase in the probability of failure beyond the nominal for a defect-free motor. Assuming a design reliability goal of 0.99 to 0.999 for the entire motor, the tolerable level for a single failure mode probability of occurrence should be at least three orders of magnitudes less, or 10^{-6} . However, it became apparent after further analyses that lack of variability data for case erosion rates would hamper valid calculations of case burnthrough probability. It was decided, therefore, to arbitrarily set the probability of case burnthrough, with insulation burnthrough at 10^{-3} . The failure mode was then reidentified as insulation burnthrough with the limit criteria set at 10^{-3} . Essentially, this follows the laws of conditional probability where:

$$P(CI) = P(I) \cdot P(C/I)$$

where $P(CI)$ = probability of burning through insulation and case

$P(I)$ = probability of burning through insulation

$P(C/I)$ = probability of burning through case, given that insulation burnthrough has already occurred.

Thus, if it is desired to limit $P(CI)$ to 10^{-6} , and $P(C/I)$ is estimated at 10^{-3} , then $P(I)$ must be limited to 10^{-3} .

IV.A. Case Burnthrough (cont)

2. Sequence of Failure

The sequence of failure of insulation burnthrough originates with an advancement of the flame front at a rate faster than planned, resulting in the flame front traversing through the propellant or along the propellant-liner interface and eroding through the insulation prior to the end of action time. In terms of defects, any void, region of porosity, fissure, and crack in the grain extending radially from either the inner or outer surface might be considered the initiator of the failure sequence. Included are defects in the cylindrical part of the grain and at the base of the fin slots. Propellant-liner unbondedness can also advance the flame front. Depending on motor geometry, any propellant-liner bond failure that results in a net increase in flame front advancement over that expected can be considered as an initiator of the failure sequence.

3. Defect Limit Characterization

The calculation of maximum allowable undetected defect size for an insulation burnthrough probability of 10^{-3} was performed by using a requirements vs capability (R/C) analysis. In this type of analysis, statistical distributions are established for the requirement, expressed as the maximum exposure time that must be provided for, and the capability, expressed as the total time required to burn through propellant and insulation. In the usual R/C analysis, failure probability is calculated as the probability of the requirement exceeding the capability. In this analysis, however, the failure probability is known and the capability is reduced by the unknown term relating to minimum defect size. Thus, the usual formula:

$$\Phi = \frac{\bar{X}_C - \bar{X}_R}{\sqrt{(s)_C^2 + (s)_R^2}}$$

IV.A. Case Burnthrough (cont)

where $\bar{X}_C$ = average capability in sec
 $\bar{X}_R$ = average requirement in sec
 s_C = standard deviation of capability in sec
 s_R = standard deviation of requirement in sec
 Φ = number of pooled standard deviates between $\bar{X}_C$ and $\bar{X}_R$ (which can be converted into probability of R exceeding C)

now becomes:

$$\Phi = \frac{(\bar{X}_C - V/r_b) - \bar{X}_R}{\sqrt{(s_C)^2 + (s_R)^2}}$$

where V = minimum defect size, in. (cm)

r_b = propellant burning rate, in./sec (cm/s)

$\bar{X}_R$ was considered to be the equivalent of the nominal action time of 147.5 sec (time to 10% of maximum chamber pressure) and was evaluated from the following formula:

$$\bar{X}_R = \frac{t_w}{r_w} + \frac{t_{to}}{r_{to}}$$

where t_w = maximum thickness of propellant consumed by web time

r_w = burning rate propellant prior to web time

t_{to} = maximum thickness of propellant consumed between web and action time

r_{to} = burning rate of propellant consumed between web and action time

IV.A. Case Burnthrough (cont)

Using propagation of variance analysis and the estimated variances for the above parameters (Figure 2), a value for s_R of 1.92 sec was obtained.

Although $\bar{X}_R$ and s_R are constant for the entire 260-in.-(6.6-m) diameter, $\bar{X}_C$ and s_C vary longitudinally depending on the propellant web and insulation thickness at each station. The general formula is as follows:

$$\bar{X}_C = \frac{t_p}{r_w} + \frac{t_i}{r_i}$$

where t_p = propellant thickness at longitudinal station
 r_w = propellant burning rate prior to web time
 t_i = insulation thickness
 r_i = insulation erosion rate

Figure 3 summarizes the calculations performed at 13 longitudinal stations. The location of these stations is shown in Figure 4. In these calculations, a value of 3.09* for Φ was used to limit the insulation burnthrough probability to 10^{-3} . The results indicated that the minimum size defect that can be tolerated is one which will advance the flame front 4.1 in. (10.4 cm). This 4.1-in. (10.4 cm) advancement could develop from a single spherical void 4.1 in. (10.4 cm) in diameter, or cracks, fissures, or propellant/propellant separation extending 4.1-in. (10.4 cm) perpendicular to the burning surface. The advancement could also result from a series of smaller voids or defects so aligned as to result in a cumulative 4.1-in. (10.4 cm) flame front advancement. In an extreme instance, a region of porous propellant could also provide a 4.1-in. (10.4 cm) flame front advancement. The lack of applicable data for estimating probable void size distributions makes it difficult to establish the finite allowable limit in terms other than a net 4.1-in. (10.4 cm) flame front advancement.

*Taken from a table of normal distribution (areas under normal curve).

IV A. Case Burnthrough (cont)

The results of Figure 3 were also used to determine the maximum allowable propellant-liner separation. Because the sidewall in the aft head is approximately perpendicular to the flame front advancing from the unrestricted surface of the end of the grain, the 4.1-in. (10.4 cm) maximum criteria also apply to the maximum permissible longitudinal extent of undetected propellant-liner separations (no width specified). In the forward head, the maximum allowable separation ranges from 64.5 in. (164 cm) at the forward equator to 12 in. (30.5 cm) at a point 150-in. (381 cm) aft of the forward equator. In the cylindrical section between the aft equator and the location where the maximum web thickness of 87.5 in. (222 cm) is reached, longitudinal separations of 160 to 297 in. (406 to 754 cm) are permissible in terms of flame front advancement; however, such extensive separations would probably fail to meet other criteria. It was determined that the 1.125 in. (2.858 cm) of insulation in the forward head provided such a large margin that complete propellant-liner unbondedness and defects up to the size of the propellant web of 24.5 in. (2.2 cm) could be tolerated without violating the insulation burnthrough criteria.

B. PROPELLANT EJECTION

1. Failure Mode Identification and Criteria

The decision was made after careful analysis that there were actually two different failure modes that must be considered which involve propellant ejection. The first mode is where an ejected segment of propellant blocks the throat area sufficiently to increase the chamber pressure above a tolerable limit. The second mode consisted of a segment of propellant creating an overpressure or pressure differential sufficient to cause failure of the exit cone. The tolerable limit for the pressure rise could have been based on an increase in failure probability above 10^{-6} , however, the work statement limit of a 1% rapid pressure increase was used.

IV.B. Propellant Ejection (cont)

The failure criteria for the exit cone failure mode could also be set at an increase in failure probability above 10^{-6} . However, a finalized design or stress analysis has not been prepared for a full-length 260-in.-(6.6-m) dia motor nozzle and exit cone, so a failure criteria using the R/C analytical technique could not be prepared. Instead, to provide a preliminary estimate of the size of defect that must be detected, it was decided to use the 260-SL-3 nozzle data.

2. Sequence of Failure

The failure mode sequence involving throat blockage results when a segment of propellant becomes separated from the grain because of fissures or lack of propellant-liner bond, and is propelled through the nozzle. As the segment passes through the nozzle, a thrust decrease and a subsequent pressure increase occur.

Ejection of a propellant segment could be the result of a propellant-liner separation. As the burning front approaches the chamber wall, flame penetration into the separation would occur and, depending on the local gas velocity and propellant strength, breakage and ejection would result. The possibility also exists that a fin could break off in the forward area because of excessive voids or other defects. However, because of low gas velocities in the fin area, ejection would probably occur only during a flight test.

3. Defect Limit Characterization

Using the 1% chamber pressure increase as a failure criteria, a conservatively small estimate of the size of propellant segment required to cause failure was obtained by calculating the steady-state throat area reduction required to produce a 1% increase in chamber pressure. Using the relationships expressed in the mass balance equation, the following formula was obtained:

IV.B. Propellant Ejection (cont)

$$A_{t_2} = A_{t_1} \left(\frac{P_1}{P_2} \right)^{1-n}$$

where A_{t_1} = throat area before pressure increase

A_{t_2} = throat area after pressure increase

P_1 = chamber pressure before pressure increase

P_2 = chamber pressure after pressure increase

n = burning rate exponent

Using a value of 0.42 for n , an initial throat area of 6,235-sq in. (4.02 m^2) and a P_1/P_2 chamber pressure ratio of 1:1.01, it was calculated that a 36.2-sq in. (234 cm^2) decrease would be required for conditions existing immediately after motor ignition. As a NDT requirement, it would be necessary to detect defects capable of resulting in propellant segments being ejected that would present a cross-sectional area of 36.2-sq in. (234 cm^2). A 6-by 6-in. (15.2 by 15.2 cm) defect would appear to be in the same order of magnitude as the 4.1-in. (10.4 cm) defect determined to represent the maximum allowable for the case burnthrough failure mode.

Since the propellant segments would move through the nozzle at an extremely rapid rate, a piece much larger than 36.2-sq in. (234 cm^2) in cross section would actually be required to produce an actual chamber pressure increase of 1%.

The other failure mode sequence propagating from propellant ejection involved structural failure of the nozzle or exit cone. In the 260-SL-3 postfiring analysis⁽³⁾, it was concluded that structural failure of the exit cone

IV.B. Propellant Ejection (cont)

could have occurred as result of a uniform overpressure that would cause the exit cone liner to fail in hoop stress, or a non-uniform pressure differential that would cause the rivets attaching the exit cone to the nozzle to fail in shear because of induced bending moment. Since a pressure differential of only 11.3 psi (7.8 N/cm^2) would be necessary to fail the rivets as opposed to a uniform pressure of 411 psia (284 N/cm^2) (an increase of about 370 psia (255 N/cm^2) above ambient at the 2.6 expansion ratio), the pressure differential produced by the passage of ejected propellant through the exit cone was considered to be the most likely to occur.

In attempting to estimate the size of an ejected propellant segment that caused the structural failure of the 260-SL-3 exit cone, a calculation was performed to determine the amount of propellant burning surface in the exit cone necessary to produce the pressure increase from 40 to 411 psia (27.6 to 284 N/cm^2) in 40 msec. The resulting value of 77,800-sq in. (50.2 m^2) was a 4 by 198 by 198-in. (10 by 503 by 503 cm) segment of propellant, which is more than twice the nozzle throat area; therefore, it was concluded that the pressure differential mode of failure was more likely to have occurred.

The amount of exit cone area reduction necessary to produce a differential of 11.3 psi (7.8 N/cm^2) was estimated, and it was determined that a 1800-sq in. (1.16 m^2) object would be required. Since a 42.5- by 42.5-in. (108 by 108 cm) piece would match this dimension, it was concluded that the minimum size of an ejected piece required to cause structural failure would be significantly larger than that required to cause a pressure increase of 1%.

As with the previous failure mode of case burnthrough, it must be recognized that while these minimum size calculations represent the smallest sized single defect that could have caused the failure, a combination of even smaller segments of propellant being ejected at the same time could have produced the same results. There is evidence that during the 260-SL-3 firing, several pieces passed through the nozzle during the 66.2- to 66.7-sec interval when the exit cone failure is believed to have been initiated.

IV. Failure Mode Analysis (cont)

C. ABRUPT CHAMBER PRESSURE INCREASE

1. Failure Mode Identification and Criteria

The failure mode involving abrupt chamber pressure increase is considered in this study to be the one originating from increased burning surface. The failure criteria could have been specified in terms of probability of case structural failure in excess of 10^{-6} , the probability of exceeding a given thrust performance limit, or the probability of imposing an excessive shock loading on the upper stages or payload. However, the 1% sudden pressure increase criterion used in this study is a more conservative value. To provide a practical limit, the time of occurrence of such a critical pressure increase was limited to the interval between the end of the ignition interval and the beginning of tail-off.

2. Sequence of Failure

This failure mode originates when a propellant grain defect such as a void, fissure, propellant/propellant separation, or crack is exposed to the flame front. With a rate depending on the width, orientation, and local gas velocity, the surface of the defect ignites and produces a chamber pressure rise in excess of that normally expected at that time in the firing. This failure mode can also originate when an area of propellant-liner unbondedness is exposed to an advancing flame front. For this study, failure is assumed to have occurred when a 1% pressure increase occurred.

3. Defect Limit Characterization

The following formula, derived from the mass-balance relationship, was used to calculate the increase in burning surface required to produce a 1% increase in pressure:

IV.C. Abrupt Chamber Pressure Increase (cont)

$$A_{P_2} = A_{P_1} \left(\frac{P_2}{P_1} \right)^{1-n}$$

where A_{P_1} = burning surface before pressure increase

A_{P_2} = burning surface after pressure increase

P_1 = chamber pressure before pressure increase

P_2 = chamber pressure after pressure increase

n = burning rate exponent

Using a burning surface of 519,000-sq in. (335 m^2) (the minimum during web action time), a burning rate exponent of 0.42, and a ratio of P_2 to P_1 of 1.01, a value of 3010-sq in. (1.95 m^2) is obtained. This is the equivalent of a spherical void 31 in. (78.7 cm) in dia, a 39- by 39-in. (99 by 99 cm) propellant/propellant separation, or a 55- by 55-in. (140 by 140 cm) propellant-liner separation. The same failure mode could be initiated, however, with many smaller defects in different locations. Thus, the effect of a single, large 31-in.- (78.7 cm) dia void in causing a 1% pressure increase could be duplicated by 106 small 3-in.- (7.6 cm) dia voids, or 958 one-inch- (2.5 cm) diameter voids. However, to cause a sudden pressure increase, all of the voids would have to be exposed at the same time, which is extremely unlikely. Additionally, a calculation was performed similar to that used in the case burnthrough failure mode to determine which burning surface increase above the nominal maximum during the firing would result in a failure rate of 10^{-6} . For a failure mode of longitudinal weld hoop stress rupture, an increase of 15,000-sq in. (9.68 m^2) was obtained, indicating the 3010-sq in. (1.95 m^2) value is conservative. A 2 to 3% pressure increase at the time of maximum pressure could actually be tolerated before the case rupture probability was increased to more than 10^{-6} .

IV. Failure Mode Analysis (cont)

D. GRAIN STRUCTURAL FAILURE

1. Failure Mode Identification and Criteria

The failure mode of grain structural failure is envisioned as one where a grain defect propagates in a crack or rupture to the extent that either case burnthrough occurs or the chamber pressure from the increased burning surface rises to an unacceptable extent. Along with the previous sections of the analysis, the failure criteria would, therefore, be either a 10^{-3} probability of insulation burnthrough prior to the end of action time or a 1% sudden chamber pressure increase.

2. Sequence of Failure

The sequence of failure involves a void or grain defect at, or relatively close to, the inner bore surface. Because of the stress concentration factor a local crack is initiated. If this crack propagates, either a case burnthrough or an unacceptable pressure increase occurs.

3. Defect Limit Characterization

Preliminary stress analysis indicates that unlike the other failure modes, the smaller the defect size, the higher the chance of the failure mode initiating. A study of a 52-in.-(132 cm) dia grain with a 5-in.-(12.7 cm) dia cylindrical bore indicated that a spherical void 0.50 in. (1.27 cm) dia near the bore surface could produce a strain concentration factor as high as 4.15, while an increase of the void diameter to 0.75 in. (1.90 cm) would reduce the strain concentration factor to 3.48. To evaluate the probability of such a void initiating a crack, the following modification of the R/C formula was used:

$$\phi = \frac{\bar{X}_C - K\bar{X}_R}{\sqrt{s_C^2 + s_R^2}}$$

IV.D. Grain Structural Failure (cont)

where $\bar{X}_C$ = average propellant strain capability, percent
 s_C = standard deviation of propellant strain capability, percent
 $\bar{X}_R$ = average propellant requirement, percent
 s_R = standard deviation of propellant requirement, percent
 K = strain concentration factor due to voids
 Φ = number of pooled standard deviates between $\bar{X}_C$ and $\bar{X}_R$
(which can be converted into the probability of R exceeding C)

In a previous reliability study, it was determined that the probability of the strain requirement exceeding the propellant capability was $10^{-6.9}$ for storage conditions and $10^{-7.4}$ for flight conditions. With a strain concentration factor of 4.15, these probabilities were increased significantly to 0.0129 for storage conditions and 0.0197 for flight. Since these values were unacceptably low, it appeared at first that the minimum void size requirement that must be detected would be extremely small, i.e., less than 0.50 in. (1.27 cm) in diameter. However, further investigations revealed that although local cracks might be initiated by small voids or defects caused by increased strain concentration factors, these cracks will not propagate unless the remaining grain cross section is at or near the point of failure. A conditional probability situation exists where the probability of crack propagation through the grain to a critical extent is the product of the probability of crack initiation due to void stress concentration times the probability of the grain failing without a void existing.

Because the product of $10^{-6.9}$ and 0.0197 will be even less than $10^{-6.9}$, it would appear that the probability of small defects causing motor failure due to burnthrough or pressure increase is negligible and that a minimum NDT defect size should not be established for the grain structural failure mode.

IV. Failure Mode Analysis (cont)

E. CONCLUSIONS

The analysis of the minimum size of defect capable of initiating the four major failure modes (case burnthrough, 1% pressure increase, propellant ejection, and grain structural failure) indicates that as a minimum, an NDT technique capable of detecting a 4.1-in. (10.4 cm) void, propellant/propellant separation, and propellant-liner separations must be developed for the proposed 260-in.- (6.6 m) dia motor. This dimension is on the basis of minimum size of a single defect acting alone that could result in the failure criteria being exceeded.

For the configuration analyzed and the failure criteria specified or adapted, it appeared that the case burnthrough failure mode was more critical than any of the others in that it required smaller size defects to initiate (Figure 5). However, it is important to realize that once the threshold capability of a particular NDT method is known, the same techniques used to determine the minimum defect size that must be detected to prevent burnthrough for a specified thickness of insulation can be used to determine the required thickness of insulation. Thus, if an NDT method was selected that could only detect a 10-in.- (2.5 cm) dia void, it would be possible to determine either (a) how much the insulation thickness or other design parameters would have to be changed to meet the established failure probability criteria, or (b) how much the failure probability would be increased in excess of the established criteria.

V. EXPERIMENTAL EVALUATION PROGRAM

During the evaluation of the microwave, radiographic, and ultrasonic inspection techniques selected in the capability survey it became apparent that there was no real element of competition in the evaluation, except to determine if any three methods used in combination would prove adequate.

V. Experimental Evaluation Program (cont)

It was not possible of course to have either a full-scale motor or even a good prototype inspection facility. Despite the limitations of not testing the desired inspection equipment, it was possible to determine many of the necessary requirements with available equipment. The experiments to be described in this section are comparable to the failure mode analysis presented in the previous section. The experimental results can establish guidelines for the design and establishment of an inspection system, and will enable the determination of the desired balance between reliance on detection of flaws and designing in tolerance to flaws.

A. DEFECT SPECIMENS

The defect specimen (Figures 6 and 7) represents 6 ft (1.8 m) of the motor axially and 30 degrees (0.52 radian) circumferentially. Actually, it is a right prism whose base is 30 degree (0.52 radian) of the cross section at the forward equator and is slightly different from a section extending 3 ft (0.91 m) on either side of the equator. A construction error led to the case-to-fin-point dimension being 3-in. (7.62 cm) longer than in the motor. As a result, and because of some problems in casting, the mold was actually 6-in. (15.24 cm) short of complete fill so that the specimen is actually 67-in. (170 cm) high and not 72 in. (183 cm). Otherwise the specimen is as shown in the drawings.

V. Experimental Evaluation Program (cont)

B. HIGH ENERGY RADIOGRAPHY

For the purposes of this discussion no distinction is made between X-rays and gamma-rays. Source characteristics are mentioned where significant; otherwise, the origin of the radiation is of no importance, and the distinction between X-rays and gamma-rays is artificial in the present context. In general, the thick sections of propellant to be penetrated require photon energies in excess of those obtainable with isotope sources, so that accelerator-type sources such as the linac are required, although Co60 radiation was used for several experiments.

The experiments are divided into two categories, those using film and those using non-film detectors. The non-film technique utilizes detectors which did not produce images. There are non-film imaging detectors, but those available do not have the demonstrated capability for high-energy radiation required for 260-in. motor inspection.

The relative merits of film and non-film detection are discussed briefly in the following paragraphs.

1. Detection Considerations

a. Integration

High energy electromagnetic waves, unlike coherent micro-waves, show conspicuous quantum effects. In practice this simply means that the energy distribution in the radiation field does not precisely follow the pattern calculated from electromagnetic theory. The calculated pattern gives the average distribution over a long interval; thus, information cannot be obtained from an instantaneous field measurement. In experimental terms,

V.B. High Energy Radiography (cont)

microwave measurements can be instantaneous insofar as instrument limitations allow. With high energy waves (X- or gamma-rays), the limitation is fundamental. All detectors for high energy radiation are similar to photon counters even if, like film, they do not display digital information. The detector must be exposed long enough for many photons to be recorded, otherwise statistical fluctuations will be large compared to the variations which constitute data. This is not a limitation of the equipment but is a fundamental feature of high energy radiation and depends entirely on the count rate. All detectors in common use for NDT have adequate integration capability. Therefore, the time required for an exposure or a data point depends on detection efficiency.

b. Detection Efficiency

High energy radiation is useful because of its capability to penetrate matter. Unfortunately high energy radiation penetrates detectors as well as specimen. Radiation that passes through the detector is not recorded. Thus an efficient detector must be a good absorber, and must be dense and thick. The use of large scintillation crystals is advantageous because they have more mass than a film (even with lead screens) or a gas-filled counter.

c. Dynamic Range

The capability of detectors to record high count rates and low count rates varies. The use of film is advantageous within wide limits. A given dose of radiation produces the same effect regardless of the rate when film is used for detection. Other detectors, such as photon counters, have a dead time after a count is registered during which a second count cannot be registered. A current mode of operation is possible with scintillation counters. Rather than integrating only the current produced by absorption of one photon and recording it as one count, it is possible to register the average current.

V.B. High Energy Radiography (cont)

Some modifications are required so that the detector does not saturate, however, the result is a mode of operation more analogous to that of film. This is important with a radiation source such as a linac which produces photons in brief but intense bursts. In general, some of the sensitivity of a scintillation counter is sacrificed when it is adapted for very high instantaneous dose rates.

d. Energy Discrimination

Some of the primary beam attenuation is total absorption or large-angle scatter which prevents the photon from reaching the detector. Much of the attenuation, however, is by processes which enable a photon of reduced energy to reach the detector, generally by an indirect path. Since only the direct path radiation is information, energy discrimination can be useful. Scintillation detectors in the discrete counting mode, and several other types of proportional counters, also operate in a similar manner. Energy discrimination is not possible to any significant extent with film or other imaging systems.

e. Directional Sensitivity

Some of the radiation reaching the detector is scatter which does not arrive at the detector from the direction of the source. Since there is no lens for X-rays it is not possible to discriminate on the basis of direction when an imaging system is used. Non-imaging detectors, such as scintillation counters, can be collimated by surrounding them with a lead shield with a small hole or slit.

f. Resolution

Film resolution is determined by the grain structure of the emulsion, or by the source size and the geometry of the exposure, usually by the latter. With non-film image systems there is usually a scanning involved

V.B. High Energy Radiography (cont)

which can set the resolution limit. In the case of relatively large non-image detectors such as scintillation counters, collimation determines resolution. The finer the collimation the more difficult the alignment. It is not possible in practice to collimate precisely enough to approach the resolution of film even if the scans are very closely spaced.

2. Source Considerations

Isotope and acceleration are the two basic types of radiation sources. The former produces gamma-rays of discrete energy from transitions between excited states of nuclei produced in the decay of radioisotopes. The photon energies obtainable are usually being below 1 mev (1.6×10^{-13} j). The accelerator sources strike a target with a beam of high-speed electrons, and their output is the continuous distribution of bremsstrahlung radiation from the slowing of the electrons. Discrete vs continuous energy distribution is thus the fundamental difference and the fact that isotope sources produce relatively low photon energies.

In practice, several other features are important. First, with isotope sources, the source cannot be turned off, thus requiring a bulky shield and shutter mechanism with safety devices. Also, once the photon energy is fixed, penetration is increased by going to higher R (rad) output (more photons), and this means a physically large source in the case of radioisotopes. Resolution is adversely affected, since ideally the source should be a point. Since focussing with lenses and reflectors is not possible with high energy radiation, collimation must be used. Thus much of the beam is wasted which restricts the minimum source spot obtainable. On the other hand, the beam angle can be as wide as desired since the radiation is isotropic.

With accelerator sources, the source spot can be made quite small, even for very high R output, and the source is harmless when turned off. Therefore, the radiation can be delivered from a very compact target assembly.

V.B. High Energy Radiography (cont)

A disadvantage in the use of accelerators is limitation of the narrow beam angle. Isotope radiation is emitted from a nucleus at rest and is isotropic. The emitting system in an accelerator is a fixed target nucleus and a moving electron, i.e., a system with moving center of mass. The radiation is emitted in a moving coordinate system and detected in a fixed coordinate. The result is that in the fixed laboratory, the radiation is confined to a cone in the forward direction. The higher the photon energy, the higher the electron-beam speed, and hence the narrower the beam. This can be modified only by moving the target at speeds comparable to those of the electrons, and presents a limitation because a stationary target must be used.

Considering the available sources, it is quite apparent that a linac is the accelerator source most desirable. The Van deGraaff generator and the betatron are also commonly used, although the linac currently dominates the market for high energy high output machines. At energies/outputs obtainable with all three machines the only differences would be that the linac can be more compact, while the Van deGraaff is not pulsed as are the other two. Pulsed operation places more severe demands on non-film detectors because of the higher instantaneous count rates for a given total dose.

On the basis of previous rocket motor experience, the use of isotope sources appears to be impractical because there are no 10 to 30 mev ($1.6 \text{ by } 10^{-12} - 4.8 \text{ by } 10^{-12} \text{ j}$) gamma-ray emitters available, and it is known that high energies are needed for deep penetration in propellant. However, experiments were conducted with a Co60 source to determine the feasibility of isotope sources because some experimental data can be obtained which are independent of the source used.

V.B. High Energy Radiography (cont)

3. Experimental Program

The experiments using the fin specimen and propellant slabs were designed to provide the information needed to estimate the performance of various inspection systems. Because of the numerous combinations of geometry, detector, and radiation source which are possible, no attempt was made to actually test all combinations.

The radiation sources used were a 900 curie (3.33×10^{13} disintegrations/sec) Co60 source, and a 10 mev (1.6×10^{-12} j), 500 R (5j/kg) linac. In addition to the customary film types, scintillation counters in both the discrete counting and current modes were tested. From these results it is possible to select the most satisfactory inspection techniques.

a. Film Radiography

The first experiment described was conducted on conventional film radiography. The Aerojet linac of nominal 10 mev (1.6×10^{-12} j), 500 R (5j/kg)/m at one meter was used and exposures were made of the fin specimen. The results showed voids of various sizes through sections up to 65 in. (165.1 cm) of propellant. Three additional 8-in.- (20.3 cm) thick slabs of propellant were utilized to reduce edge effects and to closely simulate scattering geometry of a motor. The test arrangement is shown in Figure 8. Figure 9 shows the exposures made with the pertinent data such as penetrameters, cassette loading, etc. The results are summarized in Figure 10. Two-inch (5.1 cm) voids were visible through 65 in. (165.1 cm) of propellant. Additionally, voids smaller than 2 in. were detected on some of the films. The full 88-in. (223.5 cm) thickness of the 260-in. grain cylinder section was not available in the specimen. The 10 mev (1.6×10^{-12} j) linac is inadequate for the full thickness, but verified actual void detection and provides a firm basis for extrapolation. For this purpose, some additional data were taken. The following calculations were made by Applied Radiation Company (ARCO) Walnut Creek, California, from the Aerojet data and characteristics of available linacs.

V.B. High Energy Radiography (cont)

(1) Determination of Half-Value Layer (H.V.L.)

On the basis of the experiments with both the fin specimen and a stack of 8-in.-(20.3 cm) thick propellant slabs it is concluded that the nominally 10 mev ($1.6 \text{ by } 10^{-12}$) linac is operating at about 8 mev ($1.28 \text{ by } 10^{-12}$ j) and that the H.V.L. is 6 in. (16.2 cm). Determination of the H.V.L. was more difficult than originally believed. Since absorption coefficients depend on energy, and the linac output is far from mono-energetic, there is a "hardening" of the beam as it passes through thick sections which absorbs some of the low energy components. Also, a large portion of the film density is caused by scatter so that H.V.L. measurements cannot be made under conditions that differ too much from those of the actual inspection.

(2) Radiographic Quality

The radiographs of the fin specimen show both voids and penetrameter images. ARCO calculates that the images lead to a sensitivity of 0.27% on the basis of a 2T hole penetrameter according to ASTM E-142, and a contrast sensitivity of 0.39%. Although no sensitivity calculation from penetrameters is entirely satisfactory a sensitivity of 0.77% (contrast), 0.54% (ASTM E-142) was measured for actual voids on these films.

(3) Extrapolation

The good quality with 11 H.V.L. is consistent with the general rule that deterioration from good to marginal occurs from the eleventh to the thirteenth H.V.L. All evidence indicates that from 8 to 30 mev ($1.28 \text{ by } 10^{-12}$ to $4.8 \text{ by } 10^{-12}$ j), quality is not as dependent on energy. Thus, since increasing energy inceases the H.V.L., the 11 H.V.L. limit will represent a greater thickness of propellant. Therefore, performance at 65 in. (165.5 cm) and 8 mev ($1.28 \text{ by } 10^{-12}$ j) is a firm basis for extrapolation starting from the following experimentally established data for the 260-in. propellant.

V.B. High Energy Radiography (cont)

(a) Half-value layer 6 in. (15.2 cm) and 8 mev
($1.28 \text{ by } 10^{-12} \text{ j}$)

(b) Sensitivity 0.54% ASTM E-142 through 65 in.
(165.1 cm)

(c) Target-film distance (TFD) 15 ft (4.6 in.)
minimum

(d) Required dose rate (R) vs thickness (Figure 11)

In addition, the latest experiments are consistent with previous data which extend into the range above 10 mev ($1.6 \text{ by } 10^{-12} \text{ j}$) thus it is possible to extrapolate with some confidence.

According to ARCO, a conservative basis for adequate radiograph quality would be 11 H.V.L. for good quality and 13 H.V.L. for marginal quality. Figure 12 shows the penetration capabilities and beam angles of some available linear accelerators. The 25 or 30 mev ($4.00 \text{ by } 10^{-12}$ or $4.8 \text{ by } 10^{-12}$) machine will have 11 H.V.L. or less in 88 in. (223.5 cm) of propellant and will give adequate penetration with quality comparable to that demonstrated with 65 in. (165.1 cm) propellant, although some deterioration might be expected.

(4) Film Enhancement

Selected radiographs were subjected to a color enhancement process by Aeronutronics. These radiographs, shown in Appendix E, showed images of voids and of penetrameters through propellant thicknesses up to 64 in. (162.6 cm). The radiographs were examined by several experienced radiographic technicians, and the unanimous opinion was that detail was lost. The voids

V.B. High Energy Radiography (cont)

were made more conspicuous, although all of the defects would have been detected on the original radiographs. Considering that a further quality control problem is introduced by the color enhancement processing, it is doubtful if the enhancement would be worthwhile. Flaw images most often escape notice through human error and it is difficult for the most careful technician to completely scan all of the film. However, it does not appear to be beneficial to introduce another sequence of film processes because no data are available concerning the reliability of the process in high production. Final decisions would still have to be made from the originals. An adequate number of trained radiographic technicians and frequent rest periods appear to be the more satisfactory solution.

(5) Defect Detection Capability for 260-in. Grain

The extrapolation indicates that for a linac of 11 mev ($1.76 \text{ by } 10^{-12} \text{ j}$) or higher the maximum thickness of 88 in. (223.5 cm) would represent less than 13 H.V.L. and hence the limit of detectability for a spherical void would, in practice, be between 2 in. (5.1 cm) and 4 in. (10.2 cm) at the worst. A linac in the 25 to 30 mev ($4.0 \text{ by } 10^{-12} \text{ to } 4.8 \text{ by } 10^{-12} \text{ j}$) range should give quality as good as, or better than the quality obtained through 65 in. (165.1 cm) at 8 mev ($1.28 \text{ by } 10^{-12} \text{ j}$).

(6) Sections of Varying Thickness

After establishing the fundamental detection capability the question remains if great thickness variations can be allowed within the region examined at a single exposure. As indicated in Figure 9, the cassettes were multiply loaded. The use of film of different speeds allows some compensation for the over exposure of film behind thinner parts of the fin. It is considered reasonable to expect variations of 2 to 3 H.V.L. to be adequately compensated by this customary procedure.

V.B. High Energy Radiography (cont)

Study of the films indicates that variations of 2 H.V.L. are readily accommodated. While 3 H.V.L. variations were not actually included on any of the films, data strongly indicate that 3 H.V.L. is the highest upper limit that can be safely assumed. Therefore, thickness variations will be a very serious problem in the fin section of the motor.

b. Non-Film Radiography

The non-film radiography technique utilized is an extension of the gamma scintillation methods used to inspect Polaris A1 and A2 motors. The advantage of non-film radiography over film radiography for the Polaris motors was one of speed, although the technique is based on scanning, the detectors can be more efficient than film, and can discriminate against scatter to a significant extent.

The radiation sources were a 900 curie (3.33×10^{13} disintegrations/sec) Co60 source and the 10 mev (1.6×10^{-12} j), 500 R (5 j/kg)/m/m (actually 8 mev (1.28×10^{-12} j)) linac. Detectors were the conventional integral NaI/photomultiplier scintillation detectors using a 2 by 2 in. (5.1 by 5.1 cm) crystal.

The detectors were used with both counting and current-measuring registers. Since the object was to determine only the basic flaw detection capability, the use of actual scanning fixtures was prohibitively expensive. Fortunately, it is possible to leave source, detector, and specimen fixed, and scan a void. Actually, if an antvoid consisting of a ball of propellant, as shown in Figure 13, is used the antvoid can be in one of two positions between source and specimen (SVS) or between specimen and detector (SVD). The antvoid is slightly more difficult to detect than a void.

V.B. High Energy Radiography (cont)

(1) Co60 Source

With a 900 curie (3.33×10^{13} disintegrations/sec) Co60 source and the detector surrounded by a 5-in. (12.7 cm) thick layer of lead having a 1 by 1/8-in. (25.4 by 3.18 mm) slit, the capability to detect anti-voids was tested. Both pulse-counting and current-measuring techniques were used.

With pulse-counting, experiments were performed using total thicknesses of 34-in. (86.4 cm) and 65-in. (165.1 cm) of propellant. A 2-in. (5.1 cm) void can be readily detected using the 900 curie (3.33×10^{13} disintegrations/sec) source through 34-in. (86.4 cm), and through 65-in. (165.1 cm). the 2-in. (5.1 cm) void was visible with some difficulty, although the 4-in. (10.2 cm) void was conspicuous.

Both 2-in. (5.1 cm) and 4-in. (10.2 cm) voids could be detected using the current-measuring system through 34 in. (86.4 cm) of propellant; the current-measuring instrument was not sensitive enough to measure the photo-multiplier current through 65 in. (165.1 cm) of propellant.

The significant results are shown in Figure 14. I/I_0 is the ratio of count rates through a void to that through unflawed propellant, or the similar ratio of currents. When an antivoid is used, I is the count rate without the antivoid so that no ratio should be smaller than 1 and all should increase to indicate a flaw.

The first two measurements of Figure 14 show the effect of voids in the specimen. This required moving the entire specimen on rollers, and was so inconvenient that antivoids were used for the remaining experiments. Except for the current measurement through 65 in. (165.1 cm) of propellant, the voids are detectable ($I/I_0 > 1$).

V.B. High Energy Radiography (cont)

Co60 provides limited penetration. It is estimated from the preceding results that a 50,000 curie (1.85×10^{15} disintegrations/sec) Co60 source would be needed to detect a 4-in. (10.2 cm) void through 88 in. (223.5 cm) of propellant. Such a source is impractically large, so that the possibility of using a linac must be investigated. Counting is not feasible with the pulsed linac, but the Co60 experiments suggest that the loss of sensitivity involved in changing to current-mode detection will be offset by the greater penetration with the linac.

(2) Scintillation Detectors with a Linac Source

The results of the antivoid tests with the Co60 source through 65 in. (165.1 cm) of propellant were poor. Better results were obtained with the linac. The technique was the same as with the Co60 antivoid experiments except that the linac was used, and no attempt at pulse counting was made. The linac does not emit X-rays continuously, but is pulsed so that the X-rays are emitted only during a brief interval. As a result the counting circuits used with scintillation detectors may be saturated and become unable to detect changes since several simultaneous X-rays detected may be counted as one. If the current from the detector is measured instead of counting, this problem is largely eliminated, although the Co60 experiments show that current-mode operation is slightly less sensitive. The results of the tests are shown in Figure 15.

Figure 16 shows some recordings of antivoid scans. Test 1 was made with the void moving at 6 in./sec (15.24 cm/sec); the others at a speed of 2.5 in./sec (6.35 cm/sec).

Most of the baseline fluctuations are caused by instability of the linac output. The Aerojet linac is relatively old, and is not particularly stable. Although this output instability is not a problem in film radiography, it is a problem in work with scintillation detectors.

V.B. High Energy Radiography (cont)

Fortunately, contemporary linacs appear to be stable to $\pm 1\%$. ARCO is of the opinion that the ARCO linear accelerators can be made more stable, if necessary, possibly to $\pm 1/4\%$. An output stabilized to $\pm 1\%$, however, would probably be adequate.

4. Comparison with Other Techniques

The combination of film and non-film radiography is superior to any other technique evaluated for detecting grain-body defects, and is the only technique with a demonstrated capability to penetrate as much as 65 in. (165.1 cm) of propellant with good resolution. The extrapolation to 88 in. (223.5 cm) is regarded as quite reliable so that radiography must be regarded as the method of choice. Existing problems are the fin section and flaw orientation. Thickness variations in the fin section exceed the 3 H.V.L. or less per exposure required for good quality on film. Scintillation scanning methods are even less satisfactory in the fin section. Additionally, certain orientations for flat voids are often very difficult for any radiographic technique.

Finally, it does not seem probable that radiography can be effective in examining much of the insulation-propellant bond. The large radius of curvature and the roughness of the surface of the trowelled insulation make tangential radiography very marginal at best, although possibly useful for the boot region. Ultrasonic inspection can be used for most of the motor.

C. THROUGH-TRANSMISSION ULTRASONIC INSPECTION FOR INSULATION-PROPELLANT SEPARATIONS

The through-transmission ultrasonic technique appears to be the only feasible method of inspecting for insulation-propellant separations. Contact pulse-echo inspection is usable for evaluating the case-insulation bond, but does

V.C. Through-Transmission Ultrasonic Inspection for Insulation-
Propellant Separations (cont)

not penetrate the insulation well. Microwaves are not suited for examining bonds through such great propellant thickness since they do not penetrate the steel case, and tangential radiography would be extremely difficult on a motor of this size.

1. Evaluation

Since a Krautkramer USIP-10-W instrument could be rented for the test and was similar to the instrument desired for actual use, the evaluation was a straightforward through-transmission inspection of the propellant fin specimen. The specimen had two built-in insulation-propellant separations produced by withdrawing shims, and one "contact unbond" produced by applying a patch of release agent to the insulation before casting the specimen. One transducer was fixed to the propellant and the other scanned the case. One placement of the fixed transducer was sufficient for the 6 by 6 ft (1.8 by 1.8 m) area of case represented by the specimen. The two insulation-propellant separations were detected. The "contact" unbond area apparently did not release, and hence was not detected.

It should be possible to adapt the technique to actual inspection of a 260-in. motor with good results. The technique is considered the basis for a practical inspection, and should lend itself to automatic scanning of 6 by 6 ft (1.8 by 1.8 m) areas on the outer surface of the motor.

V.C. Through-Transmission Ultrasonic Inspection for Insulation-Propellant Separations (cont)

2. Details of Technique

The technique involves transmitting a signal from the outside of the motor through the case, insulation, and propellant to a point on the inner surface of the grain. The inner transducer is usually held fixed while the outer one is moved. Either transducer can be the receiver, although the scanning transducer is normally used as the transmitter, since moving the transducer produces noise which would be large in comparison to the weak received signals, but is negligible compared with the transmitted signal.

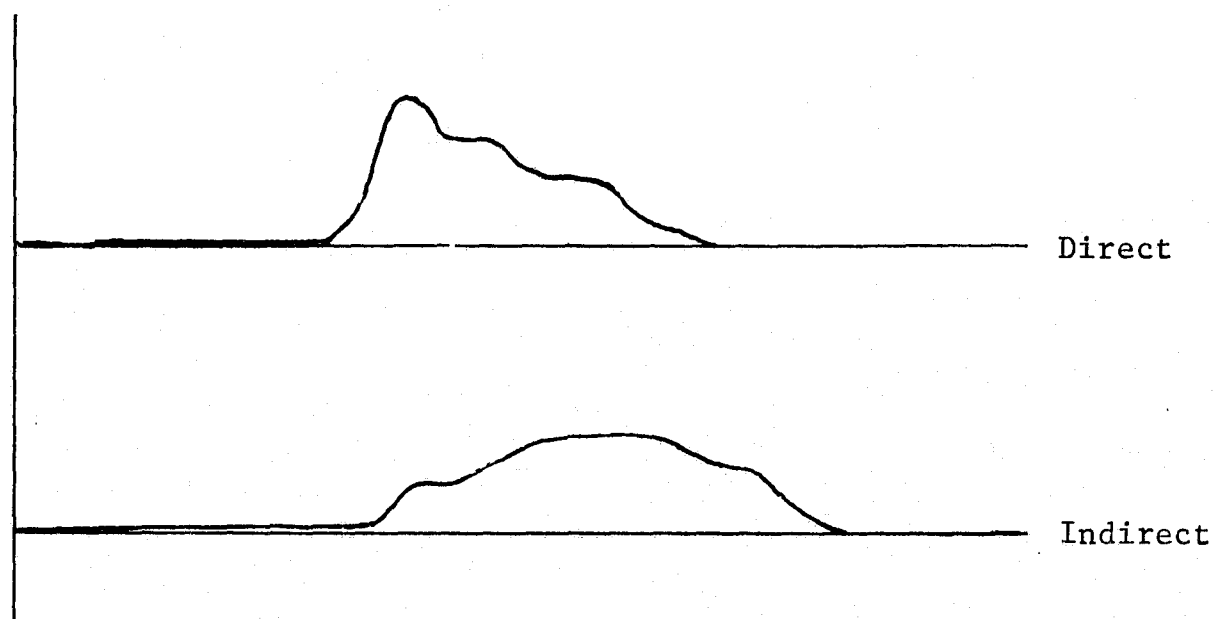
Basically, a defect is indicated by a loss of transmitted signal. Except for one complication, a continuous signal could be used and the circuit would be very sensitive and not complex. The complication is two-fold: first, for adequate penetration, low frequency is mandatory; about 50 KHz is best. This means that beam definition is poor and the effects of diffraction are severe. The second complication is that the steel case acts as a waveguide, propagating sound around it by multiple reflections. The problem is illustrated in Figure 17.

The signal propagated through the separation is weak or undetectable; however, the signal propagated around the separation through the case is quite strong. The indirect signal is delayed in time so that by using a pulse, direct and indirect signals are distinguishable. Problems in distinguishing indirect signals by these methods occur (Figure 17) because scanning will cause changes in the distance between transducers unless the transducer on the inside moves in a complicated way.

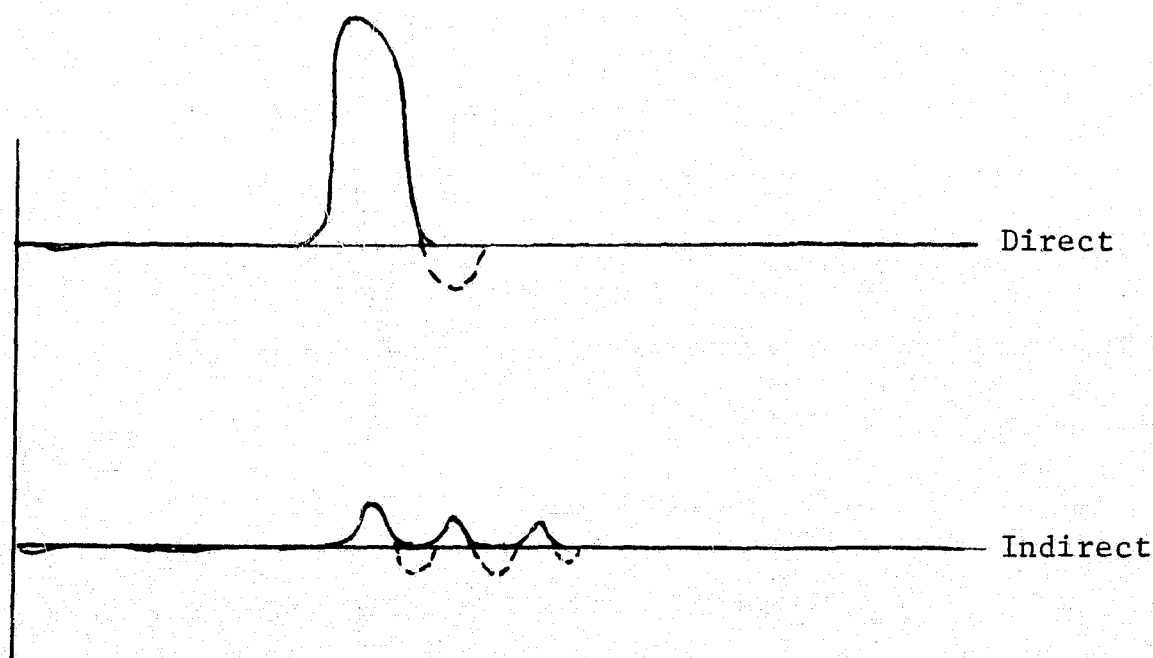
A second discrimination technique is available. Figure 18 shows propagation around a flaw in a full three-dimensional view. When all of the indirect paths are summed, the resultant signal, although eventually reaching

V.C. Through-Transmission Ultrasonic Inspection for Insulation-
Propellant Separations (cont)

nearly the same amplitude as the missing direct path signal, is marked by a much longer rise time, as well as a greater delay. The signals shown in Figure 18 are rectified 50 KHz signals, usually displayed as raw signals in ultrasonics. Typical de-modulated signals (envelopes) are shown in the following sketch.



The sharper rise of the direct signal can be distinguished from the indirect signal by differentiation, filtering, and clipping.



V.C. Through-Transmission Ultrasonic Inspection for Insulation-
Propellant Separations (cont)

Figure 19 shows a comparison of the two methods. Figure 19 is qualitative only, but has been quantitatively verified under Contract NAS7-367.

The amplitude curves of Figure 19 show an increase in the separated/bonded change if the signals are processed to discriminate against slow-rising signals. The delay time curve shows a slow change on the bonded area due to changes in the distance between receivers for direct-path transmission. When the transducers are separated by an unbonded region, the direct-path delay (dashed line) is not observed, rather a more or less linear increase in delay is seen resulting from the propagation along the case which is a linear function of C , and increases more rapidly with C than the sound speed would suggest because of the multiple refractions in the case. To utilize the delay, the signals are passed through a gate circuit which records only those signals arriving within a predetermined span of time. Of course, time delay, rise time, and amplitude discrimination can be combined. The results can be estimated from Figures 20 and 21. Figure 20 shows delay time obtained by scanning over a separation. The specimen was a 48- by 52- by 26-in. (121.9 by 132.1 by 66.0 cm) cube of propellant with flat steel and insulation on one 24- by 42-in. (61.0 by 106.7 cm) face. If, for example, a 40 μ sec gate were used, and a line is drawn horizontally across Figure 20 at the 40 μ sec level, it intersects the curve at +18-in. (45.7 cm) and -3 in. (7.6 cm), indicating that (a) an area of about 36- by 36-in. (91.4 by 91.4 cm) can be scanned with a fixed gate of 40 μ sec duration (the gate actually opened at 870 μ sec). If scans are made over a wider area, the straight-line source/receiver distance

V.C. Through-Transmission Ultrasonic Inspection for Insulation-
Propellant Separations (cont)

will increase until the direct path signals arrive after the gate closes. Likewise, when the scanned transducer goes over a defect at the center of the area scanned, it will be 3 in. (7.6 cm) into the defect before the indirect-path signals fall beyond the gate.

Figure 21 shows the results of recording the maximum amplitude of signals falling within a 100 μ sec gate. The shaded area includes every point on six scans across the separation boundary. For example, if a line is drawn across the shaded area horizontally at 1 on the relative amplitude scale, the uncertainty can be determined in the defect boundary mapping by projecting the ends of the line across the shaded area on to the horizontal axis. In this case an uncertainty of about ± 2 in. (5.1 cm) is indicated. The data of Figures 20 and 21 were accomplished under Contract NAS7-367⁽⁴⁾. No rise-time discrimination was used. The circuit for delay gating was a breadboard arrangement, and was not reconstructed for the present work, in which it was simply verified that the received signals were similar.

In fact, the received signals through the fin specimen may be somewhat more satisfactory. The USIP-10-W appears to be somewhat better for this purpose than either the older USIP-10-NF or the Aerojet-built breadboard which were used for the NAS7-367 experiments.

Figure 22 shows USIP-10-W signals through the fin specimen and through a bonded region; the signal receiver is slightly inside the unbonded region. A and B are signals from points adjacent to the boundary of fin specimen defect BD(20)B. Here the amplitude has decreased, although the increase in delay time is not apparent because the positions are quite close when the transducer is moved well within the separation; the trace will resemble either C or D.

V.C. Through-Transmission Ultrasonic Inspection for Insulation-Propellant Separations (cont)

As indicated, the signal is quite slow to rise to maximum amplitude and will increase in several steps as the indirect-path signals arrive. With the differentiation and rise-time discrimination, the dc response would be lost and the step rise of trace C would be two spikes in sequence. The maximum amplitude recorded for the entire pulse would be that of the sharp portion of the second step, and it would rise from the baseline, not from the top of the first step. Thus, a gate wide enough to accept the entire pulse would not cause a large amplitude to be recorded.

With such wide gating, it should not be difficult to scan 30 degrees (0.52 radian) of the motor and 6 ft (1.8 m) of its length.

D. A MICROWAVE INSPECTION SYSTEM

The possibility of using microwaves to inspect the 260-in. motor grain is suggested in that the signals can penetrate to a considerable depth, and by the speed and absence of hazardous radiation which are characteristic of the technique. It is possible to use less than one watt of power, and the horn need only dwell for 0.01 to 0.1 sec at a point. Detection is electronic so that there is no delay, as in film developing. Also, microwaves are reflected from interfaces so that the optimum orientation of a crack or fold for microwave detection is complimentary to the optimum orientation for X-ray inspection, which is an attenuation measurement.

Feasibility of microwave inspection for the 260-in. solid motor grain was demonstrated under Contract NAS7-367⁽⁵⁾. Experimentally, 52-in. (132.1 cm) penetration with marginal resolution and flaw sensitivity had been achieved.

V.D. A Microwave Inspection System (cont)

Both equipment and technique have since been improved. With the more elaborate specimen provided under the present contract, it has been possible to evaluate defect detection as well as penetration.

At the time of the NAS7-367 work, 52 in. (132.1 cm) was considered as the maximum penetration required. Subsequently, this has been increased to a maximum of 88 in. (223.5 cm) with a requirement to detect voids as small as 4 in. (10.2 cm) in diameter. Microwave inspection will not presently fully meet these requirements. Some defects in the specimen were detectable to depths of about 36 in. (91.4 cm) by reflections. Very large defects might be located in the same way to a depth of perhaps 50 to 60 in. (127.0 to 152.4 cm). Flaw depth would be determined whenever a flaw appeared on the record of this inspection. A through-transmission inspection with microwaves was apparently able to detect voids 6 in. (15.2 cm) in diameter quite reliable through as much as 69 in. (175.3 cm) of propellant. Both penetration and resolution could probably be improved, although this method does not provide depth information, and more significantly, is not applicable to the critical regions of the motor.

To summarize the evaluation, it was determined that microwave inspection could be of considerable use but will not suffice by itself for grain inspection. Therefore, microwaves could be as a screening inspection to help plan radiographic exposures. This application will be discussed later in more detail.

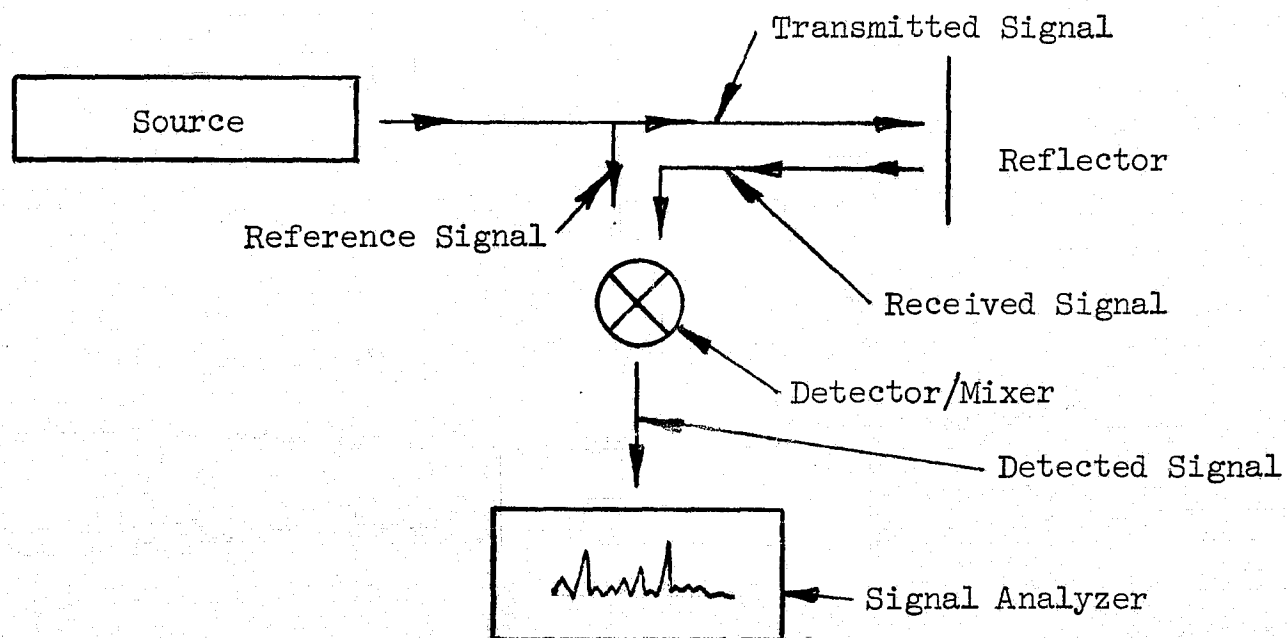
The most promising use for microwaves is the in-process inspection to examine the propellant during casting of the grain. The experiments conducted to evaluate this technique during the pouring of the fin specimen were performed with an X-band (8 to 12 GHz) system. The latest experiments with an L-band (1.3 to 2.0 GHz) coaxial system indicate that a unit small enough to use in the cylindrical section of the motor could give excellent results, detecting

V.D. A Microwave Inspection System (cont)

fairly small bubbles to a depth of 12 to 24 in. (30.5 to 60.9 cm), and large bubbles to perhaps 36-to 48-in. (91.4 to 121.9 cm) deep. The system has only been tested with cured propellant, although previous work has demonstrated that the microwave properties are very similar for cured and uncured propellant.

1. Basic Technique

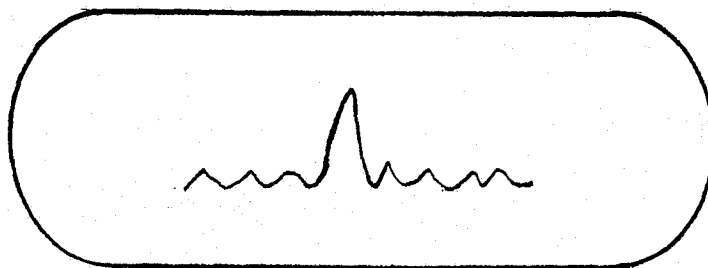
A schematic of the microwave technique is as follows:



The signal source produces a linear sweep. A sample of this signal goes straight to the detector/mixer, the rest to the reflector (specimen) and back to the detector/mixer. The detector/mixer thus receives two linear frequency sweeps one of which is delayed because of its longer path. Thus throughout each sweep they

V.D. A Microwave Inspection System (cont)

differ by a constant frequency. The detector/mixer output is then composed of one frequency component for each reflector, with the frequency being proportional to distance. To display the data, a power-vs-frequency spectrum analysis of the signal is performed. A typical display for a single reflector (note that there is a sideband structure) is as follows:



When strong reflectors are the indications of interest there is no problem; however, if weak reflections are to be detected in the presence of strong ones, sidebands are a problem. The sidebands of the strong peaks will become quite large when the signal is amplified enough to show the small peaks, and the slightest change in any of the large peaks can completely alter the trace. When a specimen is scanned, it is difficult to tell whether changes are due to the appearance of a small peak representing a flaw, or merely the result of a very slight shift in one of the large indications.

2. Waveguide Configurations

Figure 23 shows various versions of the waveguide probe.

V.D. A Microwave Inspection System (cont)

a. One-Horn Waveguide

The first waveguide system (Figure 23A) is the most compact, but displays a large front surface reflection. At the very high gain required for weak signals the sidebands of the front surface reflection are quite large. Changes in the way the horn contacts the specimen cause a greater change in reflected signal than that produced by a void deep in the specimen.

b. Two-Horn Waveguide

Figure 23B shows a two-horn version which separates the outgoing and incoming signals, and eliminates front surface reflections. The directional coupler is also superior to the tee, although it is bulkier. The tee splits any signal reaching it through one arm evenly. Thus it sends far too much of the strong reference signal to the detector, and only half of the reflection from the specimen. The directional coupler takes a sample at 10 to 30 db from the outgoing signal depending on the coupling coefficient selected. For signals in the reverse direction in the outgoing line there is a further 20 to 40 db attenuation, which is useful since reflections back down this line may result in spurious indications.

Some of the spurious indications result from reflections at the various joints and components in the waveguide system. The isolators can be positioned to absorb any signals going in the wrong direction, although at very high gain spurious signals still exist.

c. Coaxial System

Figure 23C shows the coaxial version of 23B. This is the next step in spurious signal suppression. Since coaxial cable is used instead of rigid rectangular guide, the system is more convenient and, more important, the lengths of various lines are readily changed. This is important because

V.D. A Microwave Inspection System (cont)

some of the spurious signals cannot be eliminated. The frequency at which they appear in the detector/mixer output can be altered by changes in the lengths of the various coaxial cables connecting components of the system. If these lengths are judiciously selected, the spurious signals will be far from the frequency of the actual signals in the detector/mixer output, and can be suppressed by filtering.

Figure 23C is the system used originally under NAS7-367 to demonstrate 52 in. (6.6 m)) penetration. The reflector-type antennas used were not entirely satisfactory.

d. Coaxial/Waveguide System

Figure 23D shows the latest modification in which 2.6 to 3.9 GHz horns and coaxial/waveguide transformers are used. The horns are filled with dielectric powder so that the actual frequency band is reduced to 1.3 to 2.0 GHz. Although the horns are too small for effective radiation of L-band signals into air, they perform fairly well when coupled into propellant.

3. Slowing Signal Analysis

The final technique used for improving performance is the slowing of the microwave sweep and signal analyzer. The display consisted of about 100 dots forming a reflection strength-vs-depth curve. Each dot is produced by analyzing the detector/mixer output for one microwave sweep. Previously the microwave generator was swept at 1000 sweeps/sec giving a final display sweep rate of 10/sec for the 100-dot display. This is not the speed that limits inspection speed. The present signal analyzer is a single-channel model which displays the full specimen depth in 100 successive increments, each requiring one microwave sweep. This can be done just as well with a 100-channel instrument. Duplicated circuits will readily fit onto a 4 by 5 in. (10.2 by 12.7 cm) circuit card. A single channel unit requires about 4 cards depending on layout; thus, only about 103 cards would be needed. In this case the scanning speed restriction is that the horns do not move significantly during a single microwave sweep.

V.D. A Microwave Inspection System (cont)

For the present work, the signal analyzer and microwave generator have been adjusted to sweep as slowly as 100 sweeps/sec of the microwave signal. Although this requires over one second per depth trace with a single channel, a multi-channel unit could enable the horn to move one-quarter of its width per sweep with little loss in performance. This would be a scan rate of about 200 in./sec (508.0 cm/sec), which is probably faster than is convenient from a mechanical viewpoint.

Lowering the sweep rate is desirable because it improves signal-to-noise ratio. At present, the system is still limited by spurious signal, not random noise, so that more amplification does not help. Should more spurious signal suppression be achieved, the signal/noise ratio can be lowered by another tenfold slowing and still allow 20 in./sec (50.8 cm/sec) scan rates.

4. Tape-Recorder Subtraction

It had been hoped that a tape-recorder subtraction method could be used with the slow sweep modification, but this method could not be made to work well enough for evaluation. This method will be described because it is probably feasible with the proper equipment, although this has not yet been demonstrated. Figure 24 shows the system used. The problem appeared to be getting a recorder with adequate performance since all of the recorders available perform well only for FM recording, and the signals to be recorded are above the carrier frequency of the available FM electronics.

5. Experimental Program

a. One- and Two-Horn Waveguide System (2.6 to 3.9 GHz)

Figure 25 shows the one-horn system, which must be suspended from a crane. The system weights close to 100 lb (45.4 kg) with filled horn and BWO (back wave oscillator). The two-horn version is even more cumbersome since the directional coupler adds about 30 in. (76.2 cm) in length, and

V.D. A Microwave Inspection System (cont)

another isolator would be desirable. Bench tests showed very little improvement with the two-horn version, and it proved so awkward that it was not evaluated with the specimen.

The one-horn version was used to examine various parts of the fin specimen, and was only capable of detecting voids to a depth of about 6 in. (15.2 cm). Maximum gain was not possible to use because of spurious signals, and interpretation of data was difficult. The inspection technique did not appear to be useful and was discontinued. The results of the experiment indicate that frequency domain interferometer microwave systems do not make good NDT instruments in the larger waveguide sizes. One problem is that the depth-of-field is limited in any rectangular-guide system because of the dispersion inherent in this type of guide. Different frequencies travel at different speeds in the guide, and microwave sweep linearity can be adjusted to compensate for this difference at only one range setting and for one length of waveguide. Since the large, low-frequency guide is only used for large specimens, this problem is more severe than in previous work where K, Ka, and Ku-band systems were used with small specimens.

The waveguide systems were not tested with the slowed signal analysis since the slowing was performed after they had been rejected. Slowing the signal analysis did not indicate enough improvement to make these systems practical.

b. Hybrid Coaxial/Waveguide, Two-Horn 1.3 to 2.0 GHz System

The hybrid waveguide/coaxial system, in contrast to the waveguide systems, demonstrated penetration capability. Under Contract NAS7-367, fifty-two-inch (132.1 cm) penetration had been demonstrated, although with marginal sensitivity to defects. At that time it was predicted that 52-in. (132.1 cm)

V.D. A Microwave Inspection System (cont)

penetration with usable void sensitivity could be developed, and on that basis microwave NDT work continued under Contract NAS7-544. In the present project, 88-in. (223.5 cm) penetration is required for microwave inspection to be sufficient.

(1) Comparison to NAS7-367 Results

The first experimental step was to compare the results obtainable using the hybrid coaxial/waveguide system and slowed signal analysis with those of the NAS7-367 effort. This was done using the NAS7-367 propellant block. Figure 26 shows the original results. The traces shown are with and without a metallic reflector behind the propellant block. Position A is the location of the indication calculated from the propellant refractive index; Position B is the point of maximum deviation. As indicated, the difference is small compared to the spurious signal peaks in this portion of the trace. Even with a metal reflector the back surface cannot be recognized, although superimposing traces with and without it result in a change.

Figure 27 shows the same experiment repeated with the latest hybrid system. When a metallic reflector is present at the back surface, the reflection is large enough for visual recognition on a single trace. The spurious signal peaks are then smaller than the peak representing the metallic reflector.

The capability of detecting a metallic back surface is significant. Flaws, especially spherical voids, tend to scatter microwaves isotropically so that the horn cannot receive much of the reflected/scattered signal from any one position. This makes it difficult to detect flaws by the most desirable method which is by their reflections, a method which enables their depth to be determined. When a void comes between the reflector and horn with a metallic reflector positioned behind the void, the defect, although not detectable by its

V.D. A Microwave Inspection System (cont)

reflection, can be identified by the disappearance of the peak indicating the metallic reflector. If the full grain thickness could be penetrated, the case reflection could be used in this manner. The metallic reflection peak in Figure 27 is large and conspicuous enough to be useful for this type of inspection. Although depth information would be lacking, such an inspection system could be fairly sensitive and fast.

Experiments reported in the NAS7-544 final report show that when the beam strikes a plane reflector, an area of about one-half the dimension of the horn actually returns the signal to it if the reflector distance is large compared to the horn dimensions. Thus with the horns presently used, the effective target is about 3 by 4 in. (7.6 by 10.2 cm). If a 50% reduction in the reflector peak is accepted as indication of a void between horn and reflector, the cross-sectional area would have to be about 50% of the 12 in.² (77.4 cm²) area of the effective reflector. This would vary slightly with position, but detection of a 3-in.- (7.6 cm) dia void under these conditions would be a conservative estimate, assuming a good scanning system. The assumption of a 50% decrease in signal for detection is not too severe because the back surface reflection will not be extremely conspicuous through any great thickness of propellant. Through thin sections, a 10 or 20% reduction would be reasonable.

(2) Through Transmission Experiments

An attempt to extend penetration to 65 in. (165.1 cm) for detection of the back surface by inspecting through the root of the fin section was made with no success. The presence or absence of the metal reflector

V.D. A Microwave Inspection System (cont)

could not be determined. Thus the maximum penetration for effective inspection is less than 65 in. (165.1 cm); about 55 in. (139.7 cm) appears to be the most practical limit with present systems.

Figure 28B shows a through-transmission test run on the root of the fin specimen. This would not be a practical inspection except on the fin point, but does verify void detection capability with real defects. A diagonal string of voids existed in this portion of the specimen. Since the through-transmission technique lacks depth resolution and has poor lateral resolution, it was not possible to determine the response to individual voids in the string. The specimen had so many voids that inspection was confusing, however, the voids were easily detected. Figure 29 shows signals received with the horns coupled to the specimen looking through a 6-in.- (15.2 cm) dia void (A), uncoupled (B), and looking through a good region (C). The direct path signal appears at the center line of the CRT graticule and the voids are attenuate almost below the detection threshold. The traces in Figure 29 do not show maximum gain, which was limited by a signal analyzer maladjustment and later corrected, although the gain used was quite sufficient for 65 in. (165.1 cm) of propellant. The horns used are large compared to the voids, and positioning two horns on opposite sides of the specimen is difficult. Although the loss of transmitted signal occurs at the estimated position of the voids, position determination is imprecise. The indications are, however, confined to a fairly small region and are reliable evidence of flaw detection capability.

(3) Inspection of the Fin Specimen

The final experiment consisted of a more realistic flaw detection procedure. The microwave horns were positioned side-by-side (Figure 30) and an attempt was made to detect as many of the defects in the fin specimen as possible. It is not significant that the inspection was performed from a

V.D. A Microwave Inspection System (cont)

surface which would not be exposed in a motor. The inspection could readily be performed on the cylindrical surface of the aft part of the grain of a motor. The top surface of the specimen was the easiest to inspect without complex fixtures.

The horn holder was a 1/8 in. (3.18 mm) plexiglass sheet with a styrofoam slab on one side. Square holes were cut in the styrofoam to receive the horns. The holder and horns could then be moved about on the specimen without altering the relative positions of sending and receiving horns. During the process of working out the horn holder, it was determined that firm horn/specimen contact is not essential. This means that scanning can be rapid and continuous, and that filled horns are not essential. The present horns are not designed for 1 to 2 GHz and must have a filler to operate in a 1 to 2 GHz band, however, 1 to 2 GHz horns could be obtained, and would be lighter in weight than the present filled horns, although somewhat larger. For a given gain value the 1 to 2 GHz horn has twice the aperture, although a lower gain would provide equal performance if used without filler. A nominal 15 db 6 by 8 in. (15.2 by 20.3 cm) aperture horn is now used filled. A 10 db, 1 to 2 GHz horn would be only slightly larger.

(a) Results of Fin Specimen Inspection

The results of the experiment were good, although not good enough to inspect all of the motor. Flat voids up to 24-in. (61.0 cm) deep provide very strong indications so that sensitivity to a depth of about a 36 in. (91.4 cm) can be predicted with confidence. There is some evidence of detection of a flat void 50-in. (127.0 cm) deep. For a void approaching 12-sq in. (77.4 cm²) of normal surface this would be expected, since the back surface of a block is detectable at 50 in. (127.0 cm). However, a good repeatable indication of the 50-in.- (127.0 cm) deep flat void was not obtained, so that detection cannot be positively verified.

V.D. A Microwave Inspection System (cont)

No positive detection of spherical voids was achieved. There are possible indications, although these could be edge effects and indications of other adjacent flaws; resolution was also poor. The microwave beam is wide and the flaws are too close together in this specimen. Spherical voids in the wedge section of the fin specimen do not provide a very good test because they are too close to the surface. Therefore it is necessary to estimate the capability of detecting spherical voids. A 4-in. (10.2 cm) void could probably be detected at 18 in. (45.7 cm) by its reflection but not beyond 24 in. (61.0 cm). An 8-in. (20.3 cm) void could probably be detected at about 24 in. but not beyond 40 in. (101.6 cm). When through-transmission, or monitoring a back reflection is possible, and the propellant to be penetrated does not exceed 100 in. (254.0 cm), horn-to-horn 4-in. (10.2 cm) voids or larger can be detected (Figure 31). Typically, two traces are superimposed, one over the defect and one over an adjacent area that is not defective. The indication is rather complex, particularly with spherical voids; the true position of a void is the point of greatest difference, which is the front surface of the void. Multiple reflections within the void cause various false indications at greater depths so that it is difficult to make positive identification of a deep void when there are shallow voids in close proximity. Therefore, it is not precisely known, except for flat voids, what might be expected in inspecting the cylinder section of a 260-in. grain.

c. Considerations Based on Experiments

On basis of all of the experiments conducted to date, it is possible to evaluate microwave inspection of the 260-in.-(6.6 m) dia motor grain with present technology, assuming the voids in the fin specimen are essentially representative of those expected in a motor. The evaluation is summarized as follows:

V.D. A Microwave Inspection System (cont)

(1) To a depth of 24 in. (61.0 cm) it would be possible to inspect to the criteria indicated by the failure mode analysis, at least in the cylinder section. In the fin section the possibility of fitting the horns at the proper angle would have to be studied, although wedges of inert propellant and bags of dielectric powder would eliminate contour problems if the horns can be made compact.

(2) Orientation is critical for flat voids, cracks, and folds (with separation). These would be invisible if seen on edge, just opposite to the requirements of X-ray inspection.

(3) Depth information would be provided for all detectable flaws.

(4) Scan speeds up to 20 in./sec (50.8 cm/sec) are probably possible so that the response of the instrument will not be the limiting factor.

(5) It is estimated that with feasible improvements and refinements the capabilities could be extended to detect:

(a) Flat voids could be detected to a depth of 48-in. (121.9 cm) if they have 12-sq in. (77.4 sq cm) normal surface.

(b) Spherical voids could be detected to depths of 24 in. (61.0 cm) for 4-in.-(10.2 cm) dia and 36 in. (91.4 cm) for 8-in.-(20.3 cm) dia.

(6) The use of microwaves as a supplement to X-ray depends on the following:

(a) Microwave inspection could at least detect flat voids in a portion of the grain when the orientation is unfavorable for X-ray detection.

V.D. A Microwave Inspection System (cont)

(b) Microwave inspection could provide depth information on shallow flaws, thereby reducing the need for X-ray triangulation exposures.

(c) Microwave inspection could help make X-ray techniques feasible with the source inside the motor.

The problems associated with the source inside the motor is that with film, or scintillation detectors in the absence of fine collimation, image magnification makes it difficult to interpret indications for flaws near the grain I.D. Near the grain O.D. results would be quite good. If microwave inspection could locate any voids near the grain I.D., it might allow the radiographic data to be interpreted well enough for the source-inside method to be practical.

In general, it is possible that if microwave inspection could rapidly and economically provide some information in advance of X-ray inspection, the latter could be planned to give the desired results more efficiently since better results can be obtained if one of the exposures is planned with some advance knowledge of the condition of the motor.

The extent to which microwave inspection can supplement radiography will only be known, of course, when radiographic techniques have been established in more detail.

VI. QUALITY OF INSPECTION RESULTS

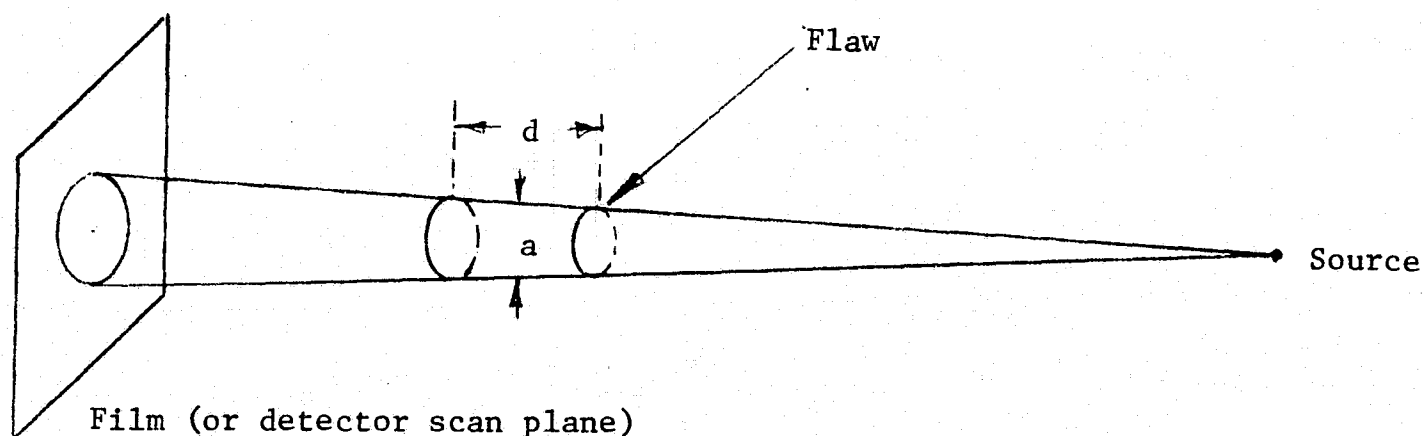
The experimental program described provided the data required for the development of an inspection system. The techniques evaluated did indicate enough flaw detection capability to permit the preliminary design of an inspection system, although the flaw detection capability was established by experiment or extrapolation from experimental results, the mechanics of inspection

VI. Quality of Inspection Results (cont)

are somewhat speculative. Interpretation of the experimental results in terms of the required inspection capability as indicated by the failure mode analysis and evaluation of the results to be expected from application of the techniques are discussed in the following paragraphs.

A. VOID DETECTABILITY CONSIDERATIONS

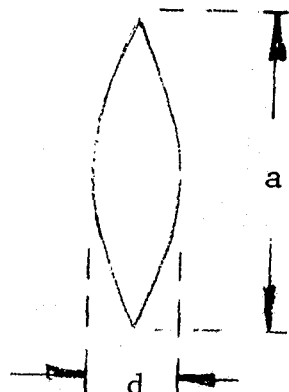
It is necessary to compare the criteria for motor failure with those for detectability for some representative flaws before considering the performance of the best available inspection method. The flaw dimension which governs detectability for each type of inspection considered must be examined; for radiography, the critical dimensions of a conical flaw are shown in the following sketch:



Dimension (d) determines detectability for a given thickness of propellant, provided (a) is large enough. There is some blurring of the flaw image so that a flaw of very small (a) might not be noticed.

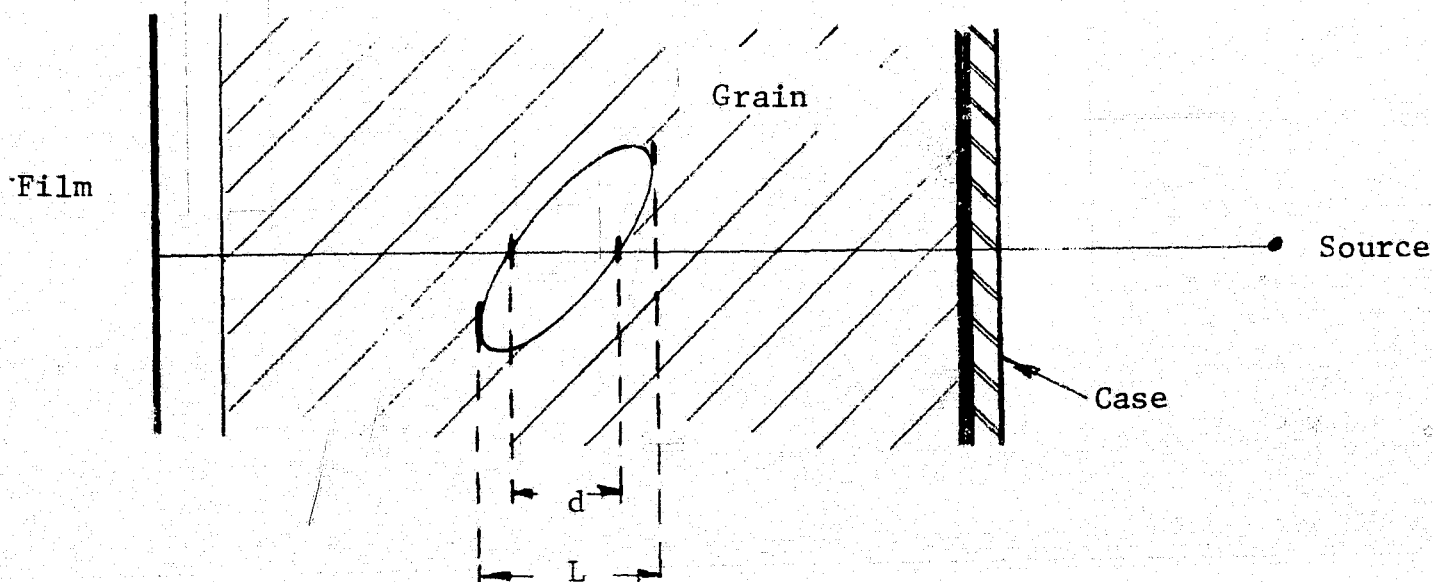
The conical shape illustrated has the sharpest image of any flaw shape and is the easiest to recognize. Detectability is assumed to refer only to the production of a certain density change on film; recognition capability is another problem. Consider the lenticular void with the following cross section, which represents the other extreme shape for a void.

VI.A. Void Detectability Considerations (cont)



If (a) and (d) for this flaw were greater than for the conical flaw the lens-shaped flaw would still be difficult to recognize because the image would have no sharp edges even though there might be a rather high density at the center of the image. Even if density measurements supplement visual examination, such a flaw image is a problem because it resembles density variations caused by uneven contact between the film and the lead screen in the cassette.

For the practical inspection of a 260-in. motor, shape and dimension (d) will be crucial. It appears that the dimension (a) will only have to be perhaps 3/4 in. (19.05 mm) or greater for a recognizable image. Obviously a spherical void, probably the most common shape in a motor grain, is intermediate between the lens and the cone in recognizability for a given (d). The 2T hole in ASTM penetrameters is very close to the cone void for any reasonable inspection geometry, and produces sharp images. The major discrepancy between detection/recognition criteria, and the acceptability criteria is as follows:



VI.A. Void Detectability Considerations (cont)

Dimension (L) determines if the flaw can cause case burnthrough while (d) determines detectability of the flaw. Obviously (L) can exceed (d) even though (d) is adequate for detection, and shape is favorable for recognition of the image. Exposures can be made with several source positions, and the location and orientation of the flaw can be determined by triangulation. This is a complex procedure, however, and the possible source positions are limited. When the thickness of propellant is near the maximum for adequate penetration, the use of any angle but straight-through will degrade image quality significantly.

Increased surface area, of importance in that it can cause pressure rise, can be deduced to some extent. A radiograph gives only a silhouette image. Density measurements enable fair estimation of thickness, but flaw orientation remains a problem unless triangulation shots can be made. When source-to-film distance is not large compared with specimen thickness, variable image magnification causes problems when the dimension (L) is large compared with source-to-film distance.

Since ultrasonic or microwave inspections might be useful for supplementary grain body data and are not expensive, they will be discussed in relation to grain void detection, although neither can be the principal inspection for such flaws.

The principal defect dimension for detection is the projection of the flaw on the detection surface for a through-transmission inspection, and the total surface area which is perpendicular to the beam (Figure 32). Actually the perpendicularity requirement is only approximate.

VI.A. Void Detectability Considerations (cont)

Both of these methods would be practical for flat defects perpendicular to the beam. In practice, the only usable through-transmission inspection is low-frequency ultrasonics. Because of severe diffraction and poor beam definition and resolution, the void in Figure 32A must be very close to the detector in comparison to its area, i.e., the method is restricted to insulation-propellant separation and to voids against or very close to the insulation/propellant interface. Both microwave and ultrasonic techniques can detect relatively thin cracks perpendicular to the beam. The thickness requirement for ultrasonics is finite separation and for microwaves probably less than a 1/4 in. (6.35 mm) separation.

B. THE OVERALL SYSTEM

The best inspection system available is one based on the through-transmission ultrasonic technique for insulation/propellant separations, and a combination of film radiography and scintillation scanning for the remainder of the grain inspection. The required radiation source for both radiographic systems is a 25 to 30 mev ($4.0 \text{ by } 10^{-12}$ to $4.8 \text{ by } 10^{-12}$ j) linear accelerator with an output of 15,000 to 20,000 R (flattened) (150 to 200 j/kg)/m/m over a field of ± 5 degrees (0.09 radians). Although expensive, the machine can be readily constructed.

Inspection is assumed to be conducted with the motor in the cast pit, thereby enabling a maximum source-to-film distance of 20 ft (6.1 m) for radial inspection. Tangential radiography is considered impractical.

While all of the details of the final inspection procedure have not been established, it is recommended that the scintillation scanning system be used as a preliminary screening inspection, with film radiography utilized to verify the condition of any regions which are considered suspect on the basis of the scintillation scanning system. Except for a portion of the star region, this method would be used for the grain.

VI.B. The Overall System (cont)

1. Inspection

For inspection purposes the motor is divided into sections: the star, star cylinder transition, and cylinder region. The cylinder region is approximately the aft 1000 in. (2540.0 cm) of the motor. The star is approximately the forward 200 in. (508.0 cm) of the motor.

a. Star Region

Results of the failure mode analysis indicate that the maximum allowable void in the star region is quite large; the case burnthrough failure mode does not establish the limit. Abrupt pressure rise failure limits the acceptable void to 31 in. (78.7 cm) in diameter for a single sphere, or an equivalent surface area in smaller voids simultaneously exposed to the flame. Thus, the smallest void which has any real probability of being involved in a potential failure is rather large.

Final conclusions have not been made as to how this region can be inspected or what results can be obtained. The problem is that the shape of the grain is such as to give very severe thickness variations on a single film. Variations of 3 H.V.L. are considered the maximum acceptable for good quality, and this variation would be exceeded. Also, large thicknesses are encountered. Figure 33 shows the best radiographic arrangement; and since the acceptance limit is not very strict in the star region this arrangement may be adequate.

Ultrasonic through-transmission will be adequate for the insulation/propellant bond inspection. Separated areas at least 4 in. (10.2 cm) in diameter should be readily detectable within the 3010 in.² (19420.5 cm²) limit calculated in the failure mode analysis even assuming the required separation area results from a rather large number of small separations. However, physical separation is necessary and, as in all rocket motors, a weak bond is not detectable.

VI.B. The Overall System (cont)

b. Star/Cylinder Transition

The star/cylinder transition is the most difficult region to inspect. The allowable single void decreases to 10.4 in. (26.4 cm) which could be included in the web or star point, and the total propellant to be penetrated increases toward 88 in. (223.5 cm) for a radial exposure. There is still enough thickness variation on a single film to cause problems. The propellant half-value layer is approximately 8 in. (20.3 cm) so that at any point where the star tips are more than 24-in.-(61.0 cm) long, radiographic quality will be a problem.

The possibility exists that wedges of plastic could be used to fill out the star at the transition to equalize the thickness. This would reduce density variations on the film, and would give adequate quality in the radiographs. Although the procedure is physically difficult, it is possible so that inspection of the transition region to the criteria indicated by the failure mode analysis may be assumed.

Ultrasonic inspection for insulation/propellant separation should be essentially the same as in the star region.

c. Cylinder Section

The principal difficulty of inspecting the cylinder section is the 88-in. (223.5 cm) grain thickness. There is an advantage, however, in that the grain geometry is not complex and void detection capability should be good. Conservative extrapolation results in the conclusion that voids at least as small as 4-in. (10.2 cm) in diameter can be detected. The failure mode analysis indicates a requirement for the detection of a 4.1-in. (10.3 cm) void. This assumes a fairly rapid scanning inspection with scintillation detectors as initial screening. The 4-in.-(10.2 cm) dia limit for this inspection

VI.B. The Overall System (cont)

assumes that void indications are quite positive. If a defect is identified on the basis of indications, which have a 50% probability of being spurious, the limit may be reduced to 3 in. (7.6 cm) or possibly to 2 in. (5.1 cm).

With sufficient time and care, very high quality radiographs can be obtained, although the entire grain could not be inspected radiographically. Rather high quality film radiography can be used for the areas indicated as questionable by the scanning inspection. This combination would allow some margin for the 4.1-in. (10.3 cm) limit and still not be unreasonably slow.

The insulation/propellant interface will be more difficult to inspect in this region, but results should be satisfactory. Any separations that include a 5-in. (12.7 cm) circle would be detected.

2. Potential Problems

The preceding discussion has concentrated on separations and spherical voids for which specific limits can be calculated from case burnthrough and abrupt pressure rise considerations. Grain structural failure and propellant ejection are too complex to be considered in this manner. Given a particular set of flaws, it would often be quite difficult to decide if they would cause either type of failure. The establishment of general criteria would also be impractical.

However, the discussion of some problems can be useful. The most serious problem is the class of flaws including grain cracks, propellant/propellant separations, and flat voids. If these flaws are thin and have their smallest dimension along the X-ray beam, they will not be detected. This is the general case with grain radiography, although the problem is not as severe in small motors where shots can be made from many angles. Nevertheless, even with a Polaris or Minuteman-size motor, the probability of detecting a crack is slight and requires a fortuitous placement of the crack. In the 260-in. grain, a 1-in. (2.5 cm) or perhaps a 2-in. (5.1 cm) crack would have to be very favorably oriented to be detected on scintillation scans or radiographs.

VI.B. The Overall System (cont)

Ultrasonic inspection may reveal large flaws or those located very near the grain O.D. Microwave inspection could reveal flaws within 24 to 48 in. (61.0 to 121.9 cm) of the O.D. of the grain if they are not oriented at about 45 degrees (79 radians) to the motor axis. However, there will be a considerable region of the grain in which large thin voids or cracks could be so oriented as to escape detection. This situation of course is not peculiar to the 260-in. motor, but is characteristic of solid propellant grain inspections in general.

3. Estimated Inspection Time

Adequate inspection quality can be predicted with confidence on the basis of the experimental results. Exact details of inspection procedure have not been planned, although a preliminary estimate of the inspection time can be made.

a. Film Radiography, Complete Grain

Assuming the use of the best available radiographic accessories, film holders, and positioning fixtures designed for the 260-in. motor, it is estimated that approximately 435 hours would be required for complete grain radiography.

b. Scintillation Scanning, Cylinder Section

The scanning of the cylinder section is estimated at about 160 hours at a scan rate which will enable good detection of a 4-in. (10.2 cm) void.

c. Overall Radiography

The film and scanning inspections must be performed sequentially. However, film radiography is not necessary for the portion of cylinder indicated as good by the scanning system. Thus, actual radiography

VI.B. The Overall System (cont)

time will be 160 hours and only a portion of the 435 hours will be required for film radiography. However, the scintillation scan can eliminate only exposures in the cylinder section. About 510 exposures are required in this section, and they require about 30 minutes each including set-up time so that about 100 hours maximum can be saved if the cylinder section is all good. Calculation of scintillation scanning time is less complex than calculating radiographic time because it is dependent on the speed at which the instruments move. It may well be that in practice considerably more than 435 hours will be needed for film radiography. Thus, the added assurance resulting from scanning is greater than the potential saving of the indicated 100 hours.

Although the precise details of the inspection cannot be presented at this time, some idea of the operation is given by a few of the established requirements. A single exposure through the cylinder section will cover an area about 2.5 ft (0.76 m) circumferentially on the O.D. of the grain and about 4 ft (1.22 m) on the I.D. The film array will have about 1,000 lb (453.6 Kg) of lead screens so that the film holding fixture will be quite heavy and difficult to position. The complete cylinder section inspection with film will produce in excess of eight thousand 14 by 17 films, a substantially larger number than has previously been contemplated in solid rocket inspection. Therefore, complications not considered may vary the time estimates.

d. Insulation Propellant Bond Inspection

The complete ultrasonic insulation/propellant bond inspection, including maximum sensitivity and 100% coverage, could probably be accomplished in about 300 hours. If the scan is made for less than 100% coverage the time is reduced significantly. A sampling inspection will probably suffice for the cylinder section and the forward head. In the former region the flame front cannot reach the separation early. In the forward head the insulation is thick enough to survive if the separation is exposed to the flame front. Thus, only the aft head and a belt around the forward equator require

VI.B. The Overall System (cont)

detailed examination. Since only sampling of the cylinder sections will be required the inspection time would be reduced considerably; however, it is difficult to estimate the extent of the reduction until the scanning mechanism is designed.

4. Capability of Radiographic and Ultrasonic Techniques

The radiographic capability can be summarized as having been experimentally verified to a thickness of 65 in. (165.1 cm). At this thickness, voids less than 2 in. (5.1 cm) in diameter can be seen on film. Voids down to 2 in. (5.1 cm) in diameter can be detected through 65 in. (165.1 cm) of propellant using non-film scanning techniques.

It is possible to make reliable extrapolations to 88 in. (223.5 cm) of propellant using absorption data for 260-in. motor propellant collected during these experiments. At a 88-in. (223.5 cm) thickness, it can be predicted that voids 4 in. (10.2 cm) in diameter and larger will be detected with either film or with scintillation detectors. A linear accelerator of 26 mev (4.2×10^{-12} j), and 15,000 to 20,000 R (150 to 200 j/kg)/m/m output (flattened) would be required; such accelerators are available. Machines similar to the 10 mev (1.6×10^{-12} j), 500 R (5 j/kg)/m/m linac at Aerojet, or isotope sources would not be practical; however, a 26 mev (4.2×10^{-12} j), 55,000 R (550 j/kg)/m/m instrument is available and will produce about 20,000 R (200 j/kg)/m/m over a $\pm$ 5-degree (0.09 radians) beam when flattening filters are installed.

With this type of equipment radiographs can be made through 88 in. (223.5 cm) of propellant with enough sensitivity to reveal voids smaller than 4 in. (10.2 cm) in diameter. For additional speed, a scintillation scanning system can be used with the same source to inspect the cylinder section at scan rates up to 6 in. (15.2 cm)/min; this scanning system could detect 4-in. (10.2 cm) voids through 88 in. (223.5 cm) of propellant.

VI.B. The Overall System (cont)

The inspection would be quite slow using film alone. The cylinder section exposure times would be about 10 min, with 12 degrees (21 radian) circumferentially and 5 ft (1.5 m) axially covered at each exposure. About 500 exposures producing 8000 films would probably be required. On the other hand, 160 hr would probably suffice for a scintillation scanning system to examine the cylinder section. With the possibility of obtaining high quality radiographs of questionable regions, the scanning system could be used with greater confidence than would probably be required. Conversely, 160 hr would probably suffice for a scintillation scanning system to examine the cylinder section. With the possibility of obtaining high quality radiographs of questionable regions, the scanning system could be used with greater confidence than would usually be placed on such a system. Since both the film and scintillation scanning systems would use the same source, the use of both systems appears to be reasonable.

The ultrasonic method appears to be practical. Although only a 6-by 6-ft (1.8 by 1.8 m) area can be covered for each transducer placement inside the grain, many transducers can be installed at once. The necessary handling fixtures could be used for several of the required inspections. The outer scanning transducer can be of a wheel or water-stream-coupled-type to speed scanning. Furthermore, 100% coverage may not be necessary except near the ends of the motors.

It should be possible to identify any separated area large enough to contain a 4-in.--(10.2 cm) dia circle and better resolution might well be achieved in practice.

Primary difficulties to be expected, in addition to those dealing with logistics, are related to the surface condition of the case. Very smooth steel surfaces, as those of the Contract NAS7-367 experiments, propagate signals around the case very well, whereas a sandblasted surface is not as

VI.B. The Overall System (cont)

effective because of propagation. The exact surface condition of the motor will have to be known to determine the severity of the problems. However, the worst case has been tested and the problems do not appear to be insurmountable.

A preliminary estimate of the total inspection time is about 800 hours including set-up times. It should be possible to inspect to the criteria indicated by the failure mode analysis. The only exceptions are unfavorably oriented cracks, which are essentially the same problems as with any other solid propellant grain.

VII. RECOMMENDED EQUIPMENT AND PROCEDURES

The recommended equipment and procedures are tentative and incomplete. Further clarification of the required equipment and procedure requires access to a 260-in. motor and the casting facility. A tentative description of the operation, equipment, and probable calibration requirements is presented in the following paragraphs. Tentative formal procedures are included in Appendix F.

The tooling costs of Appendix G were estimated on the basis of inspecting the 260-in. motor during casting with microwave and after cure with radiography and ultrasonics. Aerojet and subcontractors estimates were used and are so identified. These ROM costs are intended to give information covering installation tooling costs and do not include proofing of the equipment.

A. ULTRASONIC INSPECTION

The through-transmission ultrasonic technique was evaluated with a Krautkramer USIP-10-W instrument. This unit was adequate for inspecting the fin specimen and could be used for a 260-in. motor. Although several USIP-10-W units used simultaneously would probably be the most economical method of inspection, visual interpretation of signals and hand mapping would be required. For this reason, a more sophisticated system is also considered. The electronic circuit details of this system have not been established. It is not recommended that the circuits be established until a 260-in. motor is available for use because the details of the inspection depend on the precise nature of the handling fixtures, motor supports, etc., existing in the casting pit. These fixtures determine the areas that can be scanned conveniently and the area to be scanned at one time, which have significant influence on the circuit requirements.

1. Fixtures

The ultrasonic inspection will utilize one fixed and one movable transducer. The fixture for scanning a 6-by 6-ft (1.8 by 1.8 m) area of the case O.D. with the movable transducer is shown in Figure 34. The movable transducer is a

VII.A. Ultrasonic Inspection (cont)

wheel-search unit which scans axially and is indexed circumferentially. Coupling to the case is by means of a water spray ahead of the contact patch. Alcohol could also be used if rapid evaporation is desired. The quantity of couplant required should be small enough that there will be little or no run-off or dripping. A vacuum pick up could be used if humidity is too high for evaporation and water is used. However, no problems are expected because only a film is required.

The scanning fixture is attached to the case O.D. by vacuum cups at the corners of the frame. The fixture can be placed using the equipment which positions the X-ray source.

The transducer on the grain I.D. is fixed and remains in position while a 6-by 6-ft (1.8 by 1.8 m) area of the case is scanned; the transducer is then moved to a new position.

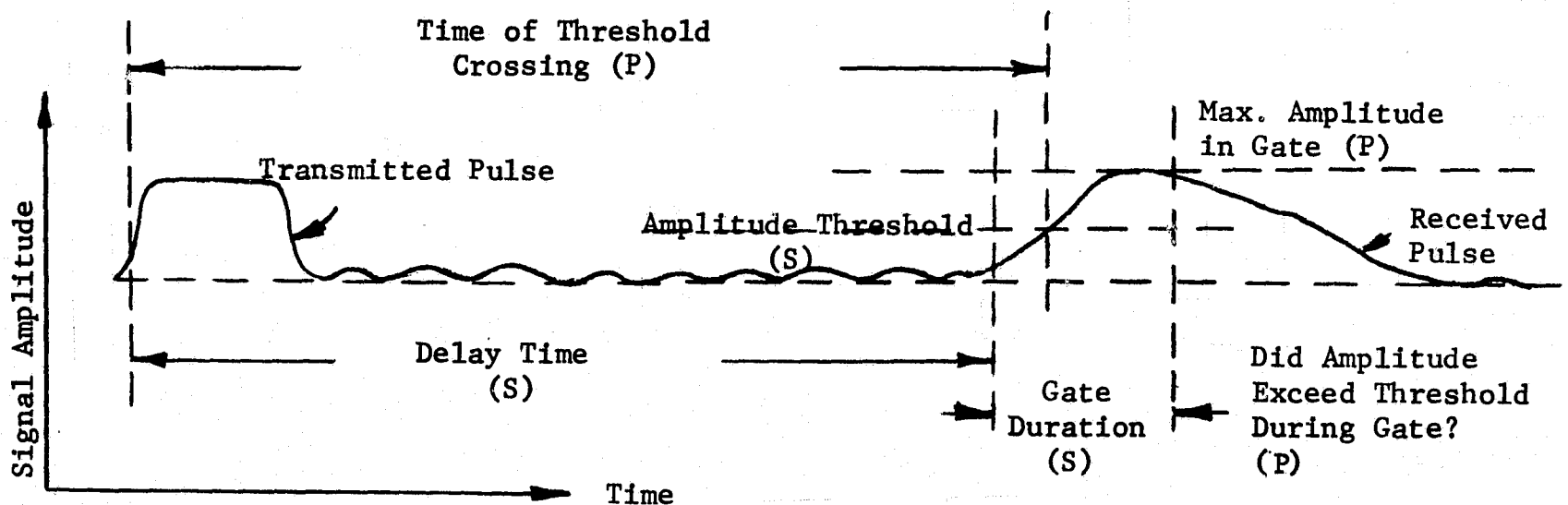
Figure 35 shows the vacuum device for attachment of the grain I.D. transducer. The fixed I.D. transducer will act as the receiver to reduce noise, because the noise generated by the scanning will not be strong enough to penetrate the grain.

2. Electronics

The necessary electronics for the inspection are shown in block form in Figure 36 along with significant internal signals to clarify the operation of the system. Details such as buffers, power supplies, and filters have been omitted from this conceptual design since they are dependent on the electronic components selected. Selection of electronic components should not be made far in advance of construction.

VII.A. Ultrasonic Inspection (cont)

A sketch of a typical cathode ray tube (CRT) presentation of the ultrasonic amplitude data similar to that which would be seen on an instrument such as the USIP-10-NF is shown below.



The variables marked (P) can be recorded as a function of position on the motor. Parameters marked (S) can be set by the operating controls. Amplitude threshold and delay-time are set by dc input voltages and can be varied according to position by potentiometers on the scanning fixture.

3. UT Signal Analyzer Operating Principles

The transmitted signal is a short burst of ultrasound at about 50 KHz (Figure 36). As the burst is transmitted a linear voltage ramp function is generated. The ramp furnishes a voltage proportional to elapsed time. The delay comparator produces a pulse whenever the ramp voltage exceeds the delay-time control voltage. This pulse discharges the hold maximum circuit (which was holding the data from the last pulse) and activates the gate multi-vibrator which opens the gate. The hold maximum circuit then registers the

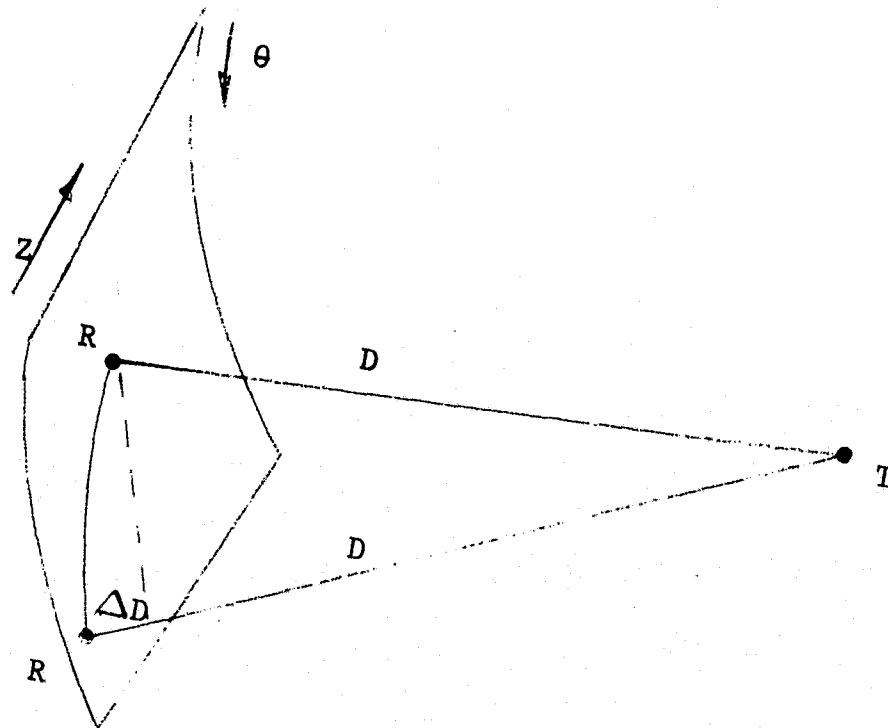
VII.A. Ultrasonic Inspection (cont)

height of any received pulse arriving during the duration of the gate. This voltage is displaced at the output until the next pulse is received. A smoothing filter removes the discontinuity of the discharge so that the output is suitable for low-speed recorders. The output provides a record of the amplitude of pulses arriving at the calculated time for direct path through-transmission. The delay-time and gate duration can be varied.

A comparator in the received-signal path produces a pulse whenever the received signal amplitude exceeds a level selected by the amplitude threshold control voltage. The amplitude comparator pulse activates a sample-and-hold circuit with an output voltage proportional to delay time. The delay-time output plots the time at which the transmitted pulse in excess of a selected amplitude is received.

The two types of record described can be made simultaneously. A third type of record is also available. By gating the amplitude comparator output rather than the received signal, a binary signal is obtained which is at one level when the received pulse during the gate exceeds the threshold selected, and at another level when it does not. This signal can activate the pen lift of an X-Y recorder or can operate a helix recorder. A C-scan record will be produced similar to that used in immersion ultrasonic inspection. A binary map of the delay-time could also be made on a helix recorder by use of a threshold circuit on the delay time output. However, a bonded region does not give constant delay time over the entire scanning grid because of the distance between transducers changes. This means that either the gate must be opened enough to compensate, or a probe position correction must be made as illustrated in the following sketch.

VII.A. Ultrasonic Inspection (cont)



The correction (ΔD) can be made by putting special Taber potentiometers on the scanning frame drives to apply the proper voltage to the delay-time control voltage input, although this will probably be unnecessary. For the circumferential scan, the case O.D. radius of curvature is 130 in. (330.2 cm), while the minimum distance between transducers will be about 87 in. (221.0 cm) in the cylinder section. Thus with a 6-by 6-ft (1.8 by 1.8 m) scan frame, the distance between transducers can vary about 3 in. (7.6 cm) with a circumferential scan. The variation for an axial scan would be about 6 ft (1.8 m). A linear correction will probably suffice for the axial scan, and the circumferential scan error is probably acceptable without correction of the delay time. Corrections would be required only if a very narrow delay gate were required. Of course, if both delay time and amplitude data are recorded, there is no problem since a change in delay time caused by a flaw will be conspicuous. The squares A, B, and C shown in Figure 36 illustrate the way in which flaws are indicated on the various inspection records. In (A) the normal trace is curved because of the change in path length; a flaw will cause an additional increase. As presently conceived, the delay-time record will indicate the last measured delay time if no pulse is received so that loss of signal will cause a straight-line trace.

VII.A. Ultrasonic Inspection (cont)

The system is quite flexible in operation. Since there are still many unknown factors in the ultrasonic inspection of a full-scale motor, provision is made for extensive data processing. Although this will probably not be required, at least not in the cylinder section of the motor, difficulties may be encountered in the star region.

The normal variation in delay time in the star region, for example, will be much greater than in the cylinder section unless the transducer can be mounted at the tip of the fin, which may not be desirable. Better results would be obtained with a smaller distance between the transducers, and the region of transition from star to cylinder might well be critical. If this region is critical, some loss of inspection speed will probably result.

In general, it will be possible to make extensive modifications and additions to the system. More signal and data processing can be done if desirable. The circuits in the blocks of Figure 36 will be compatible to those of the microwave signal analyzer used during other phases of this program. About four 4-by 5-in. (10.2 by 12.7 cm) circuit boards will be required. The gates, flip-flops, and similar elements required are available in integrated circuit packages so that additional logic operations are no problem.

After a trial period, inspection can be modified if required to produce a single record which will show the defects which are of interest. The three records A, B, and C, shown in Figure 36, are included so that all possibilities will be covered. There is still some question whether an unbond will be indicated by loss of amplitude, increase of delay time, or both. As explained previously, this depends primarily on the surface of the steel case.

4. Inspection Procedure

The ultrasonic inspection can be performed with the motor in the casting pit fitted with suitable positioning fixtures outside and inside of the motor. The positioning fixtures are those designed for radiographic inspections.

VII.A. Ultrasonic Inspection (cont)

The exterior transducer is mounted on an 8-by 8-ft (2.4 by 2.4 m) rectangular frame (Figure 34) curved to fit the OD of the motor case. The frame is held in place by four vacuum cups mounted at the corners. The vertical dimension of the frame is spanned by a bridge which carries a vertical scanning carriage. The bridge may be indexed circumferentially in increments of 1, 3, and 6 in. (2.5, 7.6, and 15.2 cm). The vertical motion is continuously variable from 1 in. (2.5 cm) to 12 in. (30.5 cm)/sec. Attached to the vertical scanning carriage is a wheel-mounted ultrasonic transducer. Coupling of the wheel to the case is accomplished by a continuous water mist sprayed onto the case, just ahead of the wheel, which carries the transmitting transducer of a through-transmission ultrasonic instrument.

The interior transducer is fixed to the inner surface of the grain. Acoustic coupling is accomplished by a thick emulsion-type couplant. The transducer is held to the grain surface by a vacuum cup. Two types of transducer mounts are used; one is for the cylinder section and the other is mounted on the side of a star point.

To perform the inspection, the case is marked off in 6-by 6-ft (1.8 by 1.8 m) squares which are numbered. The inner transducer is positioned so that the beam illuminates one of the marked squares. The scanning fixture is attached to the case OD to cover the square illuminated. The 6-by 6-ft (1.8 by 1.8 m) area is then scanned, the through-transmission data are recorded, and the records are marked with the number of the square inspected.

5. Calibration

The ultrasonic through-transmission system described requires two kinds of calibration. The electronics and the recorders constitute the first calibration group, and should be quite straightforward. The principal accuracy checks will be as follows:

VII.A. Ultrasonic Inspection (cont)

- a. Recorder calibration according to appropriate procedures.
- b. Calibration of amplitude thresholds.
- c. Calibration of delay-time indication.
- d. Check of oscillator output into nominal impedance of transmitting transducer.

These are relatively routine measurements which will require little more than a calibrated oscilloscope with minimal precision. The most convenient way to check the equipment would be to construct a pulse generator which could be triggered by the oscillator trigger signal and after a variable delay of about 1400 μ sec, will emit a pulse simulating the received signal as it emerges from the signal conditioner. This can be accomplished by a commercial pulse generator and an output pulse shaping network. A modified pulse generator and an oscilloscope can rapidly verify correct operation of all the system except transducers and attendant circuits.

Twelve transducers will be used in rotation as the receiver of the system; the transducers will be calibrated to assure that data from each will be compatible. The transmitting transducer will be attached on the outside of the case and the 12 receivers will be attached at the same location inside of the case. If the sensitivity of the transducers vary, a gain adjustment may be necessary. If the system shown in Figure 36 is used, the gain adjustment would be made at the received signal amplifier. However, because of the long cables involved it may be desirable to use a pre-amplifier at the transducer and have a variable-gain pre-amplifier for each receiver. Once the gain adjustment is made, both transducer and pre-amplifier can be changed as a unit and the operator will not have to make any adjustments to correct for transducer variation.

VII.A. Ultrasonic Inspection (cont)

Coupling variations will result in more errors than any likely to arise from instrumental causes. Calibration will not eliminate these errors, although the calibration process will aid in eliminating gross malfunction of equipment which might result in anomalous results. Therefore, it is important that a normal response be established for each motor. With the equipment free of gross malfunction, the minimum delay time for through-transmission represents direct path propagation. Because of variations probable in a motor of this size, comparing anomalous regions with good motor regions should be a more reliable method of detecting flaws than reliance on absolute calibration.

B. MICROWAVE

1. In-Process Inspection

The microwave system recommended for in-process inspection is a hybrid coaxial and rectangular guide system in L-band (1-2 GHz). The system will be coaxial except for the antenna which will be dielectric-filled horns.

The two-horn configuration would be used initially, but the single-horn version could be used when space is critical. The single-horn has a 6-by 8-in. (15.2 by 20.3 cm) aperture vs 12 by 8 in. (30.5 by 20.3 cm) for the two-horn system.

Inspection of the star region in process could probably be accomplished by lowering the instrument down alongside the bayonet. Experience with the fin specimen indicates that an attempt to examine this part of a real motor would be difficult and would in all possibility interfere with the casting operation. In any case, there is not space enough for more than a one- or two-point inspection with the L-band system.

VII.B. Microwave (cont)

a. Scanning Mechanism

The scanning mechanism of Figures 37 and 38 would be used for the cylinder section. The total vertical travel of the horn drive is 10 in. (25.4 cm) which is more than the propellant level will rise during the pouring of one pot. The desired degree of horn immersion is regulated by a fluidic sensor using air to detect the propellant surface.

b. Signal Analysis and Recording

The signal analysis is the same as that used in experiments described in previous reports of this contract. Data recording and display would include an X-Y plotter for mapping a given depth and a variable-persistence oscilloscope such as the Hewlett-Packard 141A for visual observation of bubbles or moving flow patterns as indicated by microwave reflections.

In all probability, the most common type of operation would involve no scanning of the propellant surface. Several locations around the bayonet would be selected and the horn would be positioned at these locations in rotation. At each location, the CRT display would be watched for a minute or so on the variable-persistence storage oscilloscope. The oscilloscope can show any changes in the trace that occur within a minute by adjusting the scope so that the trace requires one minute to fade; changes with time are therefore very obvious.

Because penetration to depths of 24 to 30 in. (61.0 to 76.2 cm) is likely, and because sensitivity is good using a filled, immersed horn, this inspection could plot the flow pattern of any bubbles that might be entrapped in the bayonet tube. It could tell whether they were rising, and at

VII.B. Microwave (cont)

least to some extent how far beneath the surface they had been carried. Because of the probable motion of any flaws which may be detected, it is doubtful if a scan over the propellant surface would be of much value since a good map of defects would be difficult to make with the propellant surface and the defect moving. The recording of depth scans on the CRT, however, is no problem because rising bubbles do not move fast enough to cause trouble. Therefore, it is probable that the X-Y plotter will not be used after preliminary trials.

A likely procedure is to visually monitor the depth scan on the CRT while moving the horn from point-to-point over the propellant surface. Observed indications can be recorded with a Polaroid camera. Position potentiometers on the microwave carriage can be connected to indicating devices so that the operator can record the radial, angular, and depth location when a trace is recorded. Regions of high gas entrapment can be recorded and given more careful attention in post-cure inspection; failure of bubbles to rise to the surface can also be observed.

c. Procedure

The microwave scanning fixture is assembled inside the case; sections of the assembly are inserted through the nozzle port. The fixture is then lowered to approximately the surface of the propellant. The 10-in. (25.4 cm) vertical motion of microwave antennas (relative to the fixture) is set 2 in. (5.1 cm) from the lowest position. The fixture is then levelled with the horn in contact with the propellant surface. The fluidic sensors and servo system are activated to maintain the horn in contact. The remaining 8-in. (20.3 cm) travel is used to follow the rise of the propellant surface. This motion is used until the propellant pot has been poured. While the next pot is being installed, the fixture is raised and levelled, and the antenna vertical travel reset so that it can be used as the next pot is poured.

VII.B. Microwave (cont)

The fluidic sensors and servo system hold the horn in contact with the propellant surface during the pouring of a pot. If the operator wishes to move the horns, he can over-ride the servo system to lift the horn, reposition the horn, and then let the servo system maintain contact at the new location.

Data will be displayed as a CRT depth scan. The variable persistence-type CRT will be set to display three successive traces so that changes with time will be readily apparent. The depth of any bubbles detected and the rate at which they rise can be determined in addition to horizontal movement out of the microwave beam.

It is recommended that visual interpretation be used, with a camera available to record any traces of particular interest, until experience has been gained with in-process microwave inspection. If a void indication appears at a great depth, and then the depth indication decreases, a rising bubble is obviously indicated. If a strong valid indication disappears, horizontal motion is indicated. The presence and motion of entrapped air can be noted down to the maximum depth which can be examined. The position of the horn will be indicated to the operator by potentiometers on the servo system controlling the horn position.

A defect map made in-process would be somewhat complex, and would consist of a cylindrical co-ordinate three dimensional map, or a series of polar maps. Time is also consequential because there is flow of propellant. For this reason, the initial plan does not call for recording defect maps, since many of the void indications would move while the map was being recorded and would result in much confusion.

Instead of mapping the motor, it is recommended that the operator record any positions at which there is unusual air entrapment, or a tendency of the entrapped air not to rise to the surface. Because of motion in

VII.B. Microwave (cont)

the uncured propellant, it is doubtful if a detailed flaw map would remain accurate throughout cure; the general location is of course of significant importance.

If a map of some type is desirable, a multi-channel signal analyzer would be required so that several depths could be scanned simultaneously; this type of analyzer can readily be constructed while the recorder is more complicated. An X-Y plotter can record the data, i.e., angular vs radial position on a rectangular grid. This would not be a pictorial representation although those familiar with the inspection procedure could readily locate the flaws from such a map. Use of existing electrical devices which make polar plots on an X-Y recorder would probably be an unwarranted complication.

d. Calibration

The microwave system is calibrated for range accuracy and sensitivity by means of metallic targets suspended in air. The range in air divided by the refractive index gives the range in propellant. The completed microwave system will be tested to determine the maximum penetration with good void detection capability. This is expected to be about 24 to 30 in. (61.0 to 76.2 cm). Assuming 30 in. (76.2 cm) as the limit, one would calibrate the range scale by placing a metal sheet 75 in. (190.5 cm) from the horn. With the range of the signal analyzer and depth-of-field controls set to show a metal reflector at 75 in. (190.5 cm) and also the reflection at the mouth of the horn, the required 0 to 30 in. (0 to 76.2 cm) propellant depth would be displayed.

Calibration for sensitivity would be readily performed with a solid 6-in.-(15.2 cm) dia plastic sphere suspended 30 in. (76.2 cm) from the horn in air. A smaller metal sphere could also be used. In fact, any target that will give a good reflection can be used as a calibration standard.

VII.B. Microwave (cont)

C. RADIOGRAPHY, SCINTILLATION AND FILM

1. Procedure

The procedures for both film and scintillation radiography require a common X-ray source, a 26 mev (4.2×10^{-12} j) 20,000 R (200 j/kg)/m/m linear accelerator. Exact procedures for operating this instrument in the special installation required are not available. Even though operational details cannot be given, some idea of the equipment is included in Figures 39, 40, and 41, which show the source location, positioning fixture, and control room; Figure 42 shows the film-holding fixture. The positioning fixture for the scintillation detector is shown in Figure 43. Both film and scintillation inspections will be checked by penetrameters. Using the terminology of ASTM E-142, the sensitivity required is 2%. The penetrameter should be 2% of the full grain thickness and should be in the form of a circular disc of 2T diameter with a 1T hole where T is the thickness, approximately 3.5 in. (8.9 cm), depending on the material. Apocast resin would be suitable, and for this material, a 7-in.-(17.8 cm) dia disc with a 3.5-in.-(8.9 cm) dia hole is required. This is level 2, 2T radiography by ASTM E-142 terminology except that disc penetrameters are usually of 4T diameter with both 2T and 1T holes. Because of the magnification problem, it was considered desirable to restrict the penetrameter diameter to 7 in. (17.8 cm).

If it is feasible to maintain higher radiographic quality than the worst film which will show the 1T hole in a 2% penetrameter, thinner penetrameters can be substituted, as described in ASTM E-142.

Penetrameters will be placed on the outside of the motor. In the case of film radiography, one penetrameter per exposure should suffice, although enough penetrameters should be available to place a penetrameter image on each film of an exposure if necessary. Because of the special nature of this inspection, it is quite probable that the occasional use of penetrameters on each film will be required.

VII.C. Radiography, Scintillation and Film (cont)

The use of a penetrometer to calibrate the scintillation equipment is probably the most realistic means of calibration except for a known void in a real motor. Since one has merely to attach the penetrometer and then scan over it, this calibration can be performed as often as desired. How often calibration is required will, of course, depend on the degree of stability actually achieved in the equipment.

2. Film Cassette Positioning

Precise alignment must be assured for both film and non-film radiography. Rotational alignment is maintained by tying the source and detector together mechanically, as shown in Figure 44, so that the entire system rotates when the source is moved. For film radiography, initial rotational alignment is accomplished as shown by using targets inside and outside the motor (Figure 39). When aligned, the cassette rotating system is locked securely to ensure alignment throughout the 360-degree (2π radians) rotation.

Alignment in the vertical position is accomplished in a similar manner using targets except in this case the cassette holder is not locked into place. A dc drive motor with an appropriate gear box is located on the support frame of the X-ray scanning system. A cable linked to the drive motor is used to raise and lower the cassette holder. A high resolution counter is attached to the motor and a similar counter is attached to the X-ray source. Both are monitored in the control room to maintain the source and film at the desired elevation.

A concept of the film cassette holder is shown in Figures 42 and 45. The fixture is capable of holding 16 standard 14-by 17-in. (35.6 by 43.2 cm) cassettes. Hydraulic cylinders are used to advance the holder to the propellant surface thereby placing the film in correct position for exposure.

VII.C. Radiography, Scintillation and Film (cont)

3. Gamma Scintillation Inspection

In performing the proposed gamma scintillation inspection the linear accelerator is located outside the motor using the same positioning fixture as that described for film radiography. The total source-to-detector distance is 20 ft (0.61 m). Detectors will be 2-by 2-in. (5.1 by 5.1 cm) NaI(Tl) scintillation detectors, Harshaw Integral type, having the crystal and photomultiplier tube as a unit. Twenty detectors would be used, two vertical rows of 10 each, alternated to cover 40 in. (101.6 cm) along the axis of the motor. The detectors are collimated by lead shields as shown in Figure 46.

The inspection would be performed by a synchronous rotation of the accelerator and the detectors. Source-to-detector alignment would be accomplished prior to placing a chamber in the casting facility. This would be readily accomplished by using a small isotope pellet placed at the accelerator target assembly. The isotope source should be of such strength to provide, without the motor, the same count rate as the accelerator would produce with the motor present.

The scanning rate would be approximately 6 in. (15.2 cm)/min, 136 min per revolution, and covering 40 in. (101.6 cm) on the axis of the motor. This is the highest rate verified experimentally.

The calculations on which the preliminary design is based assume a requirement of 25 mev ($4.0 \text{ by } 10^{-12} \text{ j}$), 32,000 R (320 j/kg)/m/m whereas the selected machine will produce 20,000 R (200 j/kg)/m/m with a half-intensity-width of ~ 5 degrees (0.09 radians). The detector array will subtend about 10 degrees (17.5 radians). The selected machine is therefore slightly beneath the preliminary requirements. However, the 32,000 R (320 j/kg)/m/m is known to be based on conservative assumptions, and on performance at a 65-in. (165.1 cm) propellant thickness which was slightly better than required, i.e., voids smaller than 4-in. (10.2 cm) in diameter could have been observed through 65 in. (165.1 cm).

VII.C. Radiography, Scintillation and Film (cont)

Considering the improvements which can be made in the detection system, it is reasonable to predict that at the worst, it will be possible to obtain adequate sensitivity through 88 in. (223.5 cm) of propellant by reducing the width of the detector array. The 19,000 to 20,000 R (190 to 200 j/kg)/m/m available would be adequate, although the intensity will drop below 15,000 R (150 j/kg)/m/m at 2 degrees (0.035 radians) from the beam axis and to less than 10,000 R (100 j/kg)/m/m past 3 degrees (0.052 radians) from beam axis. On the basis of these data, the inspection will be difficult, but should be possible.

The instrumentation used in the experiments from which this recommended procedure was developed had some disadvantages. As previously mentioned, better equipment can be obtained. One improvement in particular could make the estimates presented here quite conservative. The performance of the present measuring system can probably be brought closer to that of the counting system by using a phase-lock amplifier for the photomultiplier current. Since the linear accelerator is pulsed, the portion of the current which represents valid data is also pulsed. By extracting a reference signal from the accelerator at the pulse repetition frequency, the phase-lock amplifier can be made to amplify only pulsed signals in phase with the linear accelerator pulse repetition frequency. Using a phase-lock amplifier, it is often possible to measure signals smaller than the background noise fluctuations when a suitable reference is available.

D. DETECTOR COLLIMATOR ARRAY

The scintillation detector array is shown in Figure 46. Lead collimators define the beam incident on each detector. Each collimator is a slit measuring 2 by 1/8 in. (5.1 by 0.32 cm) in the plane normal to the beam and measuring 5 in. (12.7 cm) along the beam. The linear accelerator target will be located 20 ft (6.1 m) from the detectors and will have a focal spot of about 1/8 in. (0.32 cm) in diameter. The array consists of two vertical rows of 10 detectors each, staggered. All the collimator slits must be set for convergence at 20 ft (6.1 m) so that they will receive radiation from the source. This can be readily accomplished optically. Sufficient convergence will be readily obtained by the following method.

VII.D. Detector Collimator Array (cont)

A target of the type shown in Figure 47 is placed 20 ft (6.1 m) from the collimators (Figure 48) and illuminated. A peep sight is then fitted into the hole in the back of the block, which ordinarily holds the detector. The collimator is then bore-sighted on the target. For vertical convergence, the 2-in. (5.1 cm) slit dimension makes it unlikely that readjustment will be required. Initially, the collimators will be shimmed so that they converge on the target placed 20 ft (6.1 m) away.

The horizontal adjustment will have to be made more frequently since the 1/8-in. (0.32 cm) width of the slit makes this alignment more critical than the vertical adjustment. The collimators are clamped into place after being adjusted for proper convergence.

The initial setting for convergence will be made on a level floor. After proper alignment is achieved, a bubble level is attached to the array and set to indicate level. Thereafter, the level can be used to indicate correct orientation of the array. The array pivots about the front end so that the more critical adjustment in the horizontal direction can be made after the array is in place inside the motor. The array is moved about the pivot until a maximum count rate is achieved and then locked in place.

Figure 47 shows how the sight is fitted to a collimator giving a 3/64-in. (0.12 cm) rear aperture and a 1/8-in. (0.32 cm) front aperture. Pieces of tape restrict the 2-by 1/8-in. (5.1 by 0.32 cm) slit to 1/8 by 1/2 in. (0.32 by 1.3 cm). The alignment obtainable should be very satisfactory.

VIII. CONCLUSIONS

The nondestructive testing recommendations represent the best methods available for immediate use.

VIII. Conclusions (cont)

The methods which are likely to be improved enough to alter the selection in the near future should be considered. Since the decision to produce a 260-in. motor has not been made, it is advisable to monitor developments in fields likely to contribute to the inspection so that the best available NDT techniques can be specified in the future.

Any development is likely to reduce the relative desirability of film radiography. Higher photon energies will seldom help; usually the best energy is achievable, and higher R (j/kg) output results in complications because of shielding problems. Radical improvements in film are not expected, and the improvements that will be made will probably be expensive.

The most immediate challenge to film radiography is from scintillation counting and non-film image systems. Since these techniques can utilize the same source of radiation, they will have the minimal impact on the NDT program. A slight increase in speed and the elimination of film processing will be a potential cost saving, and will not result in significant change.

The developments which are most critical are those which could eliminate radiography entirely. This is essentially limited to ultrasonic and microwave techniques. Laser holography does not offer much practical application for any defects in a large motor, and none for voids which are deep in the grain. Similarly, infrared methods are not promising for deep voids, although infrared might be developed into a good inspection for separations in the case/grain bond system. Infrared radiation does not penetrate the motor, and is used simply to map surface temperature. The actual flaw interaction involves heat transfer by conduction between the interior and exterior of the specimen. Thus, this method has fundamental limitations for deep flaws. Conversely, it could have good potential for case/grain bond inspections.

Sound/ultrasound and microwaves have good penetration in propellant at properly selected frequencies. Additionally, both are adequate, for through-transmission or reflected-signal inspections. The principal difficulties are

VIII. Conclusions (cont)

encountered with spherical voids, which do not reflect much signal to small aperture receivers. Another problem is the inability to get good beam definition with a reasonably small antenna or transducer.

The basic techniques of holography are applicable to ultrasound and microwaves. In fact, the ultrasound and microwaves meet the spatial and temporal coherence requirements of holography better than light waves in the visible or infrared region of the spectrum. The use of coherent X-rays is very unlikely, although both ultrasound and microwaves permit the use of holographic techniques. In many ways these techniques work better with ultrasound and microwaves. Needless to say, there is much more to holography than three-dimensional images, and the desirability of holographic methods is in their capability to utilize signals wasted in ordinary techniques.

There is much experimental work being accomplished in holography using waves other than visible light. This is a sector of technology related to optical computers and the side-looking radar. Synthetic aperture techniques, which will enable small antennas to do the work of very large ones, also appear very promising. A spherical void returns a great deal of the incident energy to a receiver if the aperture is large enough.

Much of the work in ultrasonic and microwave holography has been directed toward duplicating optical holographic techniques, although there has been a tendency to exploit the advantages of the more coherent and manageable ultrasonic and microwave signals.

It is recommended that the developments in ultrasonic and microwave inspection continue to be monitored, especially those involving holographic methods. If further experimental work in NDT is to be done, this is recommended as the most promising field for investigation.

Motor	Time, sec	Approx. P. Prior to Increase,		Increase Pressure,		P _c , %	Estimated Increase in Burning Surface A _b			Approx. Distance Burned at Time of Increase		Approx. Web Remaining		Assigned Cause of Pressure Rise
		psia (N/cm ²)		psi (N/cm ²)			in. ²	(cm ²)	ft ²	in. (cm)		in. (cm)		
120-SS-1	14.47	449 (310)		6 (4)		3.1	700	(4,500)	5	5.6 (14.2)		30 (76)		Failure of bond between propellant and boot in aft head caused by casting difficulties with submerged aft boot extension.
				8 (6)			900	(5,800)	6					
				14 (10)			1600	(10,300)	11					
260-SL-1	107.6	551 (380)		8 (6)		1.5	5300	(34,200)	37	50 (127)		2.5 (6.4)		Failure of bond between propellant and boot in aft head. Cause ascribed to 8-ft (2.4 m) casting tube submergence that allowed surface propellant to be exposed too long.
260-SL-3	1.23	481 (332)		13 (9)		2.7	3700	(23,900)	54	0.9 (2.3)		51.4 (130.5)		20-in.-(51 cm) deep fissures in fwd portion of grain.
	11.23	570 (393)		5 (3)		0.9	2400	(15,500)	17	8.0 (20)		44.5 (113)		12-in.-(30 cm) deep fissures in fwd portion of grain.
	55.17	530 (366)		16 (11)	8.9		8800	(56,800)	61	40.0 (102)		12.5 (32)		12-in.-(30 cm) deep circumferential fissures in aft portion of grain.
	55.90	546 (377)		31 (21)			17000	(110,000)	118	41.0 (104)		11.5 (29)		
	65.48	460 (317)		52 (36)	27.5		31600	(204,000)	220	48.5 (123)		4.0 (10)		Propellant/insulation bond failure in aft portion of grain. Ejection of propellant segments.
	66.20	512 (353)		75 (52)			None		None	49.0 (124)		3.5 (9)		
	66.76 through 74.88	400 (276)		12 (8) max	-		None		None	50 (127) to 52.5 (133)		2.5 (6.0) to 0		Ejection of propellant segments.

Figure 1.- Summary of 260-in.-(6.6 m) dia Motor Program Firing Anomalies

<u>Parameter</u>	<u>$\bar{x}$</u>	<u>$\frac{\sigma}{\bar{x}} \times 100$</u>	<u>σ Units</u>
Propellant Thickness Consumed Prior to Web Time, in.(cm) (t_w)	85 (216)	0.20 (0.51)	0.170 (0.432)
Propellant Burning Rate Prior to Web Time, in./sec(cm/s) (r_w)	0.606 (1.539)	1.35 (3.43)	0.00818 (0.0208)
Propellant Thickness Consumed During Tailoff, in.(cm) (t_{to})	2.5 (6.35)	0.20 (0.51)	0.005 (0.0127)
Propellant Burning Rate During Tailoff, in./sec(cm/s) (r_{to})	0.333 (0.846)	1.35 (3.43)	0.0045 (0.0143)

Figure 2. - Standard Deviations for Insulation Burnthrough Parameter

Station	Location	Propellant Thickness,		Insulation Thickness,		Insulation Erosion Rate,		$\bar{x}_C$, sec	s_C , sec	Allowable Exposure Time Increase, sec	Allowable Defect Dia,	
		in.	(cm)	in.	(cm)	in./sec	(mm/s)				in.	(cm)
1	Ign. Boss	0	0	1.125	(2.858)	0.003	(0.076)	375	58.1	47.4	-	-
2	Fwd Equator	24.5	(62.2)	1.125	(2.858)	0.003	(0.076)	415.4	58.1	87.8	53.2	(135)
3	Sta 2 plus 35 in. (89 cm)	28.0	(71.1)	1.125	(2.858)	0.003	(0.076)	421.2	58.1	93.6	56.7	(144)
4	Sta 2 plus 80 in. (203 cm)	52.0	(132.1)	0.620	(1.575)	0.003	(0.076)	292.4	32.0	45.4	27.5	(70)
5	Sta 2 plus 150 in. (381 cm)	87.5	(222.2)	0.110	(0.279)	0.003	(0.076)	184.5	6.0	17.1	10.4	(26)
6	Sta 8 minus 274 in. (696 cm)	85.0	(215.9)	0.110	(0.279)	0.0035	(0.089)	171.7	5.3	6.7	4.1	(10.4)
7	Sta 8 minus 47 in. (119 cm)	73.0	(185.4)	0.350*	(0.889)	0.005	(0.127)	190.6	11.0	8.4	5.1	(13.0)
8	Aft Equator	70.6	(179.3)	0.450	(1.143)	0.006	(0.152)	191.4	11.7	6.9	4.2	(10.7)
9	Sta 8 plus 12.5 in. (31.8 cm)	70.0	(177.8)	0.480	(1.219)	0.00625	(0.159)	192.4	12.0	7.0	4.2	(10.7)
10	At 240-in-(610 cm) dia	52.4	(133.1)	0.950	(2.413)	0.00725	(0.184)	217.6	20.3	6.7	4.1	(10.4)
11	At 220-in-(559 cm) dia	31.3	(79.5)	1.630	(4.140)	0.00825	(0.210)	249.3	30.6	6.7	4.1	(10.4)
12	At 200-in-(508 cm) dia	15.0	(38.1)	2.650	(6.731)	0.0105	(0.267)	277.0	39.3	7.5	4.5	(11.4)
13	Nozzle Joint	0	0	4.770	(12.116)	0.0168	(0.427)	284.0	44.02	0	-	-

*Sidewall insulation thickness adjusted from Station 7 downward to meet minimum allowable defect size.

Figure 3.- Summary of Insulation Burnthrough Calculation

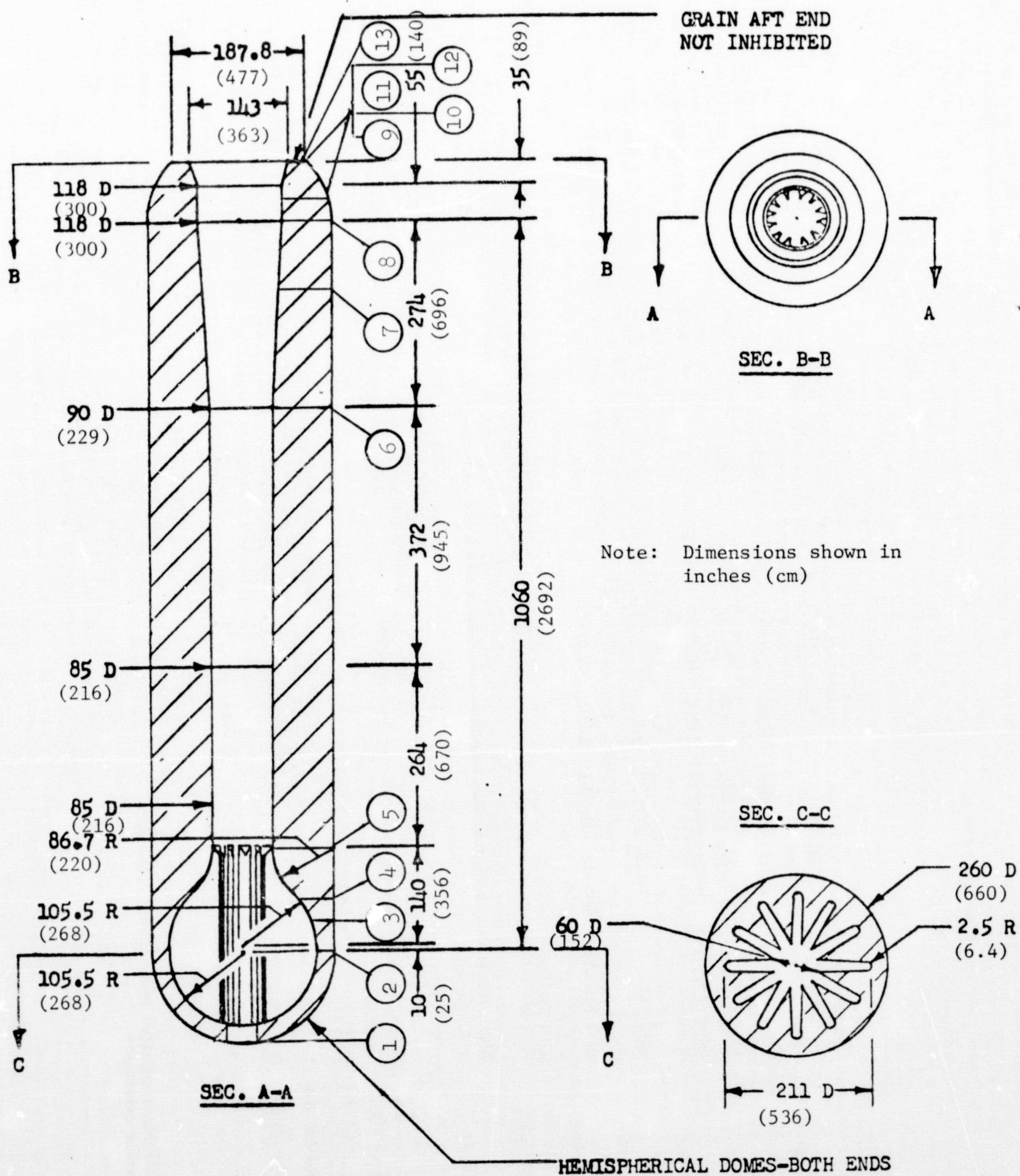


Figure 4. - Insulation Calculation Stations 1 through 13
260-in.- (6.6 m)-dia Full-Length Motor Grain Design

<u>Failure Mode</u>	<u>Minimum Single Defect Size That Must be Detected to Meet Failure Criteria</u>								
Case Burnthrough	<u>4.1-in. (10.4 cm) flame front advancement.</u> This could be either a single spherical void 4.1-in.- (10.4 cm) dia or a propellant/propellant separation, etc., that would advance the flame front 4.1-in. (10.4 cm). The extent of propellant liner separations would vary depending on longitudinal locations as follows: <table> <tr> <td>Fwd head</td><td>No limit</td></tr> <tr> <td>Fwd cyl. section</td><td>12 in. to 64.5 in. (30.5 to 163.8 cm)</td></tr> <tr> <td>Aft cyl. section</td><td>160 in. to 297 in. (406 to 754 cm)</td></tr> <tr> <td>Aft head</td><td>4.1 in. (10.4 cm)</td></tr> </table>	Fwd head	No limit	Fwd cyl. section	12 in. to 64.5 in. (30.5 to 163.8 cm)	Aft cyl. section	160 in. to 297 in. (406 to 754 cm)	Aft head	4.1 in. (10.4 cm)
Fwd head	No limit								
Fwd cyl. section	12 in. to 64.5 in. (30.5 to 163.8 cm)								
Aft cyl. section	160 in. to 297 in. (406 to 754 cm)								
Aft head	4.1 in. (10.4 cm)								
Propellant Ejection	<u>36.2-sq-in. (234 cm²) decrease in throat area.</u> This could come from a single 6.5-in. by 6.5-in. (16.5 by 16.5 cm) propellant/propellant or propellant/liner separation which resulted in propellant ejection.								
Abrupt Chamber Pressure Increase	<u>2800-sq-in. (18,000 cm²) increase in burning surface.</u> This could come from a single 31-in. (79 cm) dia spherical void; a 39-in. by 39-in. (99 by 99 cm) propellant/propellant separation or a 55-in. by 55-in. (140 by 140 cm) propellant/liner separation.								
Grain Structural Failure	<u>None.</u> Although small voids may cause small local cracks, the crack will not propagate unless entire section fails due to inadequate propellant mechanical properties.								

Figure 5. - Summary of Minimum Defect Limits

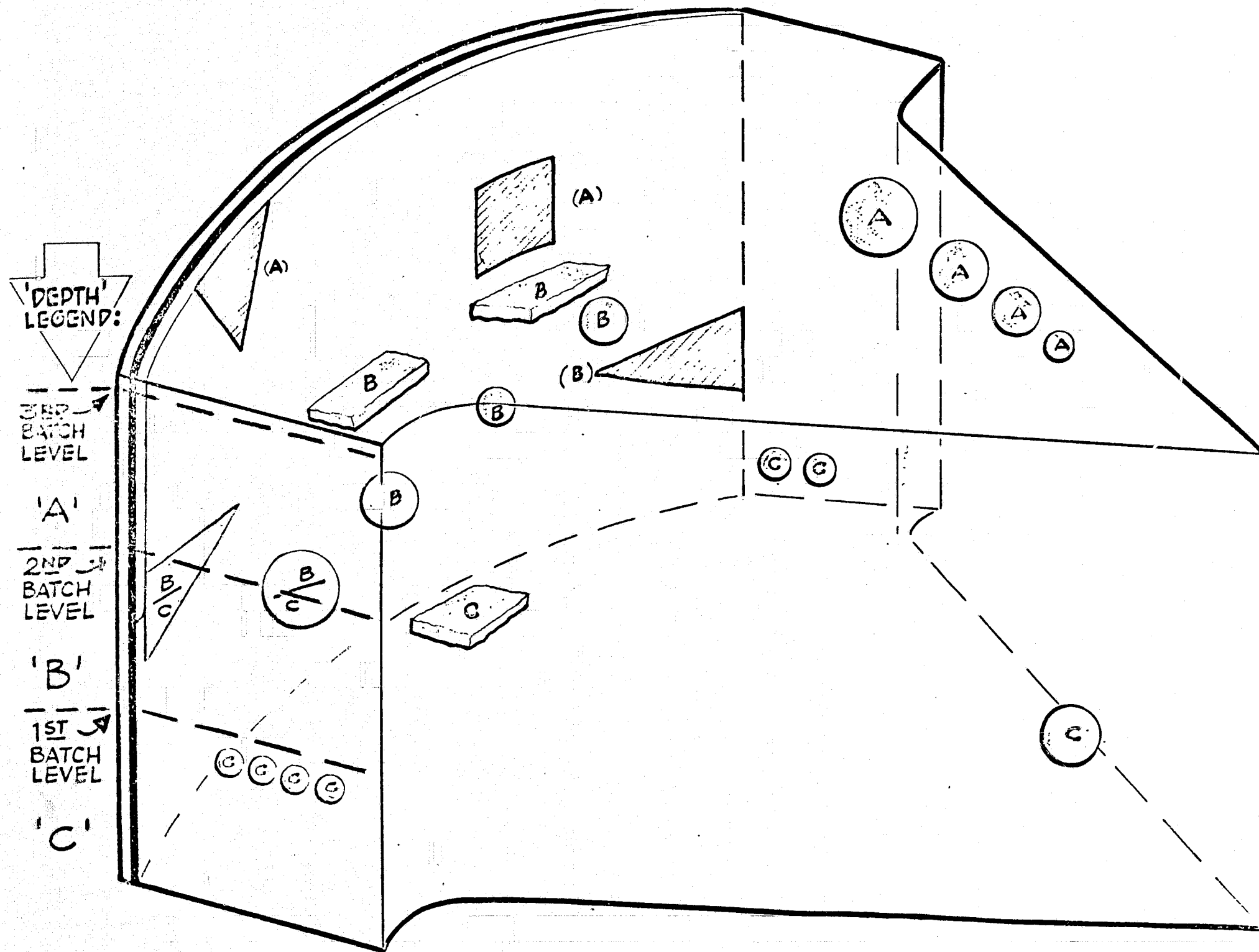


Figure 6. - Sketch of Grain Defect

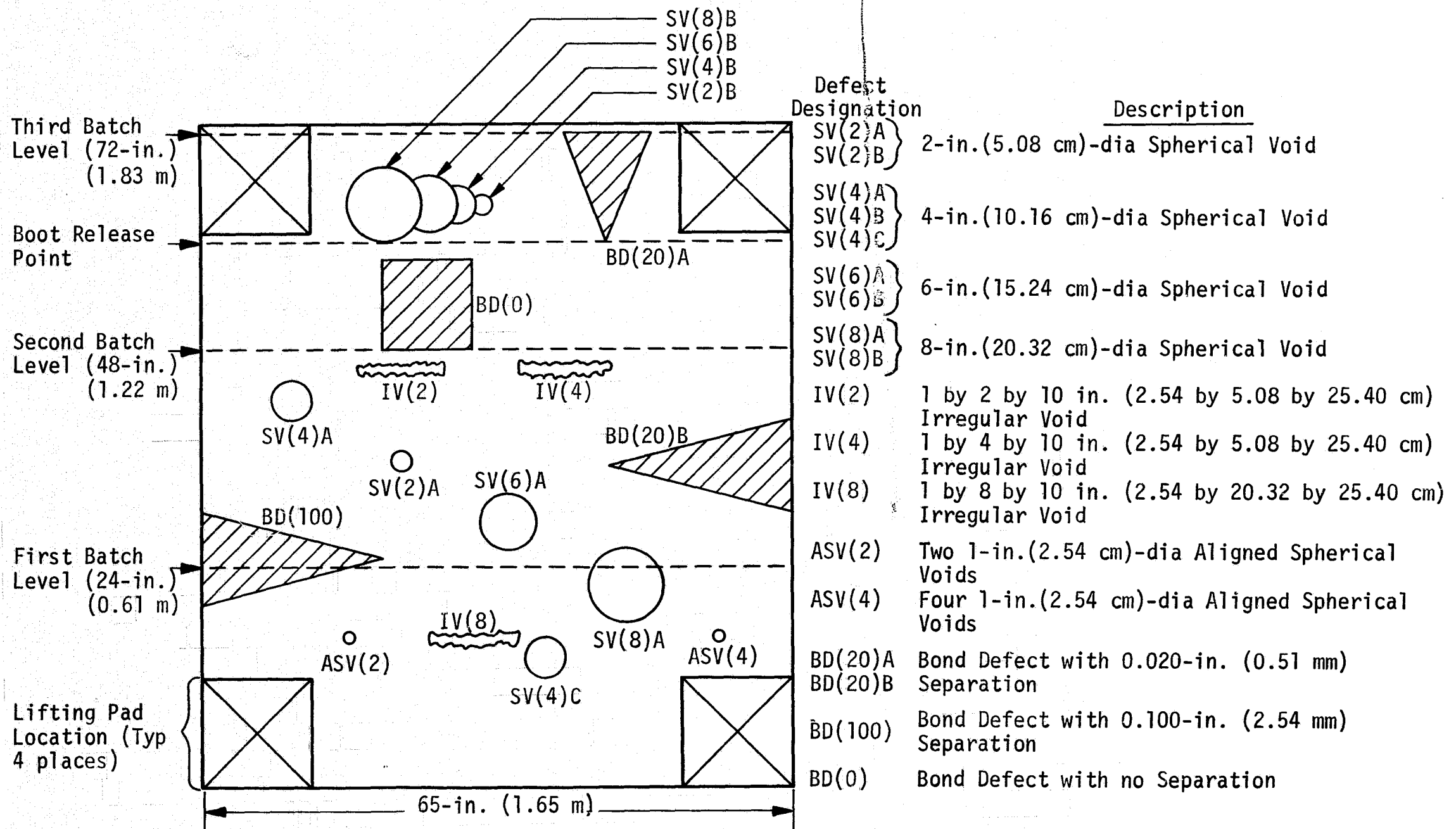


Figure 7. - End View of Defect Grain Configuration

Note:

1. 8-in. (20.32 cm) slab placed on top of ray not shown.
2. Each cassette backed with 1/4-in. (6.35 mm) lead shielding.
3. 260-F7-1, 2, 3 - linac source at 42 in. (1.07 m) from base.
260-F9-1, 2, 3 - linac source at 42 in. (1.07 m) from base.
260-F8-1, 2, 3, 4, 5 - linac source at 22 in. (0.56 m) from base.

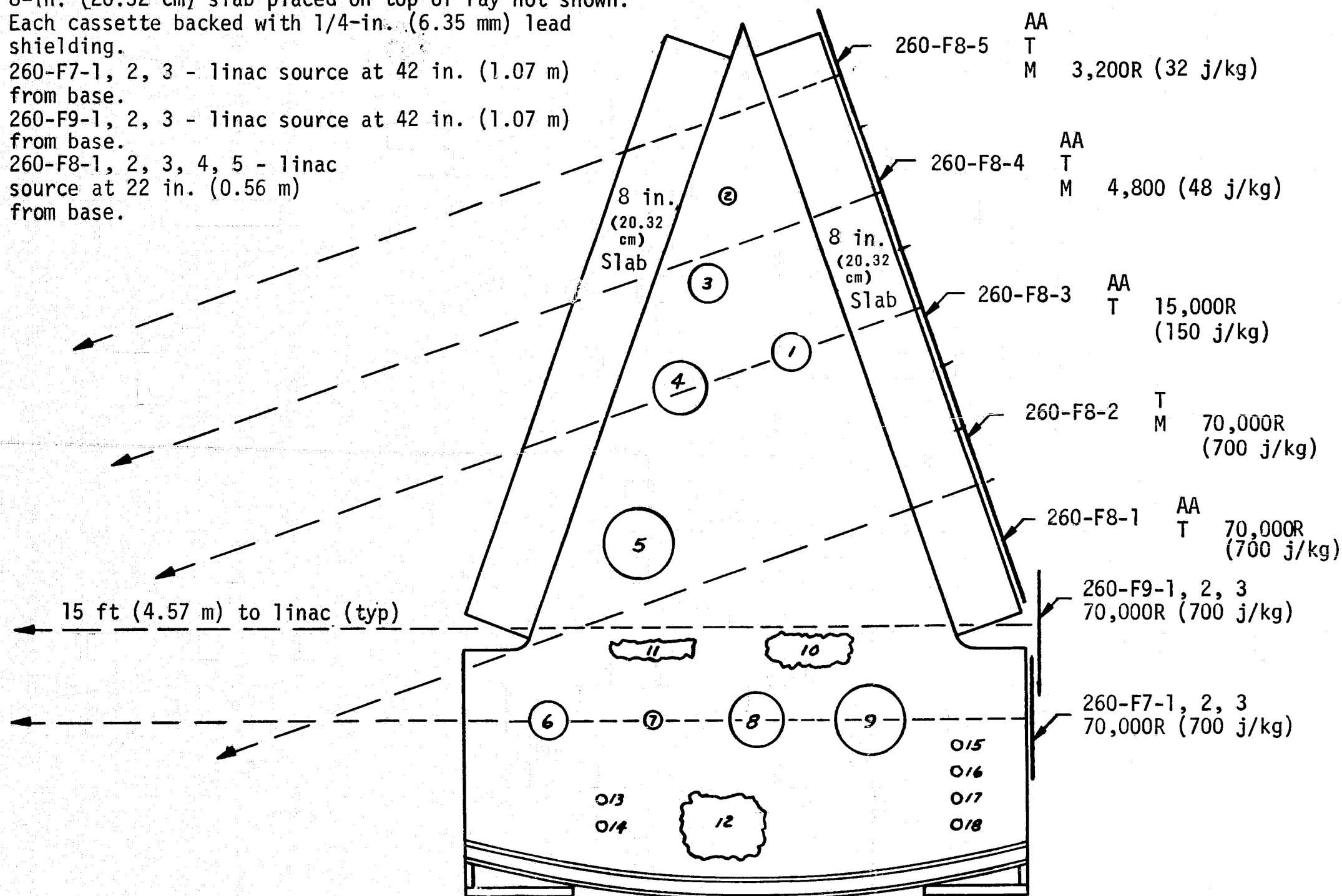


Figure 8. - Top View of Defect Grain Sample

<u>Exposure Number</u>	<u>Film Type</u>	<u>Number in Cassette</u>	<u>Exposure R (j/kg)</u>	<u>Penetrameters</u>
260-F7-1	AA	2	70,000 (700)	None
260-F7-2	AA	2	70,000 (700)	1
260-F7-3	AA	2	70,000 (700)	None
260-F8-1	AA+T	2	70,000 (700)	None
260-F8-2	T+M	2	70,000 (700)	2
260-F8-3	AA+T	2	15,000 (150)	2
260-F8-4	AA+T+M	3	4,800 (48)	2
260-F8-5	AA+T+M	3	3,200 (32)	1
260-F9-1	AA	2	70,000 (700)	1
260-F9-2	AA	2	70,000 (700)	1
260-F9-3	AA	2	70,000 (700)	1

Figure 9. - Summary of Exposure Data, 260-in. Defect Specimen

<u>Film Number</u>	<u>Significant Details</u>
260-F7-1	No penetrameter - no defects
260-F7-2	Penetrameter, 4-in. (10.16 cm) void 6, flat cracks 11 and 10 (edge only) and one unidentified void.
260-F7-3	No penetrameter, 2-in. (5.08 cm) void 7, 6-in. (15.24 cm) void 8, edge of 8-in. (20.32 cm) void 9.
260-F8-1	Clear - no penetrameter.
260-F8-2	Penetrameter (2) clear.
260-F8-3	Penetrameter (2) clear.
260-F8-4	Penetrameter (2) not clear, numerous small indications.
260-F8-5	Penetrameter, very severe density changes, small indications.
260-F9-1	Penetrameter, very severe density changes.
260-F9-2	Penetrameter, 4-in. (10.16 cm) void 6 visible, at least six separate unplanned voids visible.
260-F9-3	Penetrameter, part of 2-in., 6-in., and 8-in. (5.08 cm, 15.24 cm, 20.32 cm) voids visible.

Figure 10. - Summary of Significant Inspection Results

10 mev linac at 500R/m/m*
 $(1.6 \times 10^{-12} \text{ j linac at } 5 \text{ j/hg/min at } 1 \text{ m})$

Specimen	Thickness,		Approx. Total Intensity		Exposure Time, min
	in.	(m)	(R)	(j/kg)	
1 and 2**	16	(0.406)	550	(5.50)	1.05
3	24	(0.61)	1,200	(12.00)	2.40
4	32	(0.81)	2,600	(26.00)	5.20
5	40	(1.02	6,800	(68.00)	13.60
6	48	(1.22)	14,960	(149.60)	30.00
7	56	(1.43)	32,918	(329.18)	66.00
8	64	(1.62)	72,000	(720.00)	148.00
9***	72	(1.83)	160,000	(1600.00)	320.00
10***	80	(2.04)	350,000	(3500.00)	720.00
11***	88	(2.24)	770,000	(7700.00)	1,540.00

* Actually operated at ~8 MeV (1.28 by 10^{-12} j)

** Specimen 1 contains 0.625-in.(15.88 mm)-thick steel plate

***Intensity and exposure time estimated

Figure 11. - Total Intensity and Exposure Time for ANB-3350 Propellant

Linac Energy, MeV	(j/kg)	HVL, in. (cm)		Number HVL in Grain Thickness,				Half-Angle Degree (Radian) of			
				71 in. (180 cm)	88 in. (224 cm)	94 in. (239 cm)	100 in. (254 cm)	1/2 intensity (radian)	3/4 intensity (radian)	5.5	0.10
10	1.6×10^{-12}	6.5	16.51	10.9	13.5	14.5	15.4	9.0	0.16	5.5	0.10
12	1.9×10^{-12}	6.8	17.27	10.4	13.0	13.8	14.7	7.5	0.13	4.5	0.08
22	3.5×10^{-12}	7.7	19.56	9.2	11.5	12.2	13.0	4.5	0.08	2.7	0.05
25	4.0×10^{-12}	8.0	20.32	8.9	11.0	11.7	12.5	3.8	0.07	2.3	0.04
30	4.8×10^{-12}	8.3	21.08	8.6	10.9	11.3	12.1	3.0	0.05	2.0	0.03

Figure 12.- Linear Acceleration, Propellant Penetrating Capability.

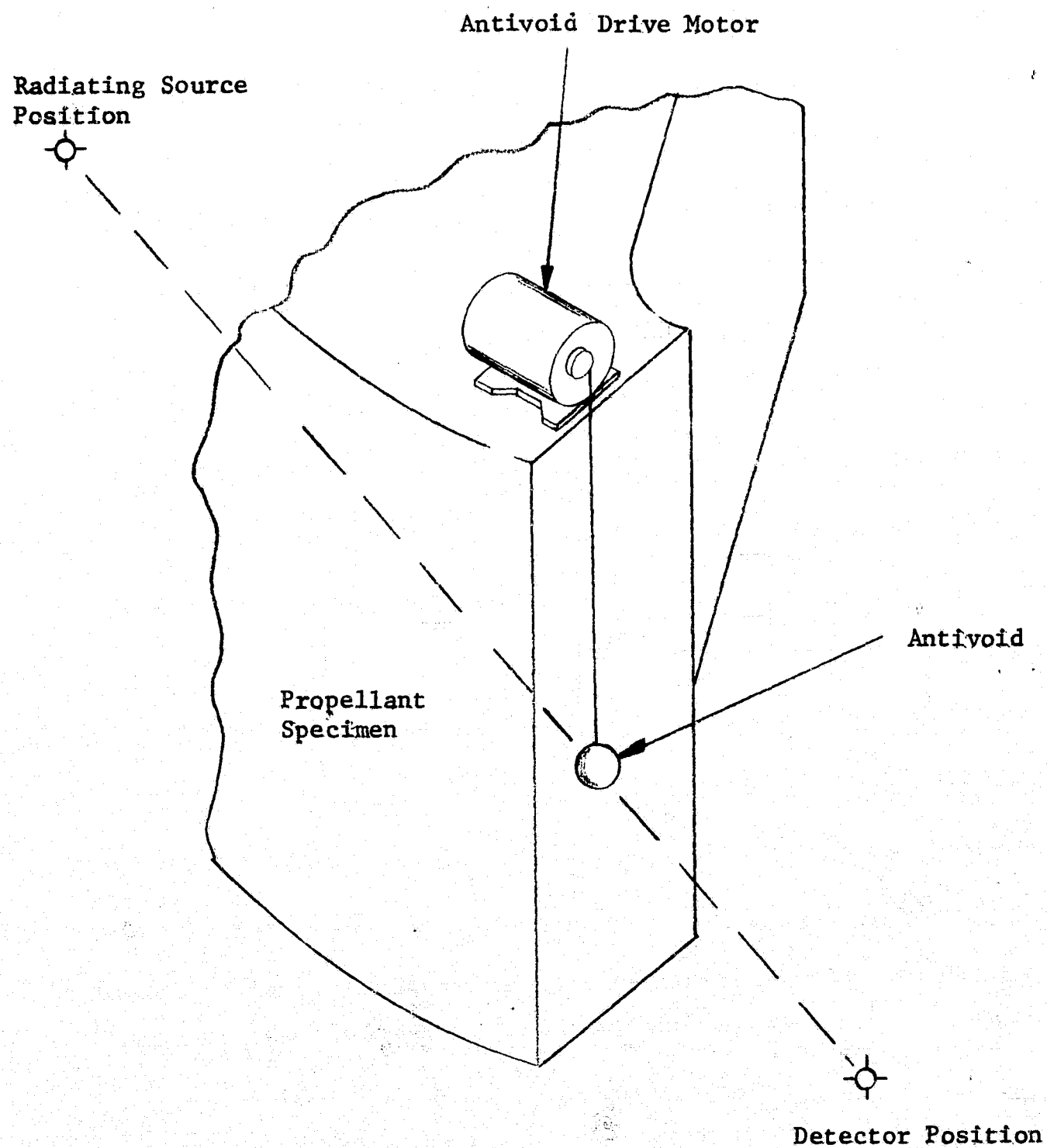


Figure 13. - Antivoid Test Arrangement

Flaw		Propellant Thickness, in. (cm)		I/I ₀		Detection
				0.5 MeV (0.08 x 10 ⁻¹²)	1.0 MeV (0.16 x 10 ⁻¹²)	
2-in. void	(5.08 cm)	65	165.10	2.46	2.56	Count
4-in. void	(10.16 cm)	65	165.10	4.72	4.30	Count
4-in. antivoid	(10.16 cm)	65	165.10			Current
4-in. antivoid	(10.16 cm)	65	165.10	1.532	1.974	Count
4-in. antivoid	(10.16 cm)	34	86.36	2.577	2.787	Count
4-in. antivoid	(10.16 cm)	34	86.36			Current
2-in. antivoid	(5.08 cm)	34	86.36	1.564	1.640	Count
2-in. antivoid	(5.08 cm)	34	86.36			Current

Figure 14. - Count/Current Mode Flow Detection (Co60 Source, 2 by 2 in. (5.08 cm) NaI Detector

<u>Antivoid Diameter,</u> <u>in. (cm)</u>	<u>Propellant Thickness,</u> <u>in. (cm)</u>	<u>Antivoid Position*</u>	<u>I_o/I</u>
4 10.16	65 165.10	SVD	1.2
4 10.16	65 165.10	SVS	1.2
2 5.08	65 165.10	SVD	1.1

*SVD - Void between specimen and detector.
SVS - Void between source and specimen.

Figure 15. - Current Mode Flaw Detection Linac Source,
2 by 2 in. (5.08 cm) NaI Detector

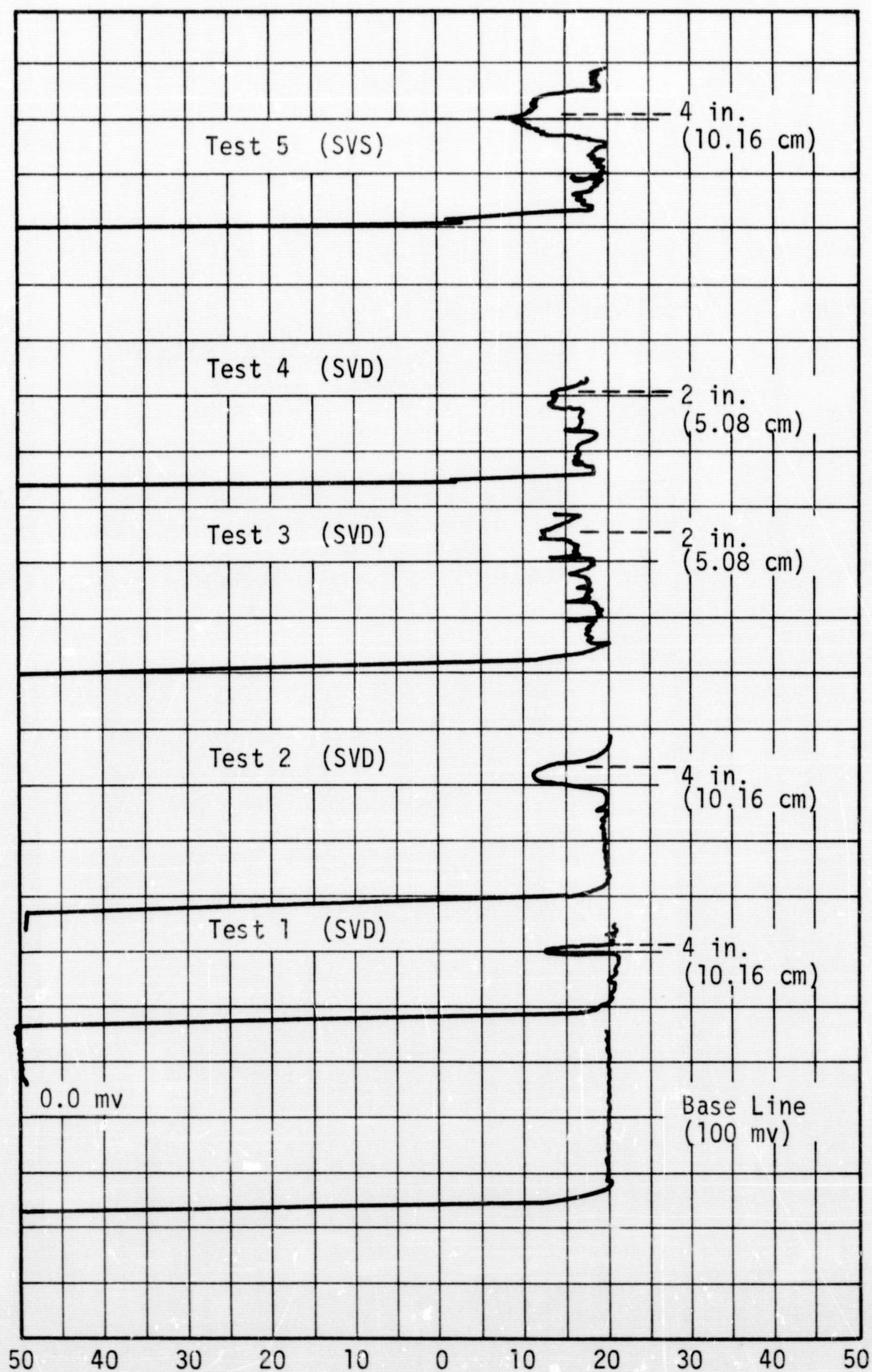


Figure 16. - Traces of 4-in. (10.16 cm) and 2.-in.- (5.08 cm) dia Voids Through 65 in. (165.10 cm) of Propellant

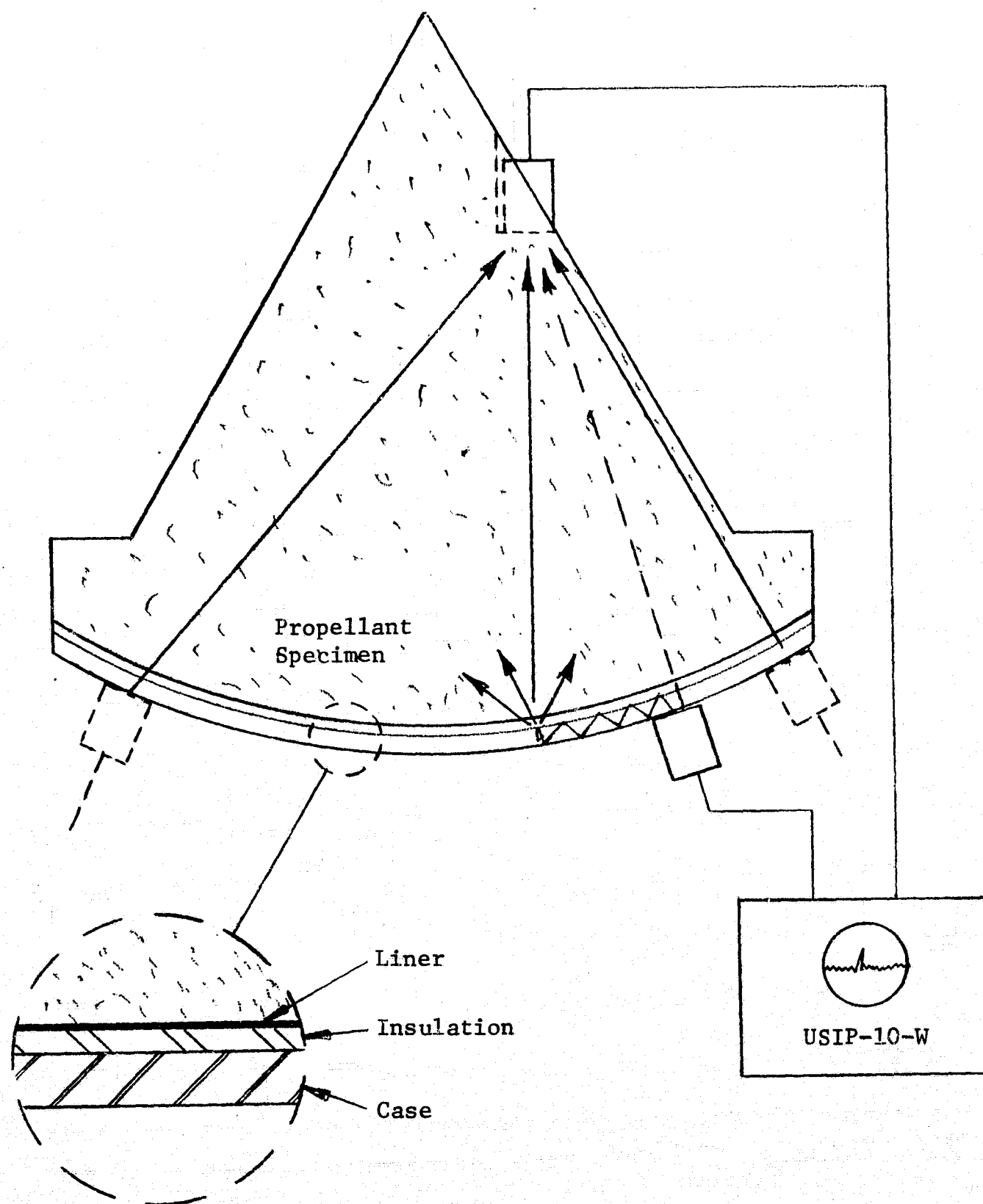
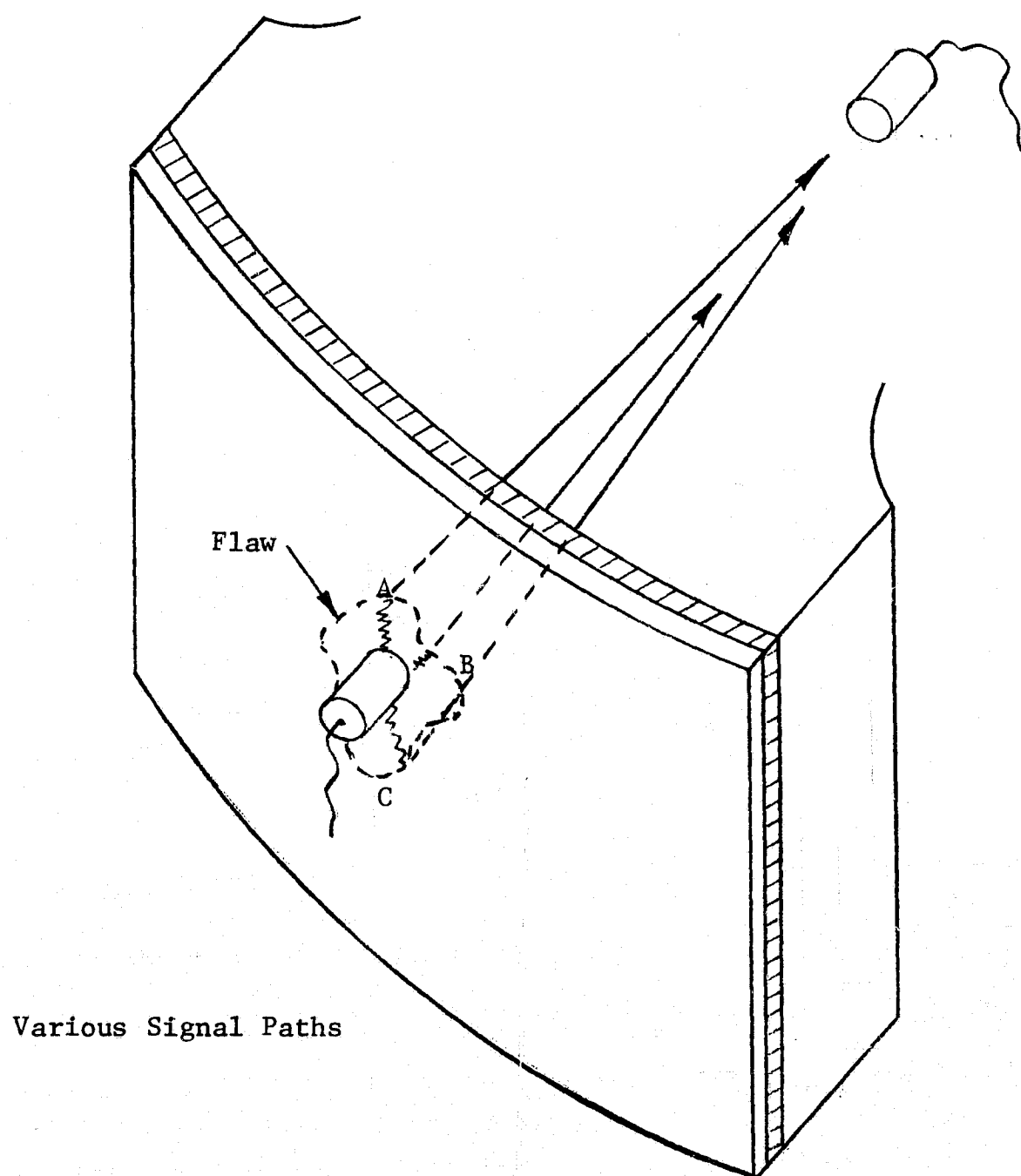


Figure 17. - Through-Transmission Ultrasonic Test



Various Signal Paths

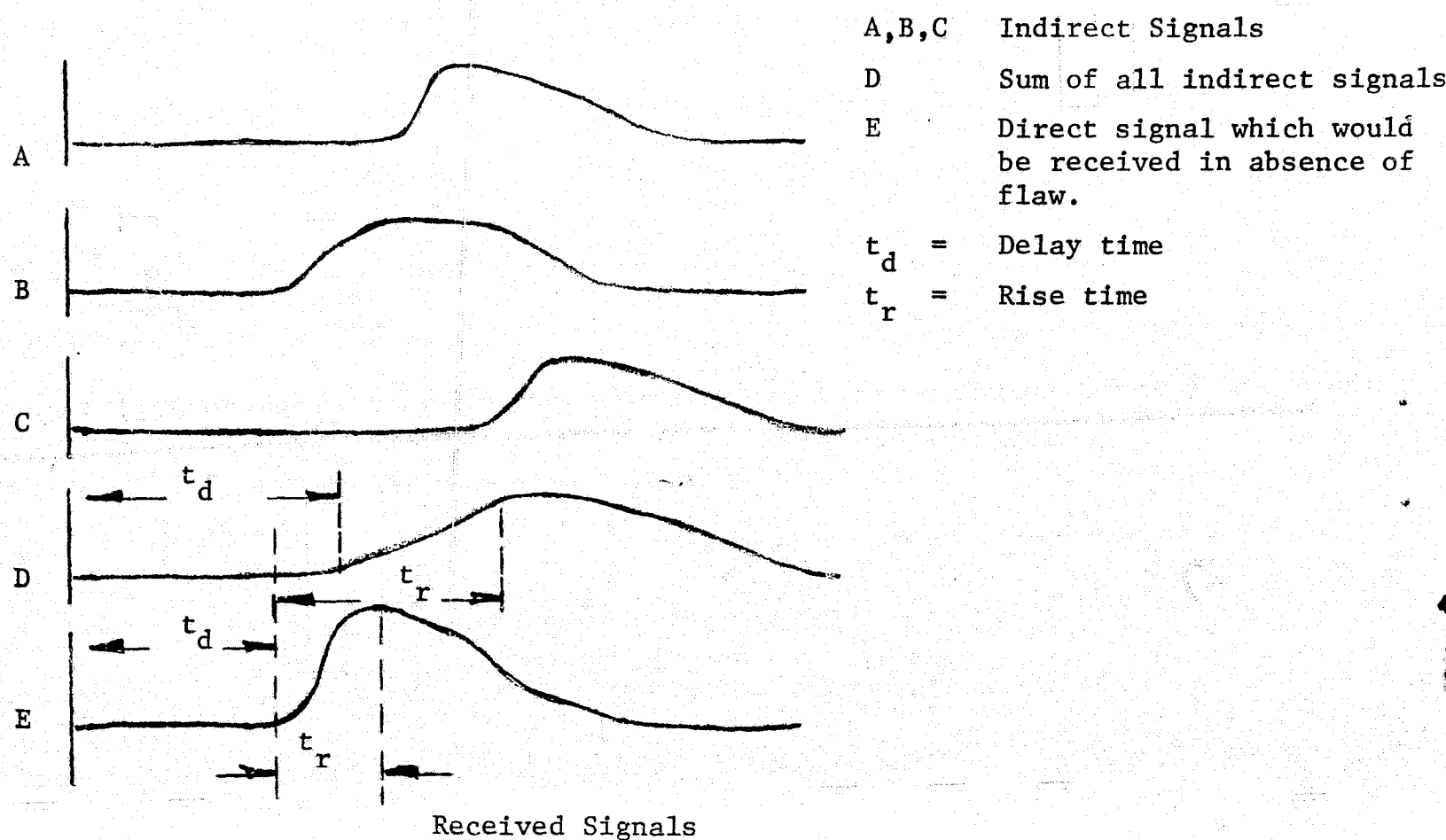


Figure 18. - Through-Transmission Paths and Signals

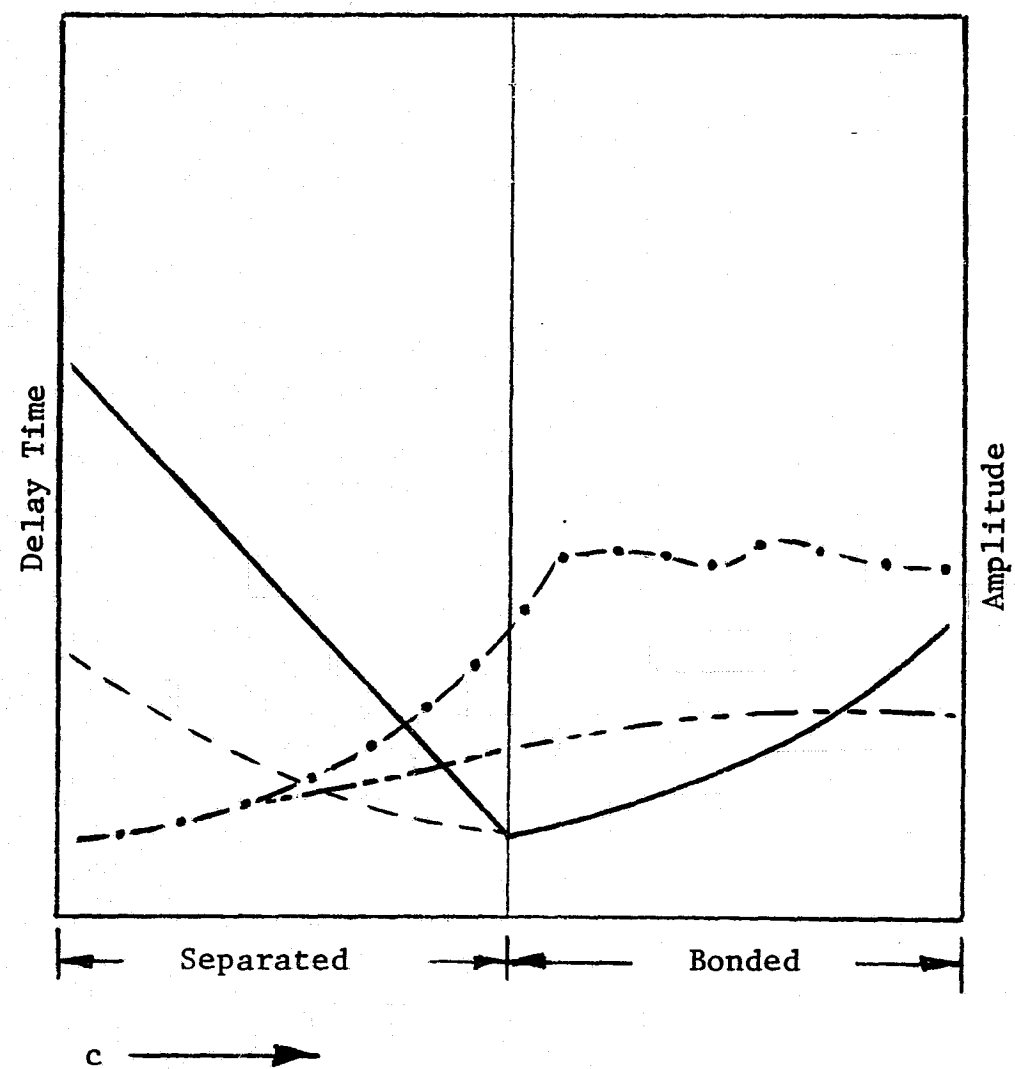
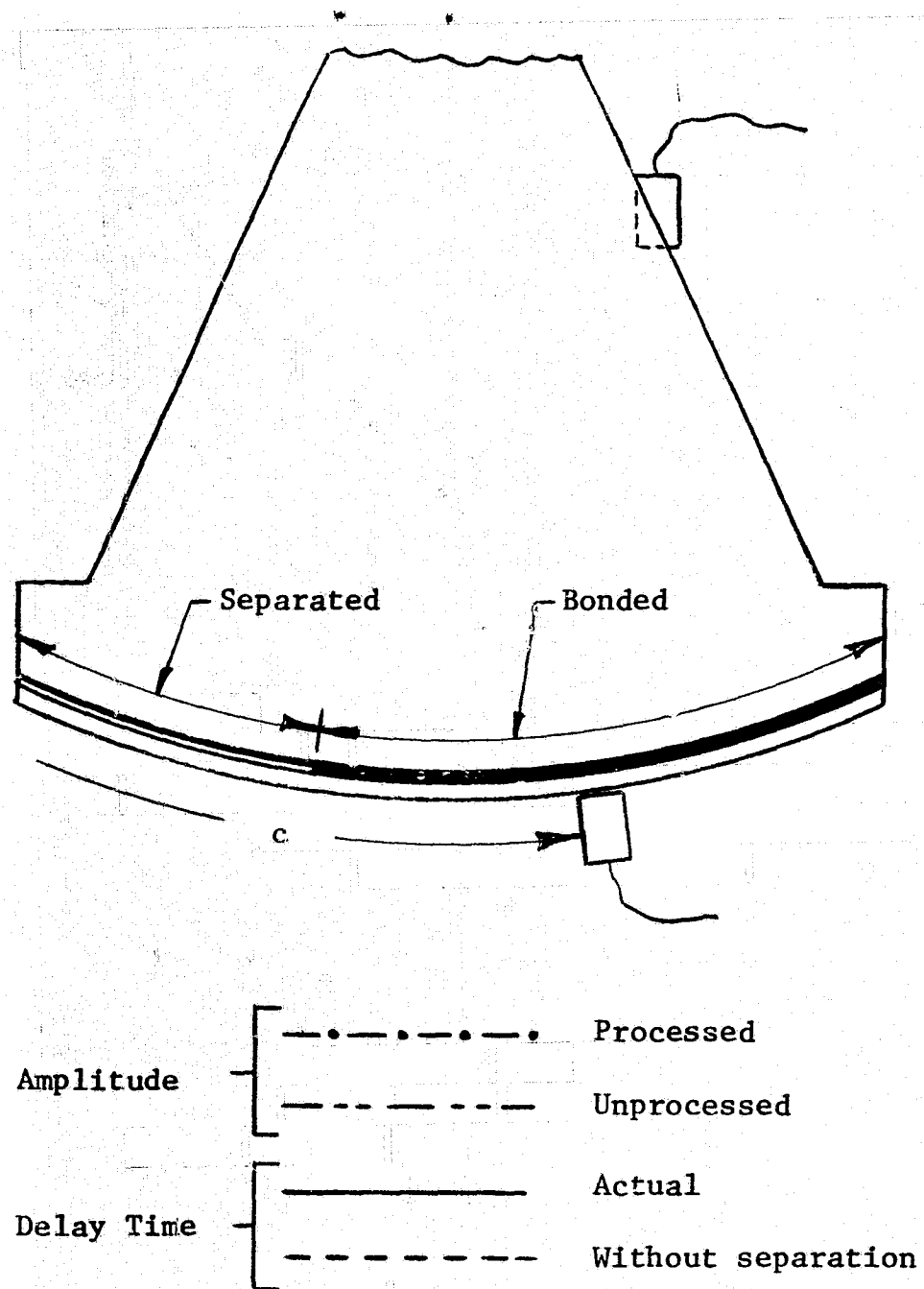


Figure 19. -- Estimated Variation of Signal Variables on Bonded and Separated Regions

Delay Time μ sec Normalized to 0 for Horizontal Position 0
(Experimental Data from Final Report Contract NAS7-367)

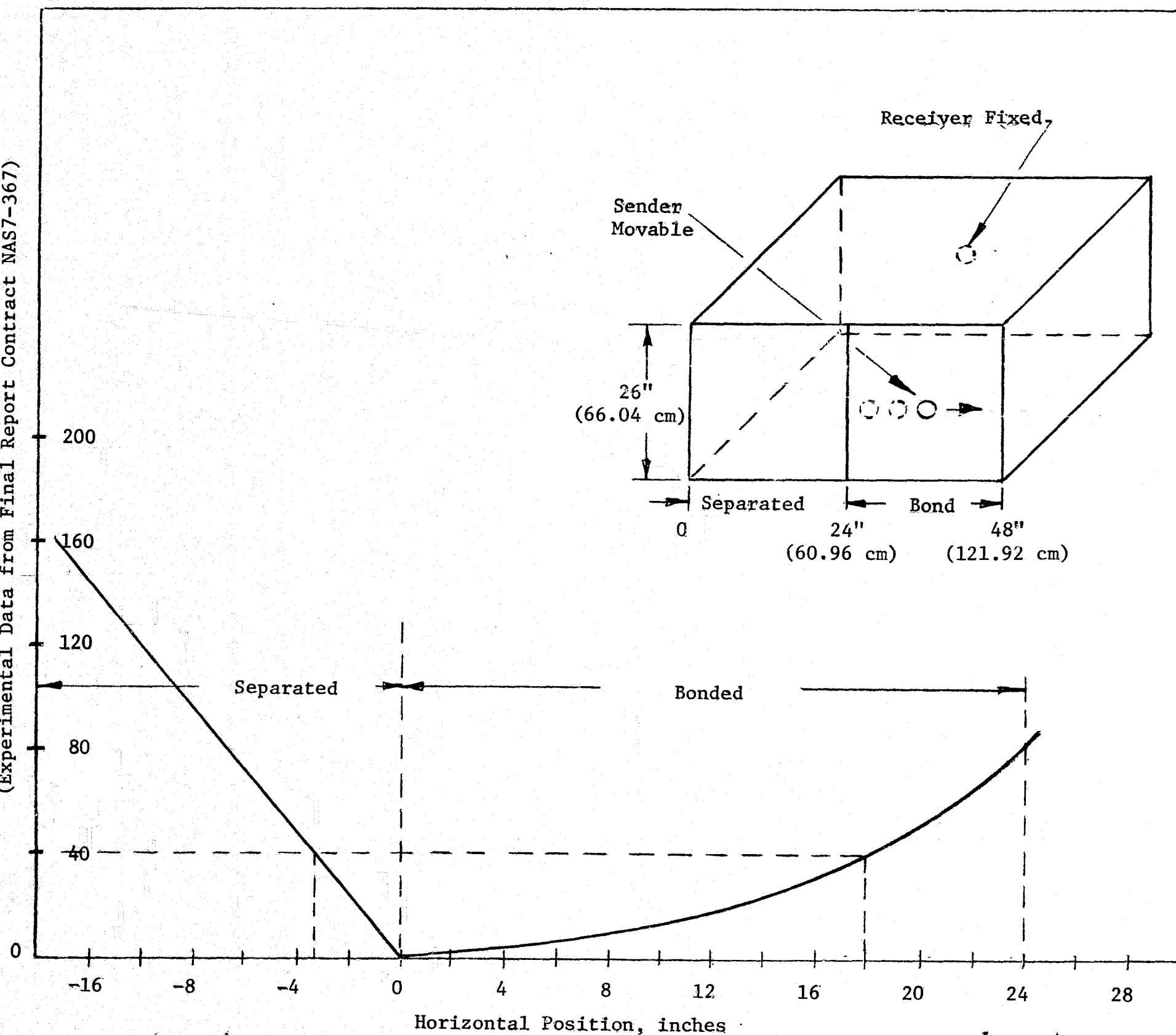


Figure 20. - Through-Transmission Delay Times

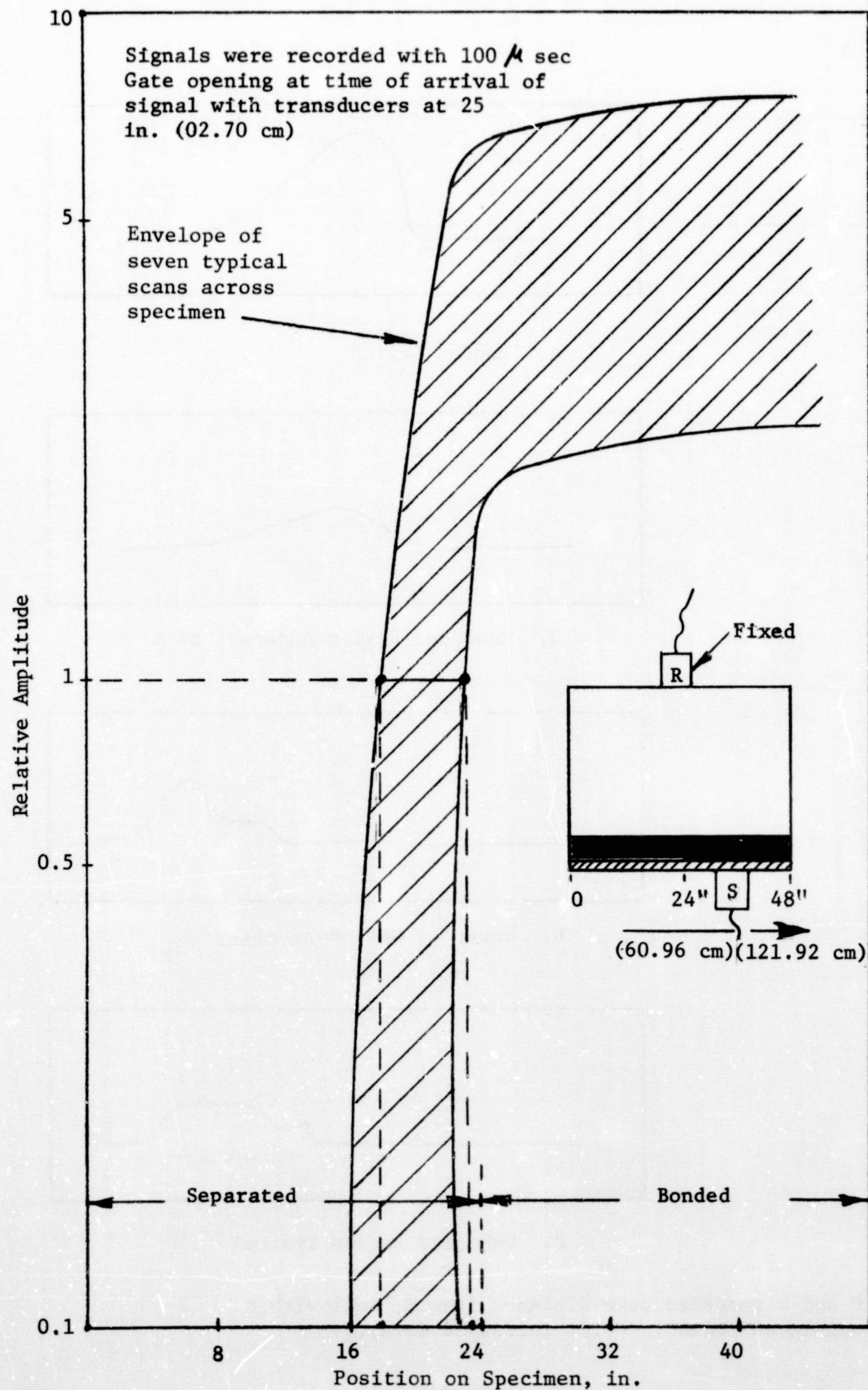
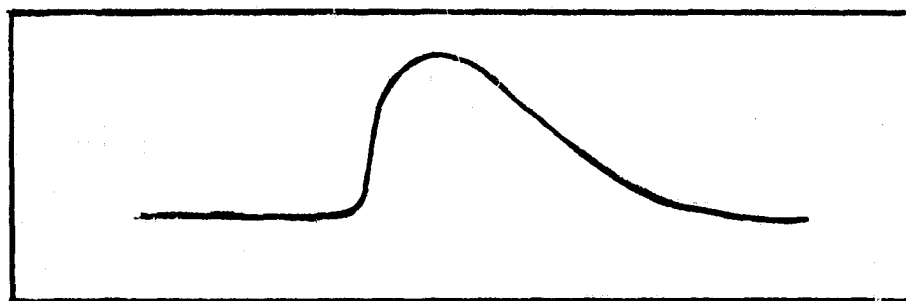
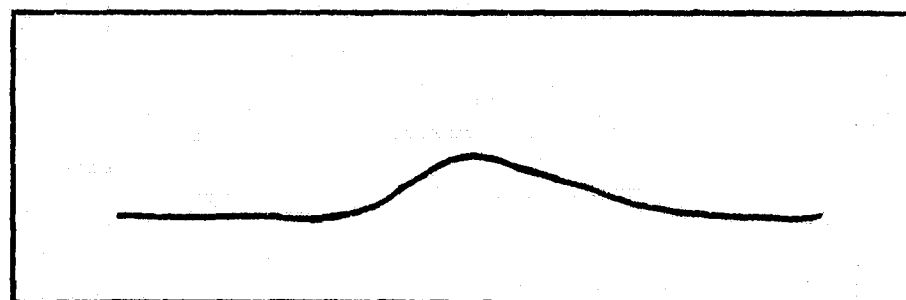


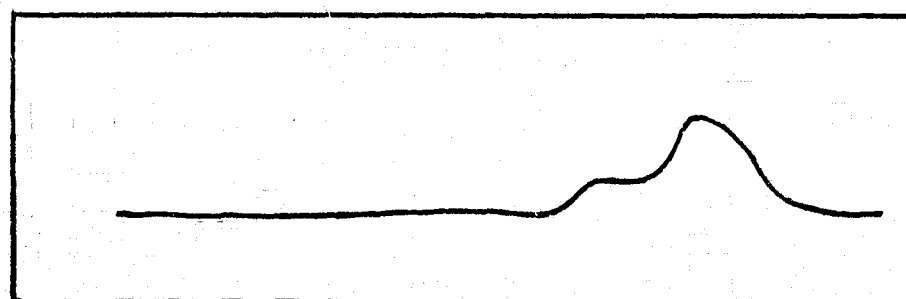
Figure 21. - Maximum Signal Amplitude vs Position Recorded through 100 μ sec Gate



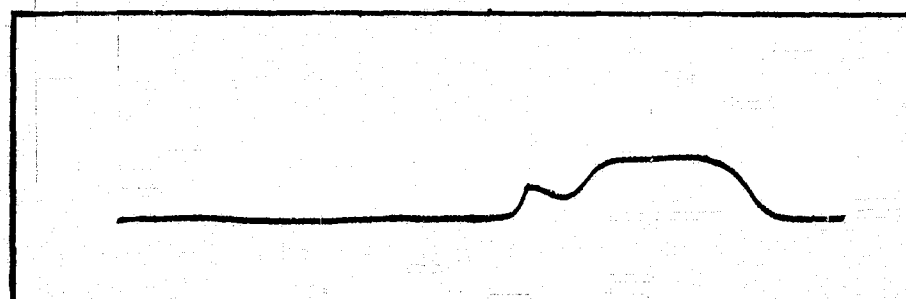
A. Bonded Region



B. Unbonded Region Adjacent to A



C. Unbonded Region Atypical



D. Unbonded Region Typical

C and D recorded some distance from B, well within separated region. NOTE: increased delay.

Figure 22. - Ultrasonic Through Transmission Received Signal Envelopes with USIP-10-W

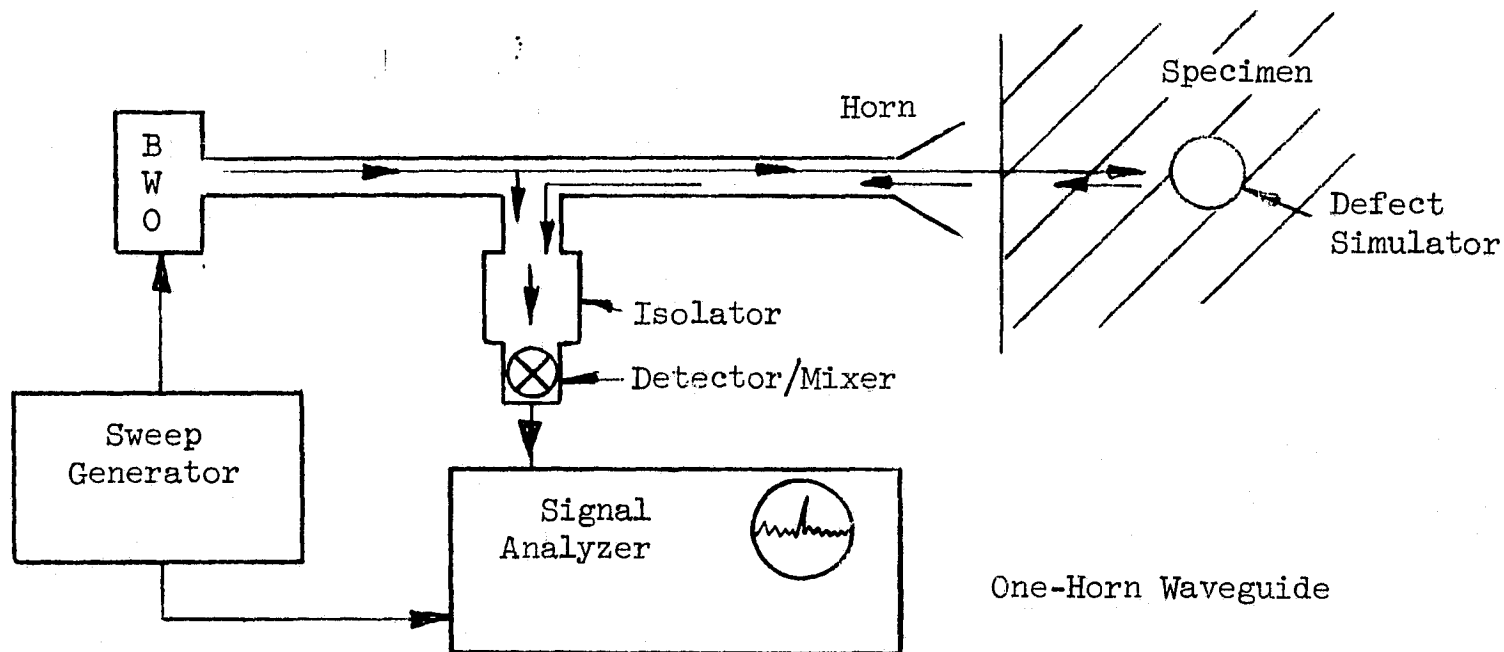


Figure 23A

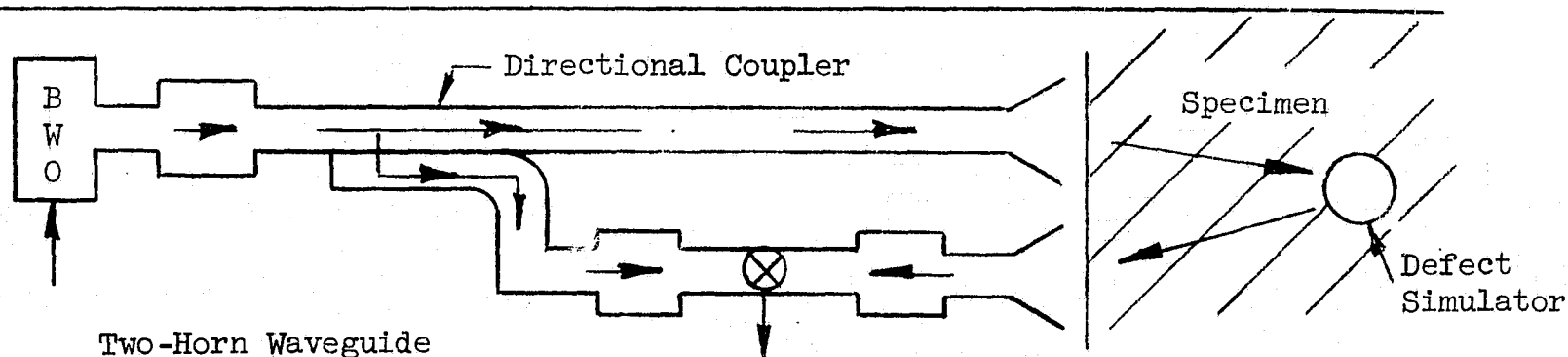


Figure 23B

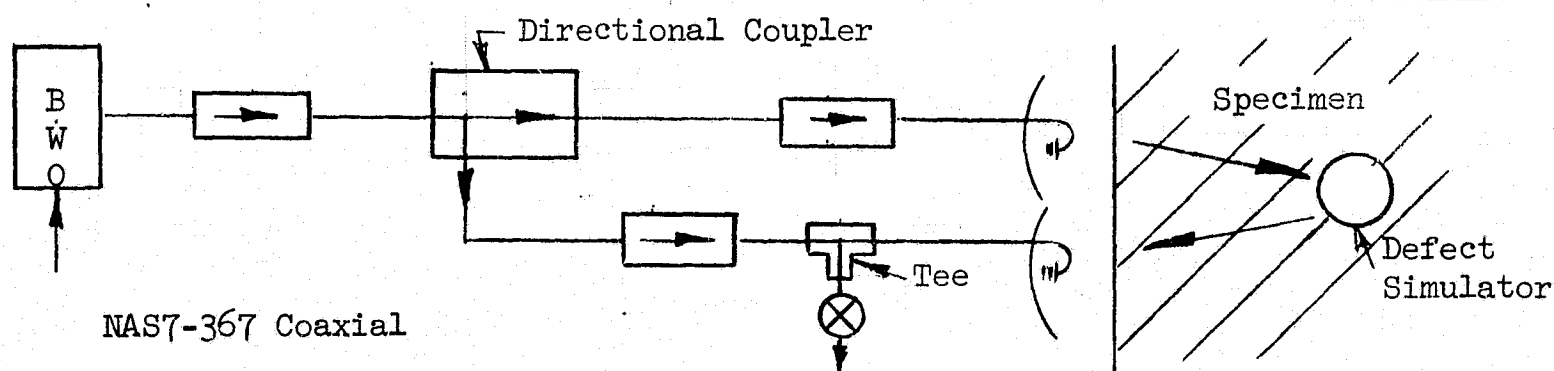


Figure 23C

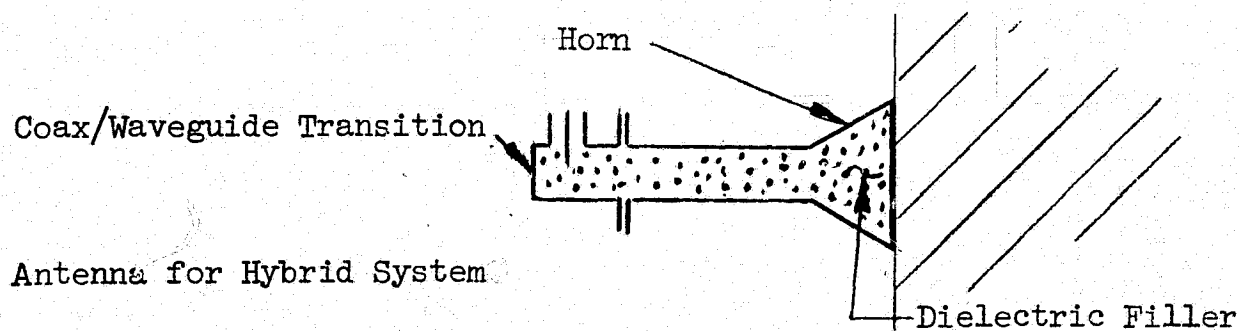
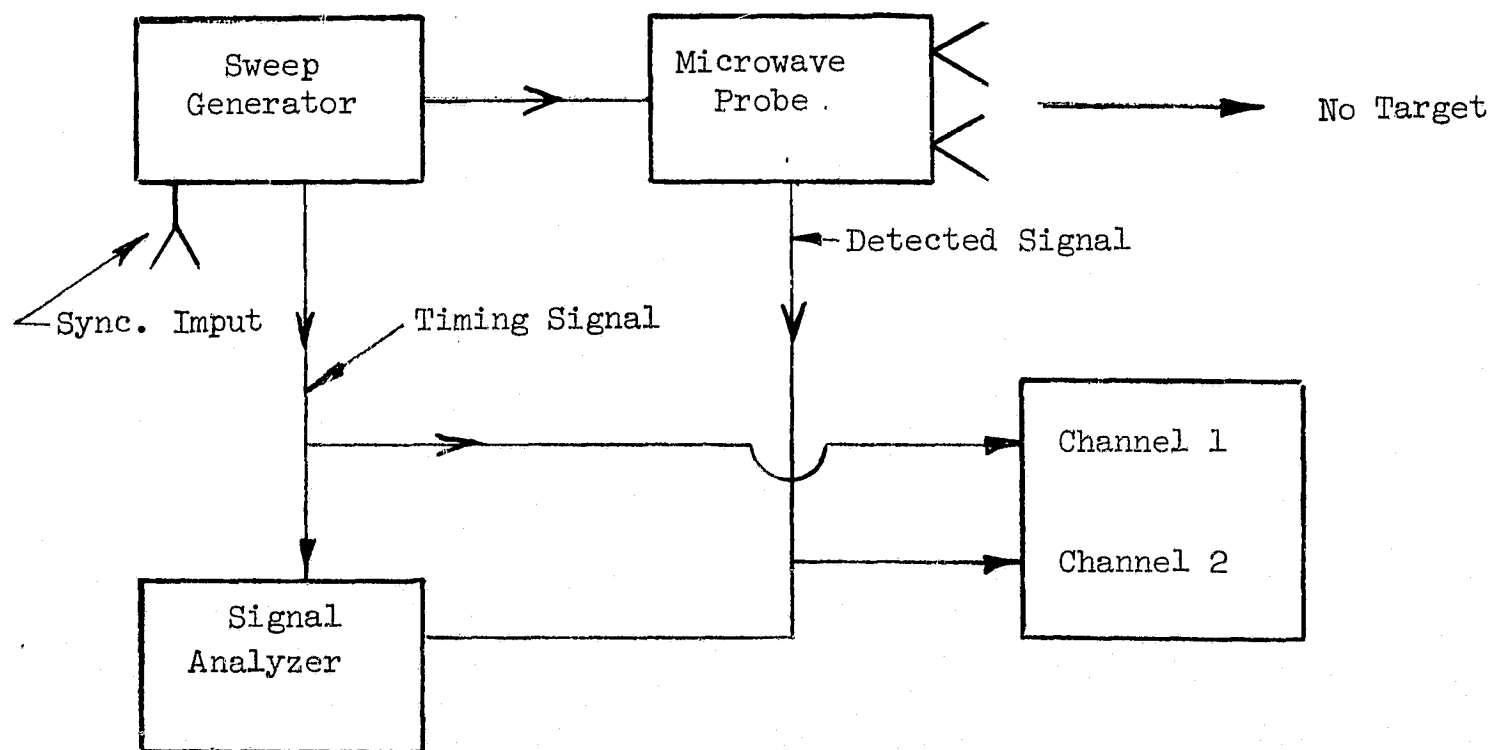
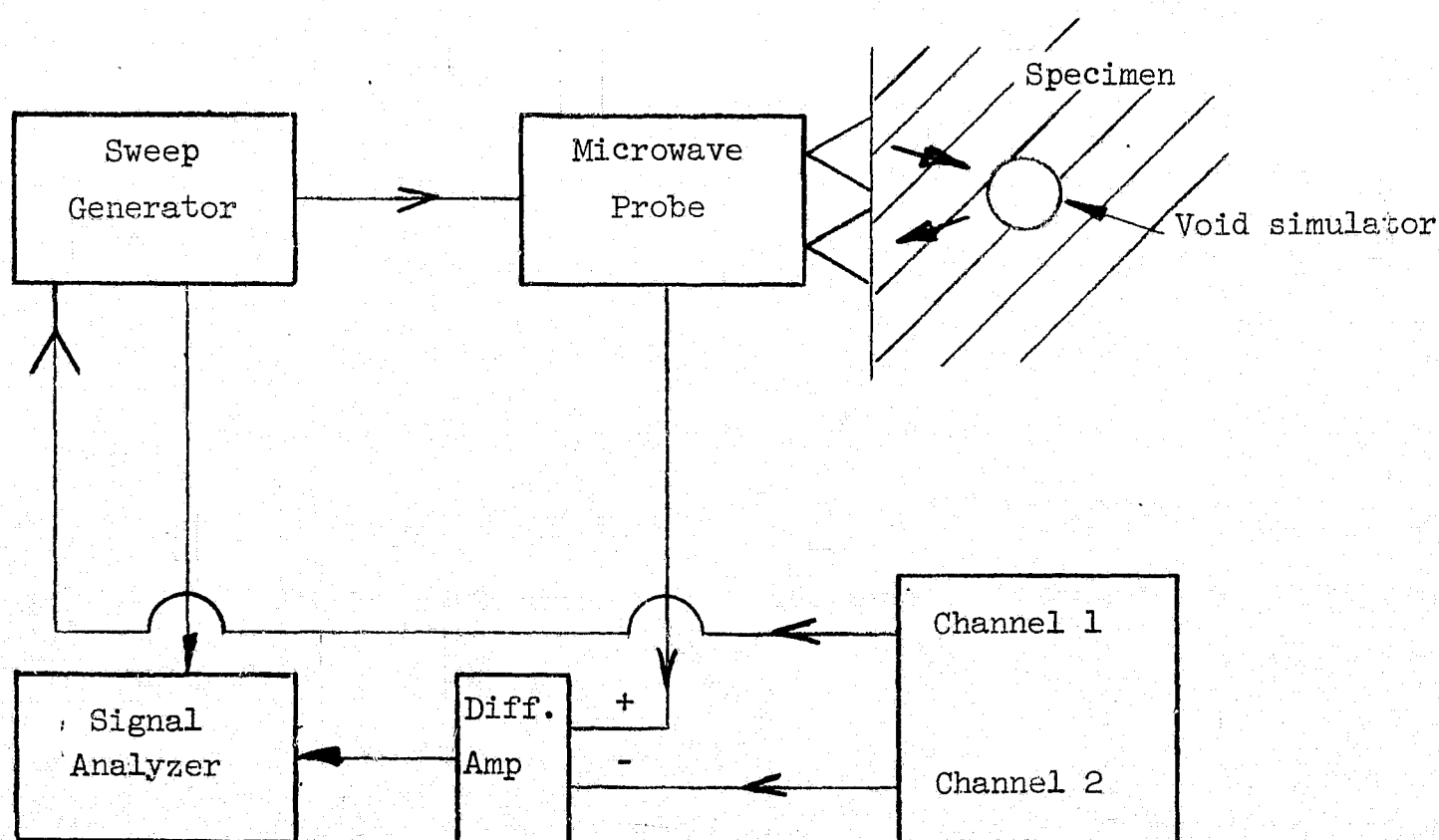


Figure 23D

Figure 23. - Versions of the Waveguide Probe



Tape Recorder (Record Mode)



Tape Recorder (Playback Mode)

Figure 24. - Recording and Subtracting Spurious Signals

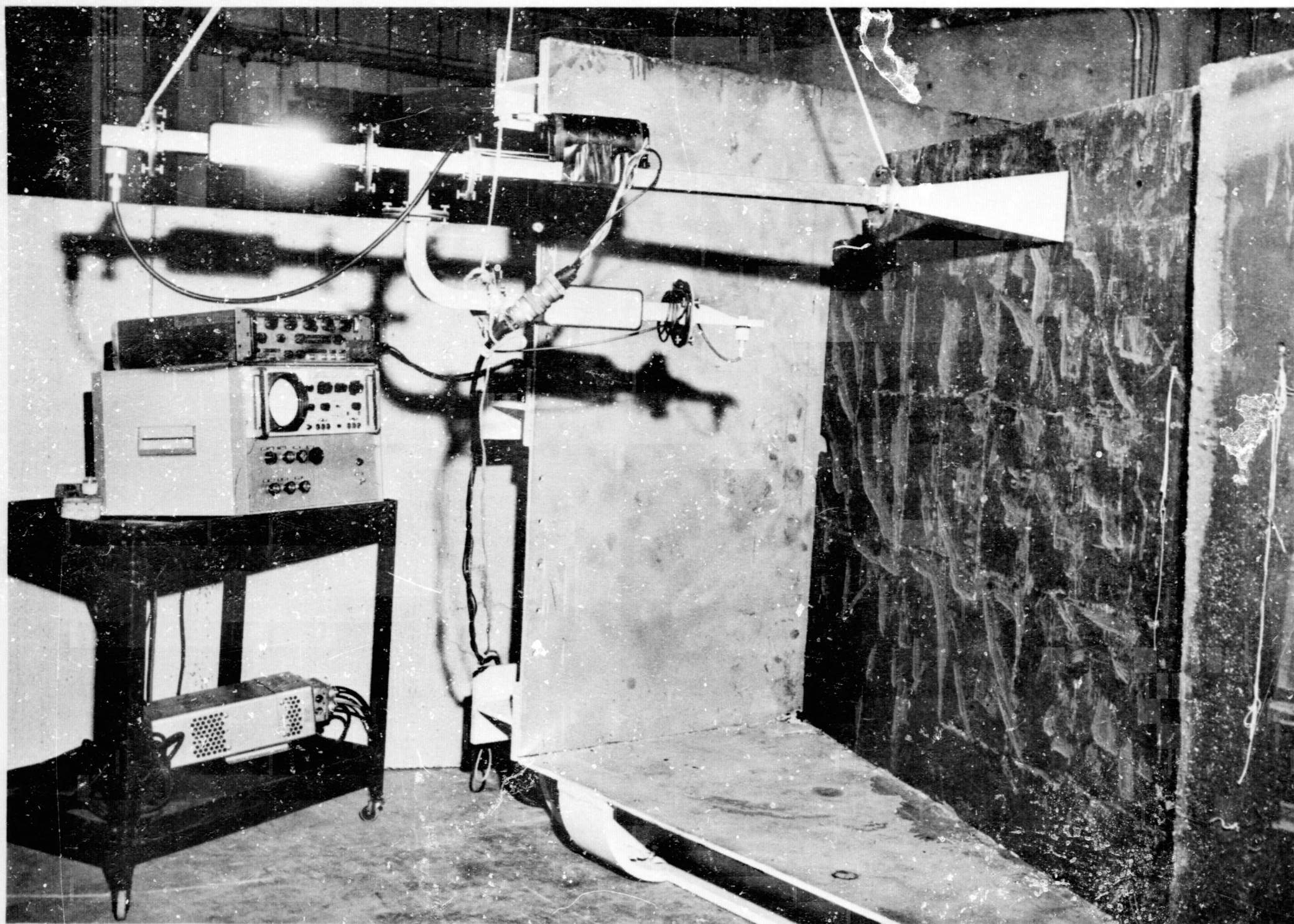
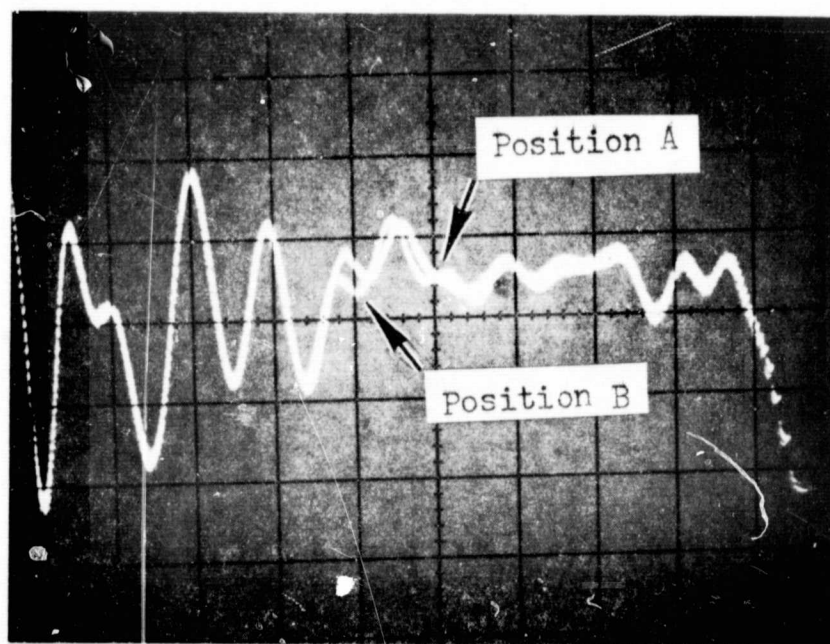


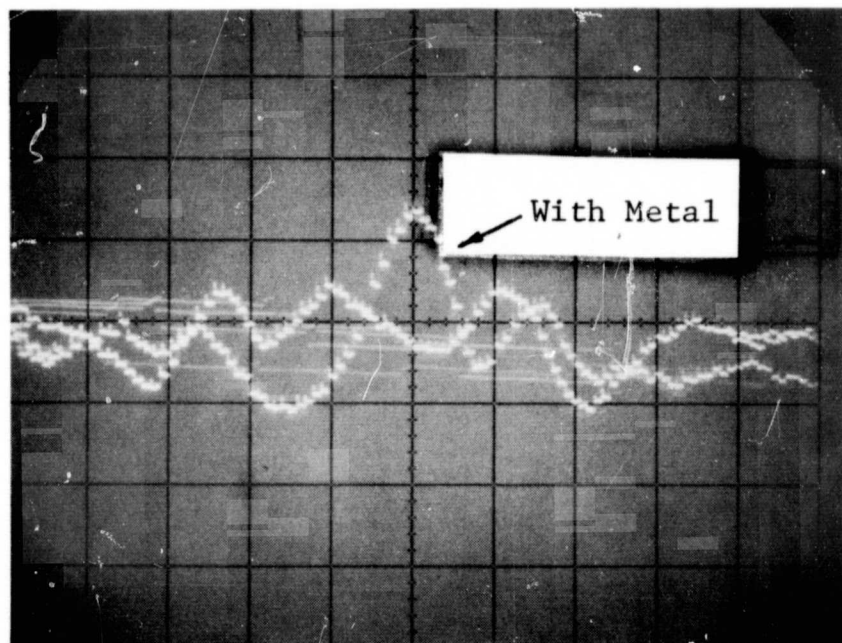
Figure 25 - One Horn Probe Positioned for Inspection (2.6 to 3.9 GHz)



Position A corresponds to 10 ft 8 in.
(3.25 m) in air.

Position B actual back reflection in
large propellant sample.

Figure 26 - Large Propellant Sample Signal Traces
With and Without Metallic Reflector



Back surface through 52 in. (132.08 cm) of
propellant with and without metallic reflector.

Figure 27 - Coaxial/Waveguide System Traces

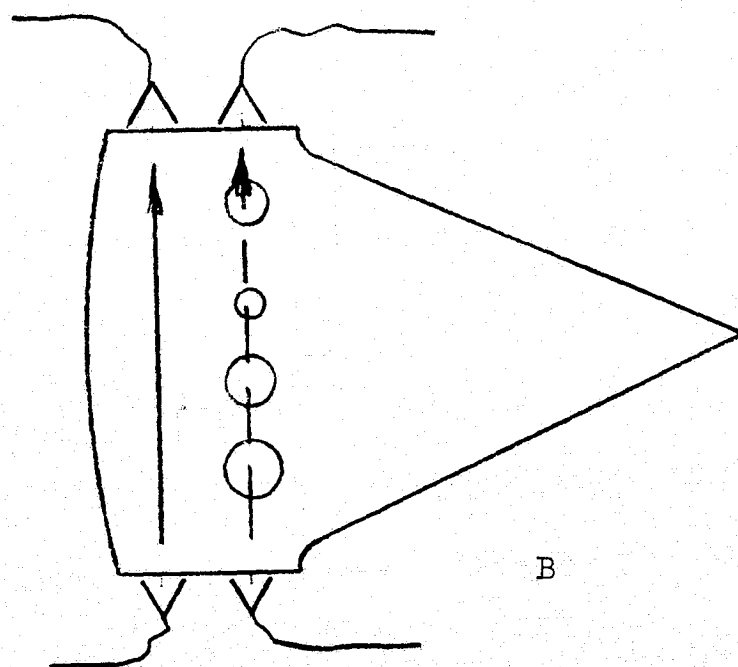
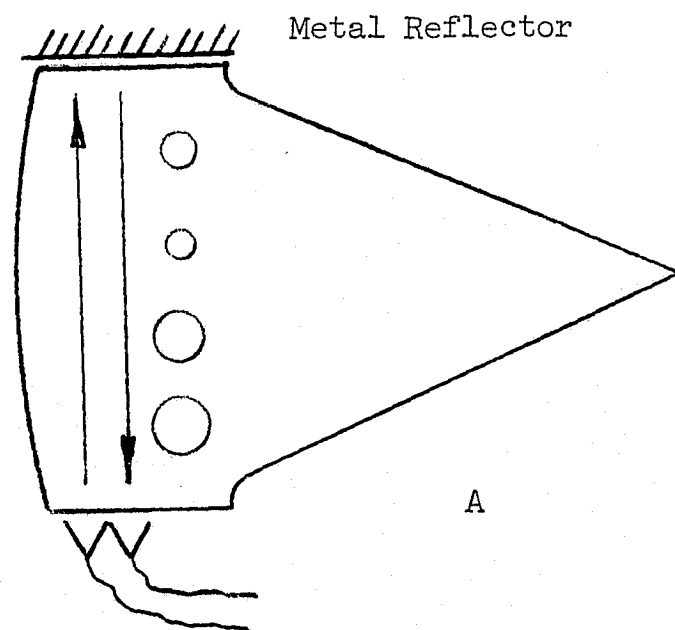
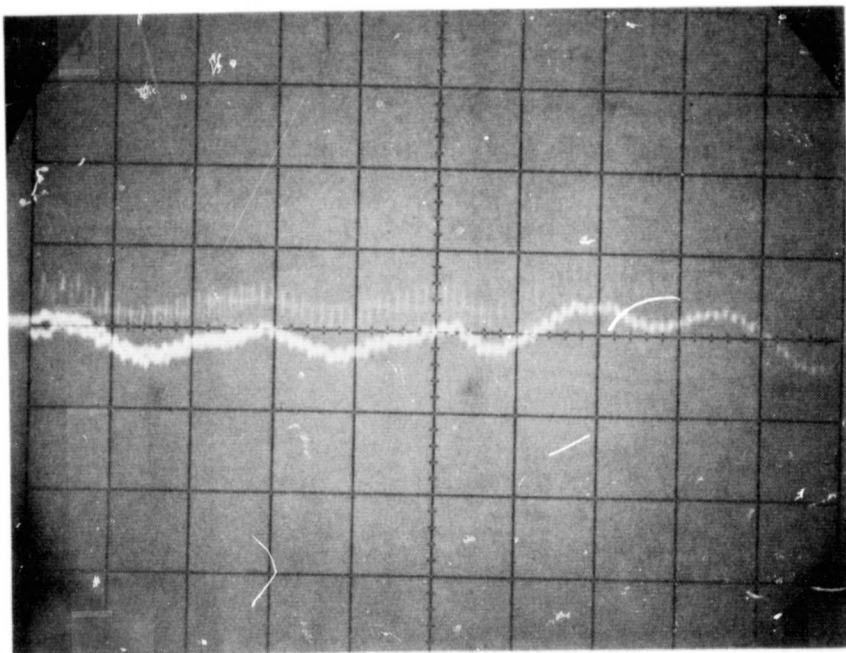
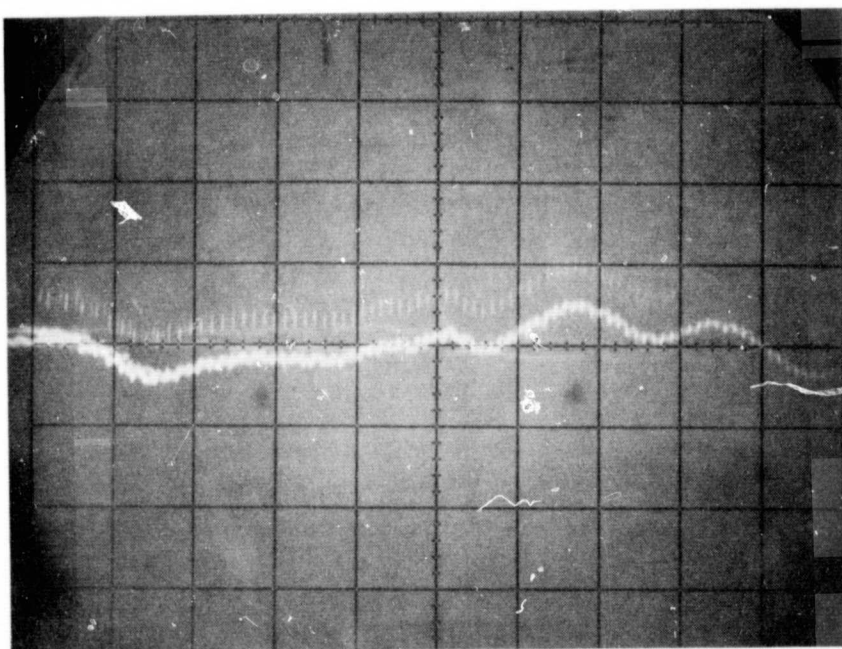


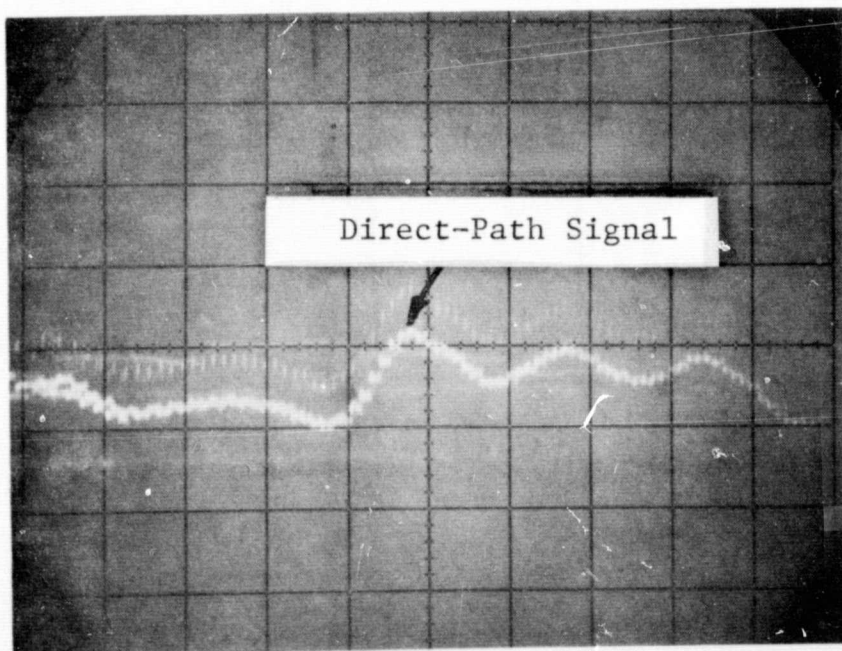
Figure 28. - Two Through-Transmission Tests



A. Horns coupled, looking through 6-in. (15.24 cm)-dia void.



B. Horns uncoupled. Only spurious signals from within waveguide system.



C. Horns coupled, looking through good propellant.

Figure 29 - Through-Transmission Traces

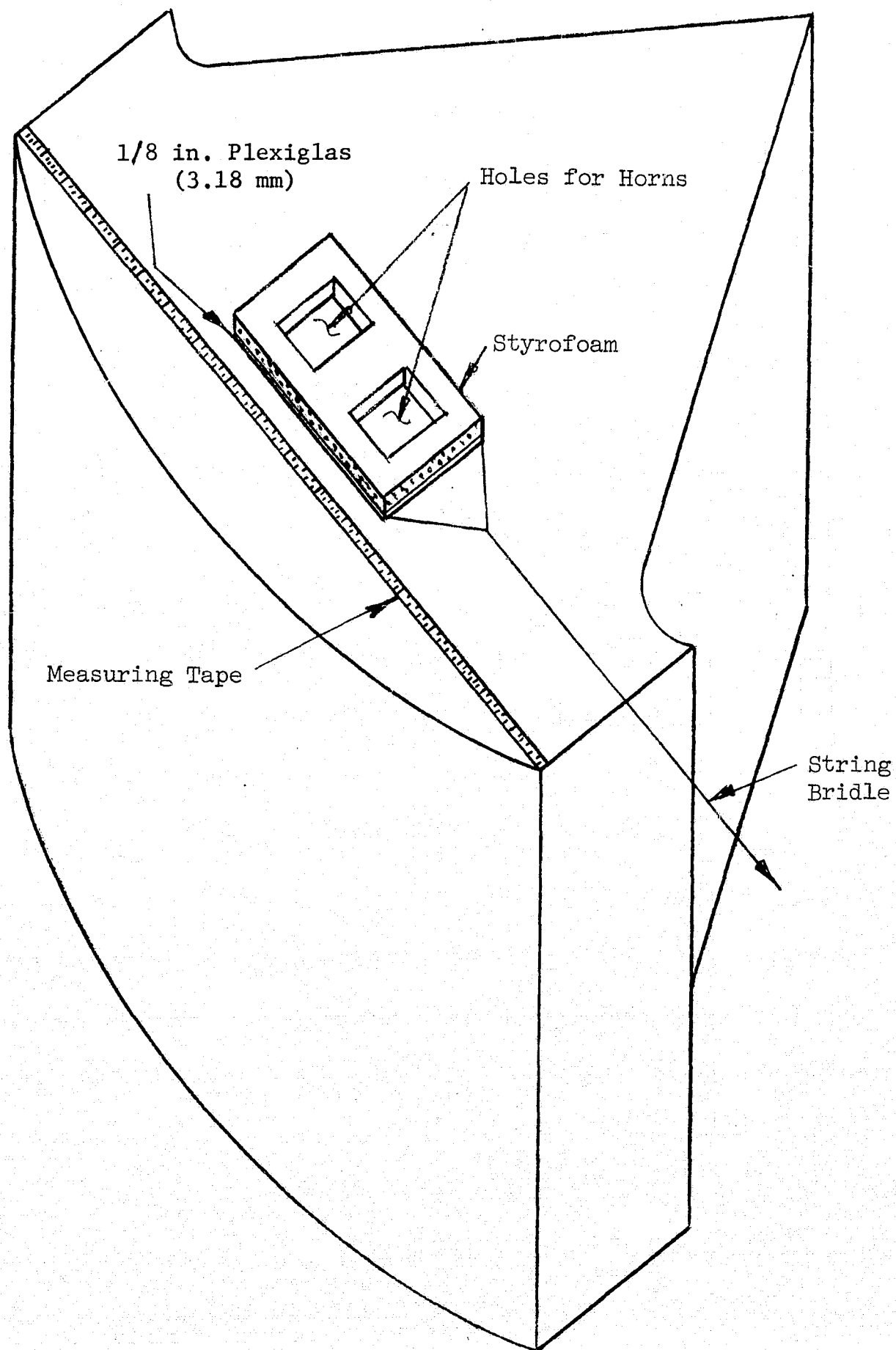
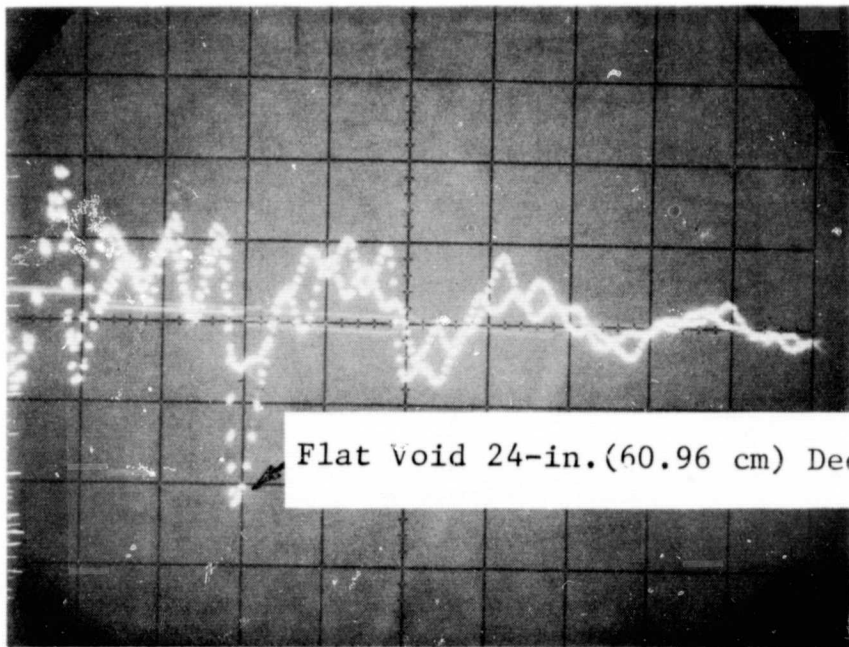
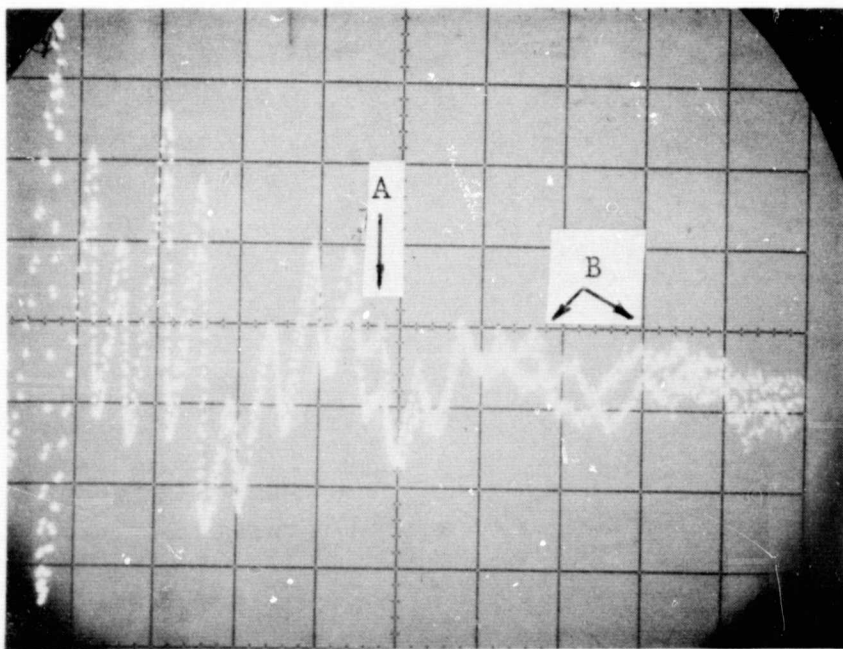


Figure 30. - Horn Scanning Procedure



- A. Flat Void 24-in.(60.96 cm) deep indicated at horizontal position 3-cm trace over void superimposed on trace over adjacent good region.



- B. Flat Void 50-in.(127 cm) deep probable indication is at horizontal position 4.6 cm (A). Note other indications (B). Trace over void superimposed on trace over adjacent good region.

Figure 31 - Fin Specimen Inspection Traces

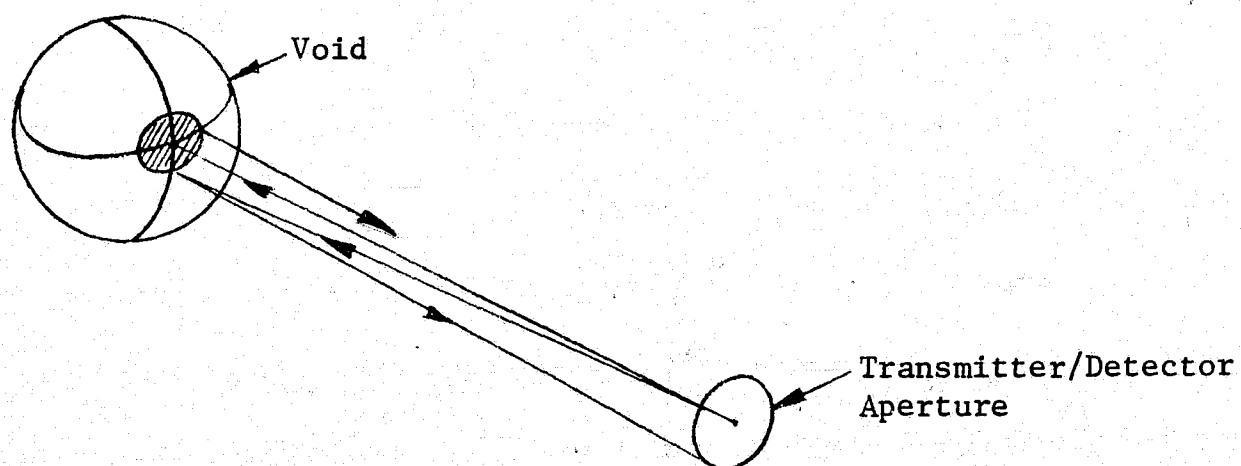
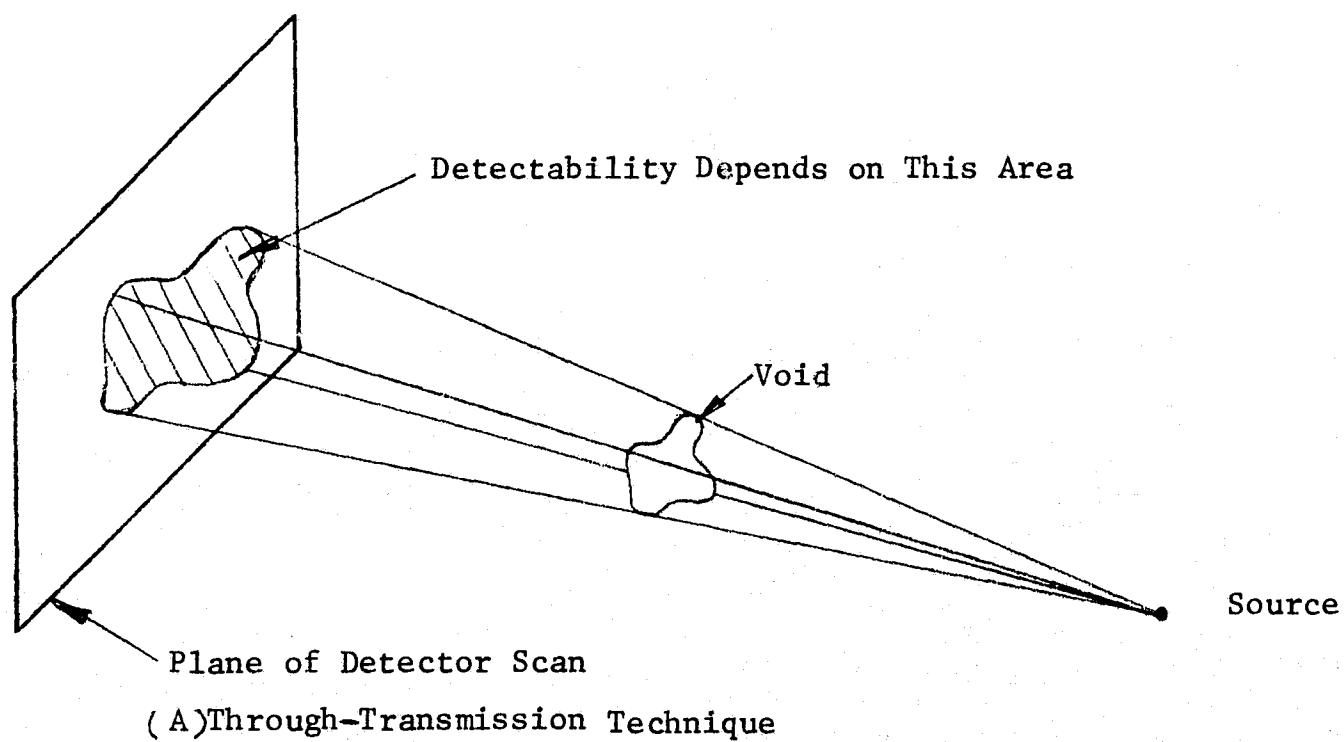


Figure 32. - Ultrasonic Flaw Detection

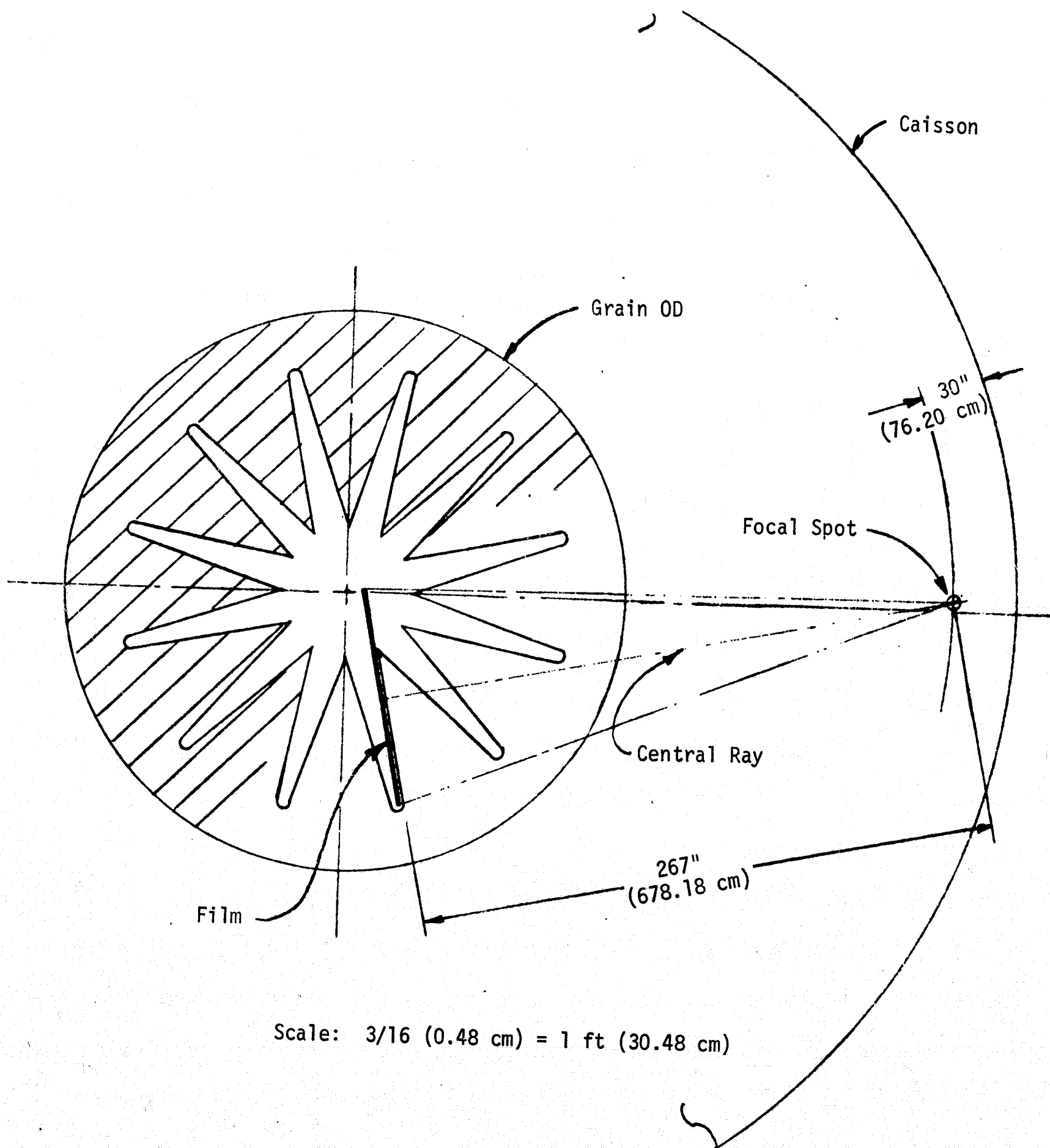


Figure 33. - Setup for Radiography of Portion of Star Configuration

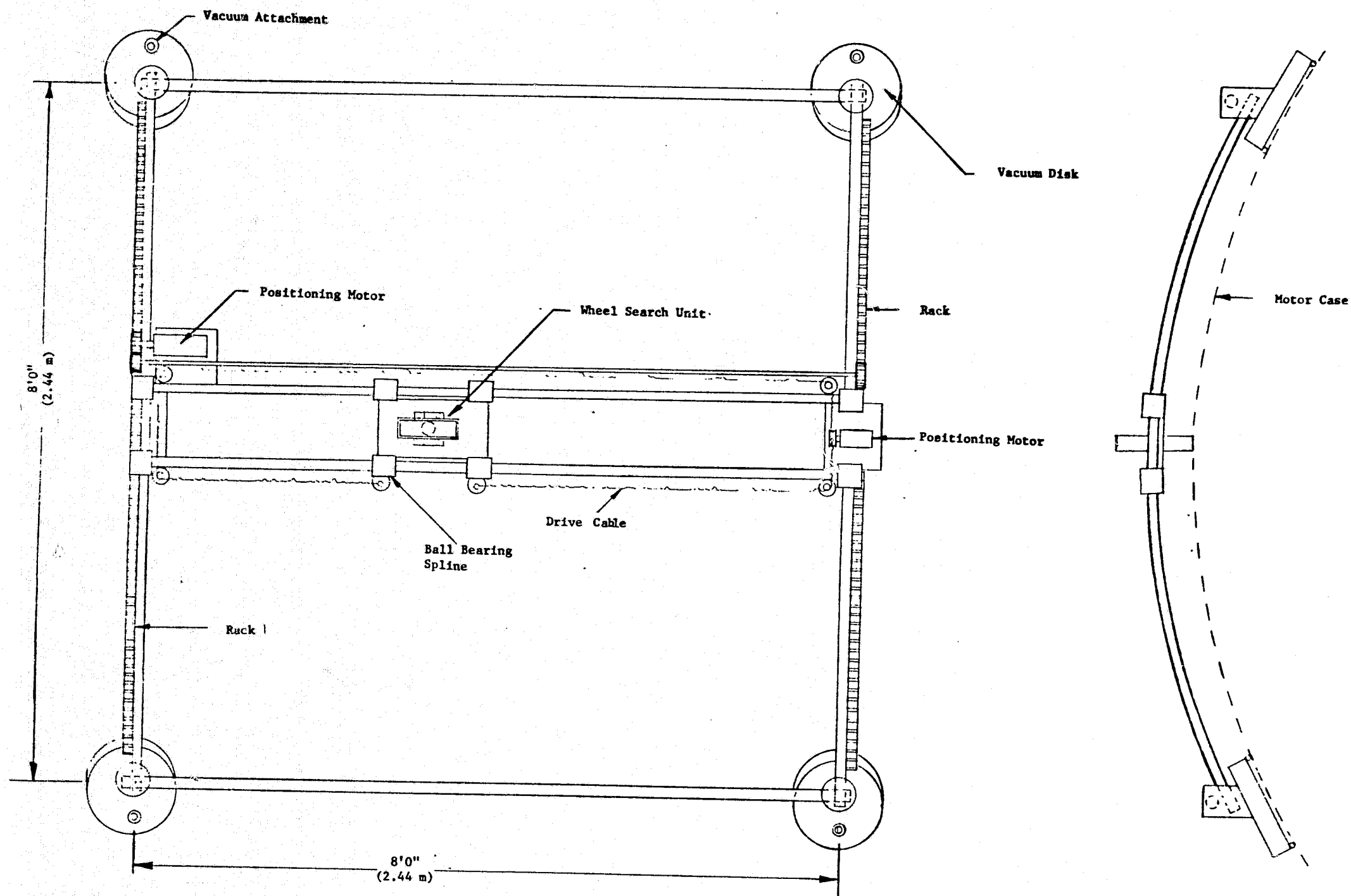


Figure 34. - Ultrasonic Scanning Fixture

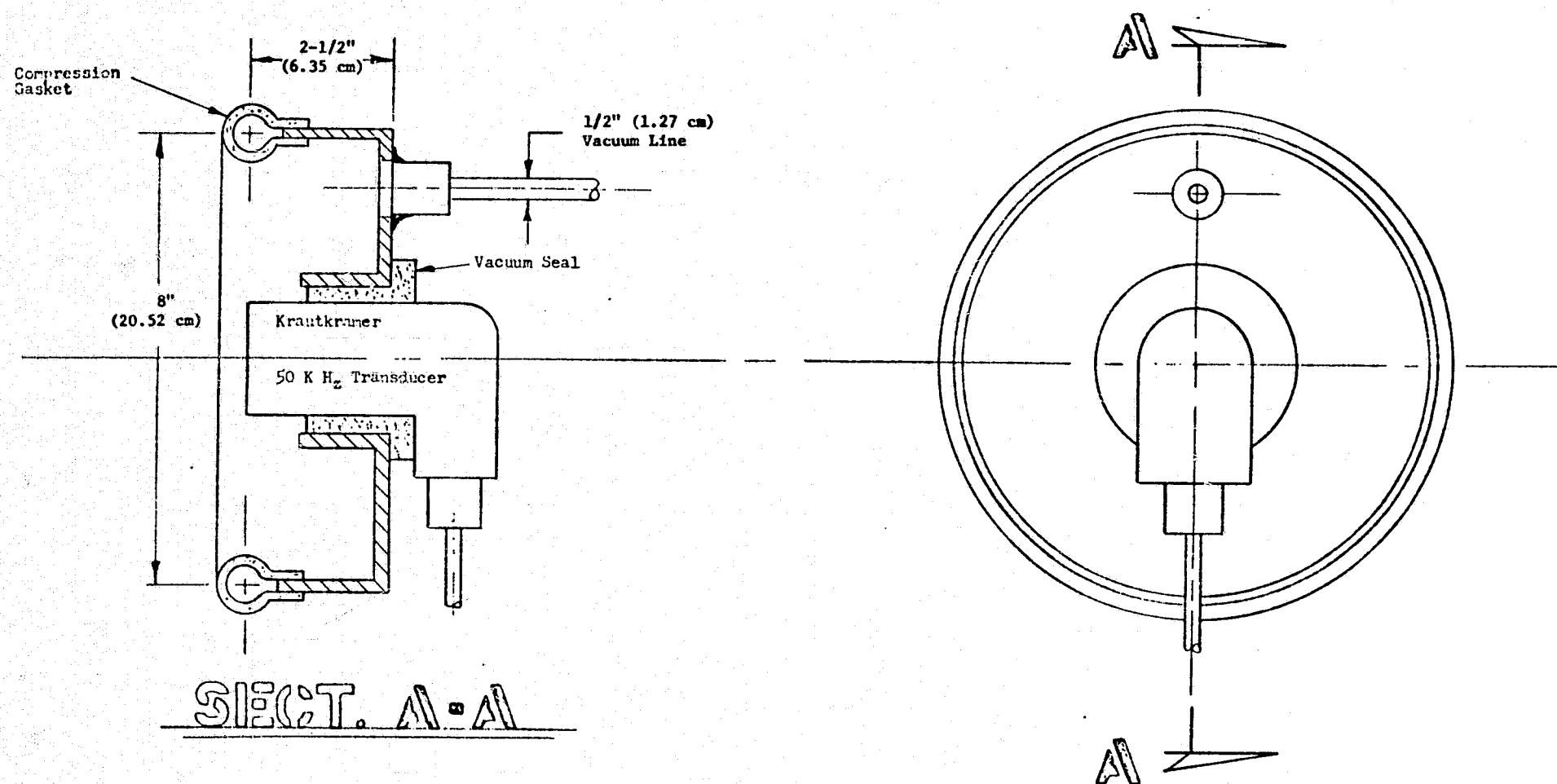


Figure 35.-- Transducer Holding Fixture

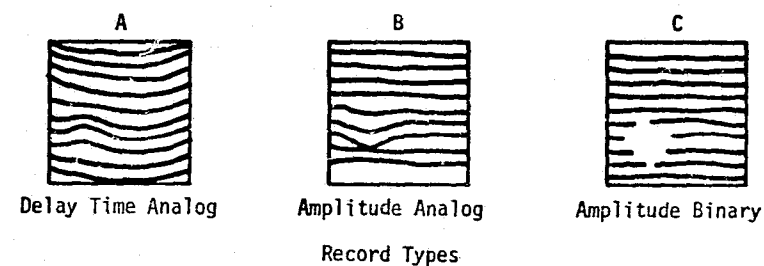
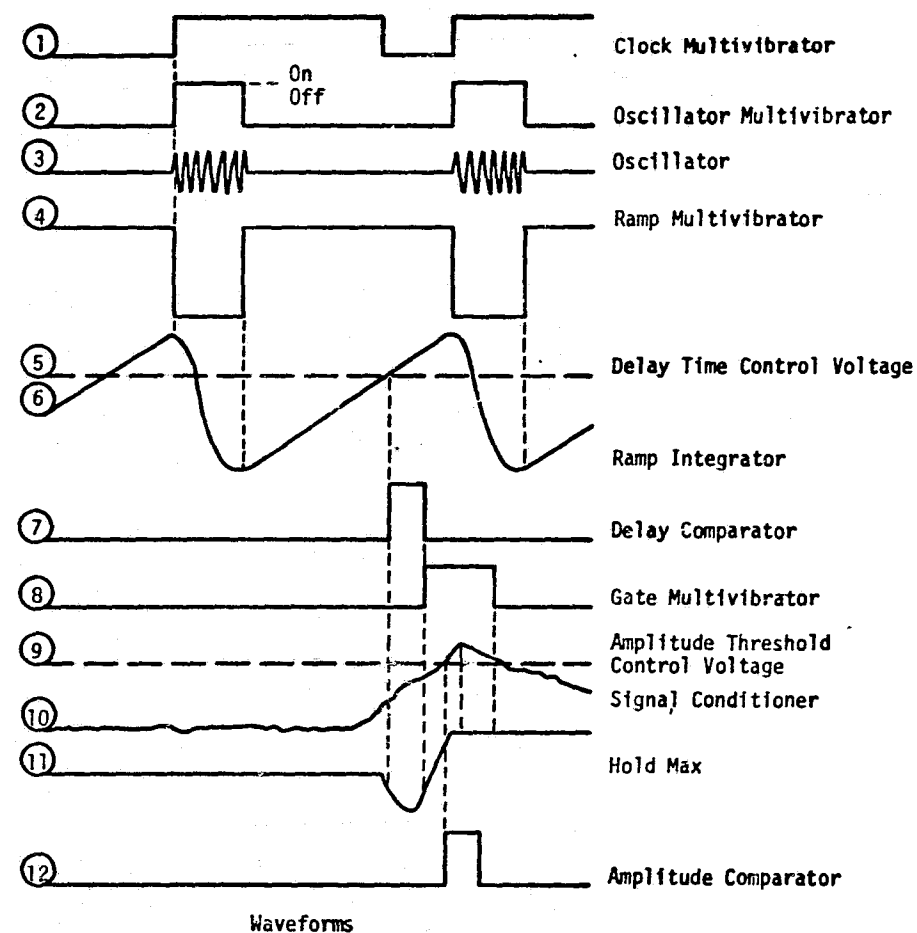
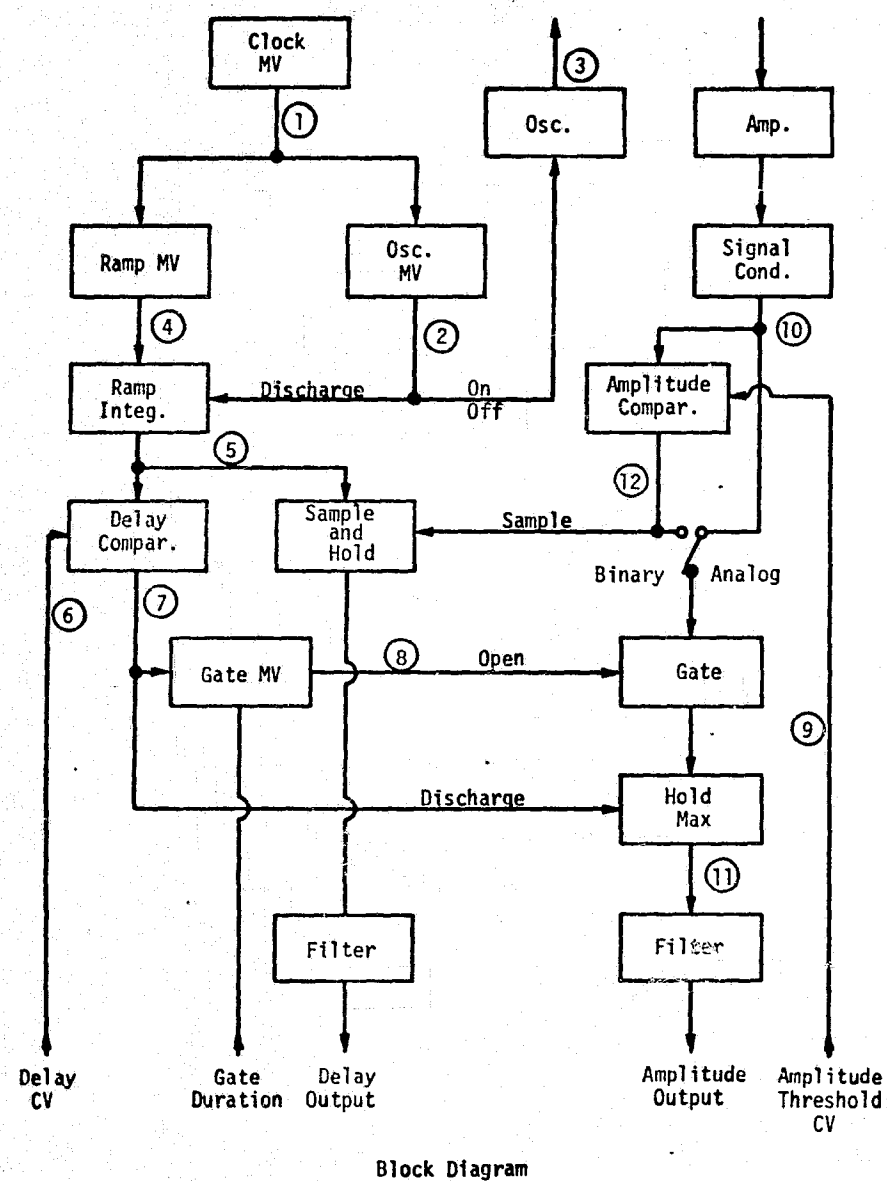


Figure 36.- 260-in. Motor Ultrasonic Inspection Electronics (Conceptual Design and Signals)

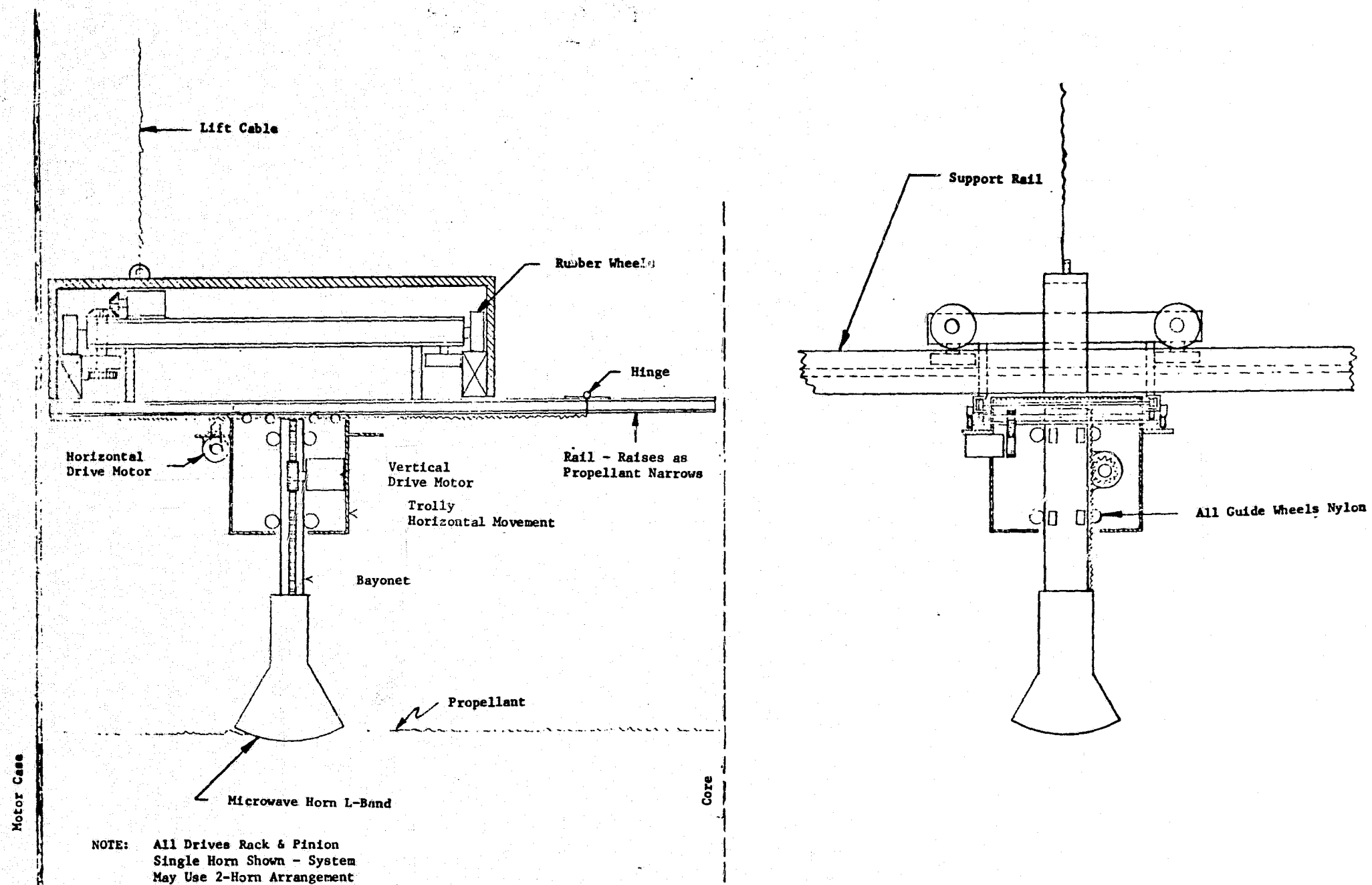


Figure 37.- Microwave Scanning System

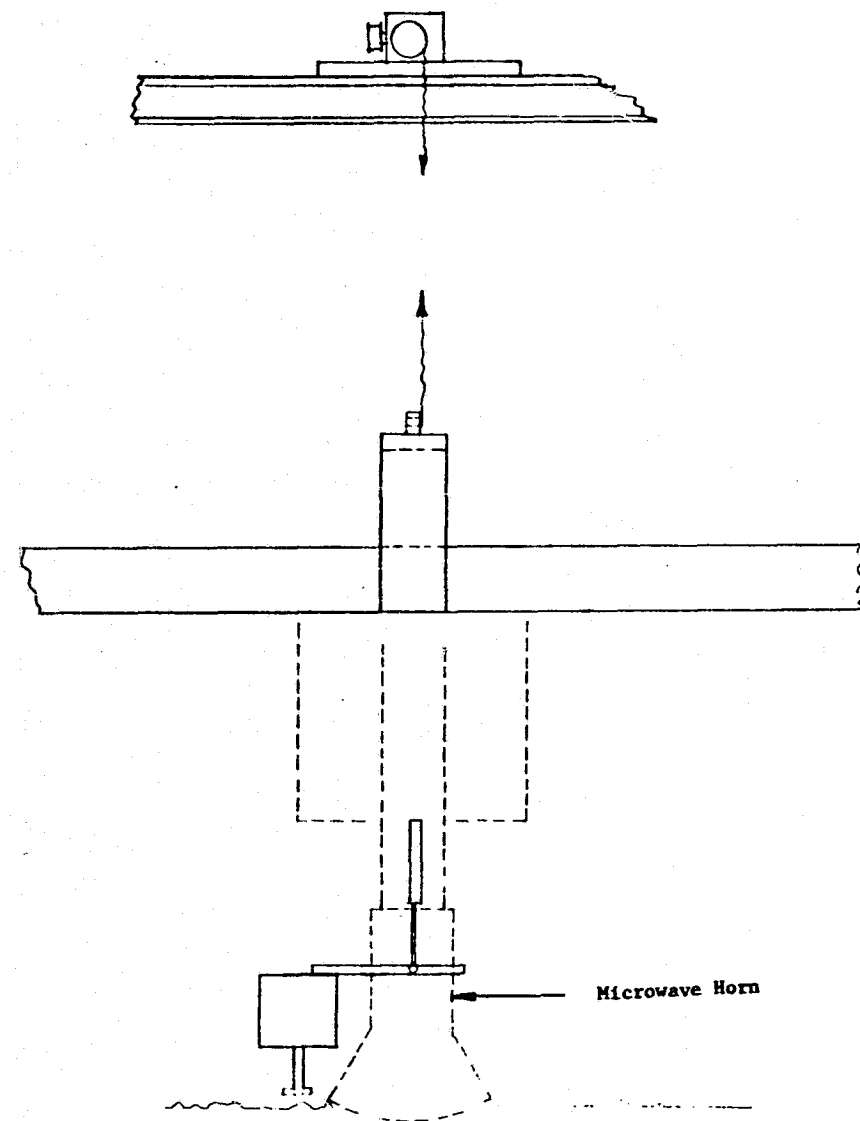
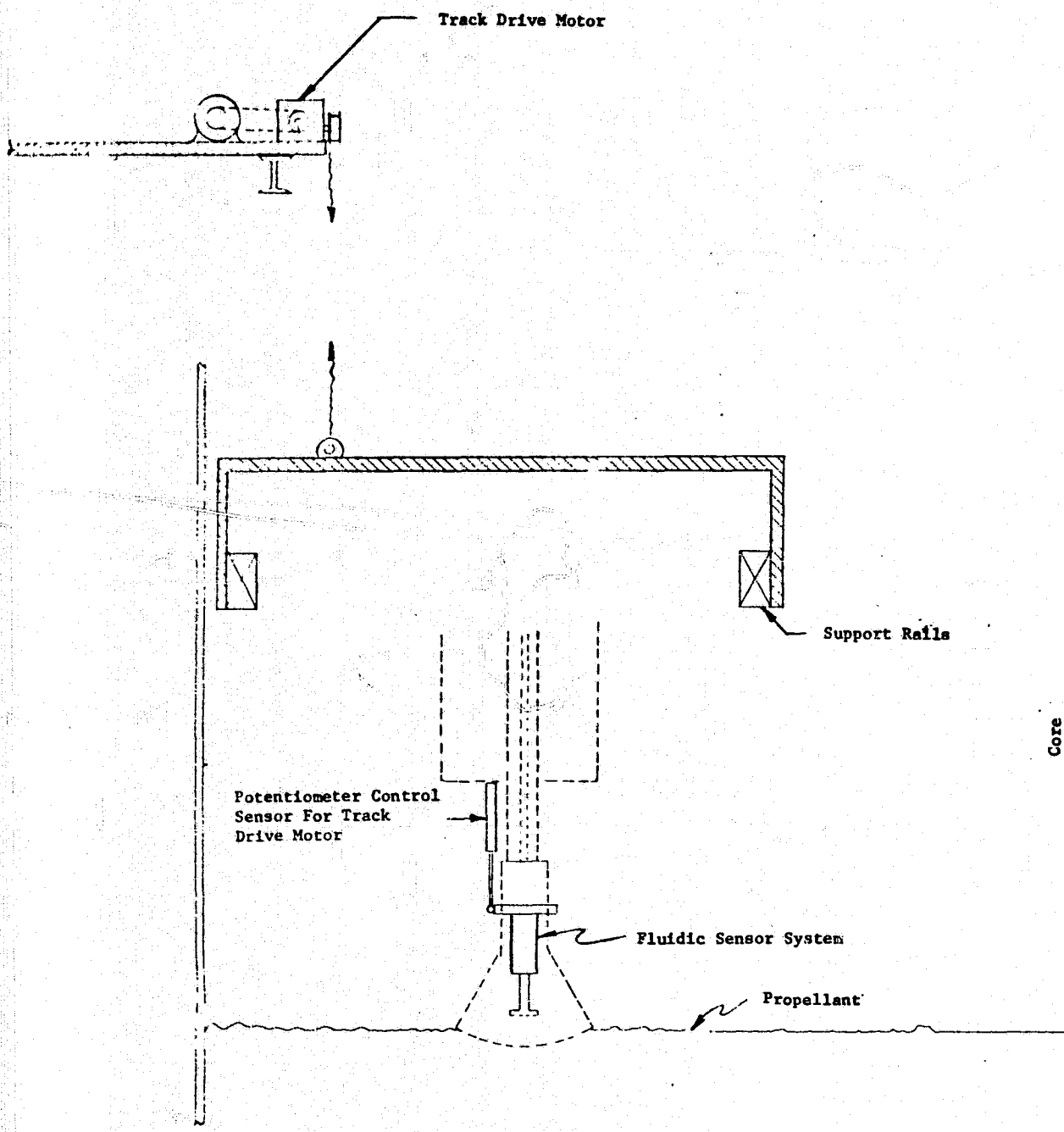


Figure 38.- Position Sensor for Microwave

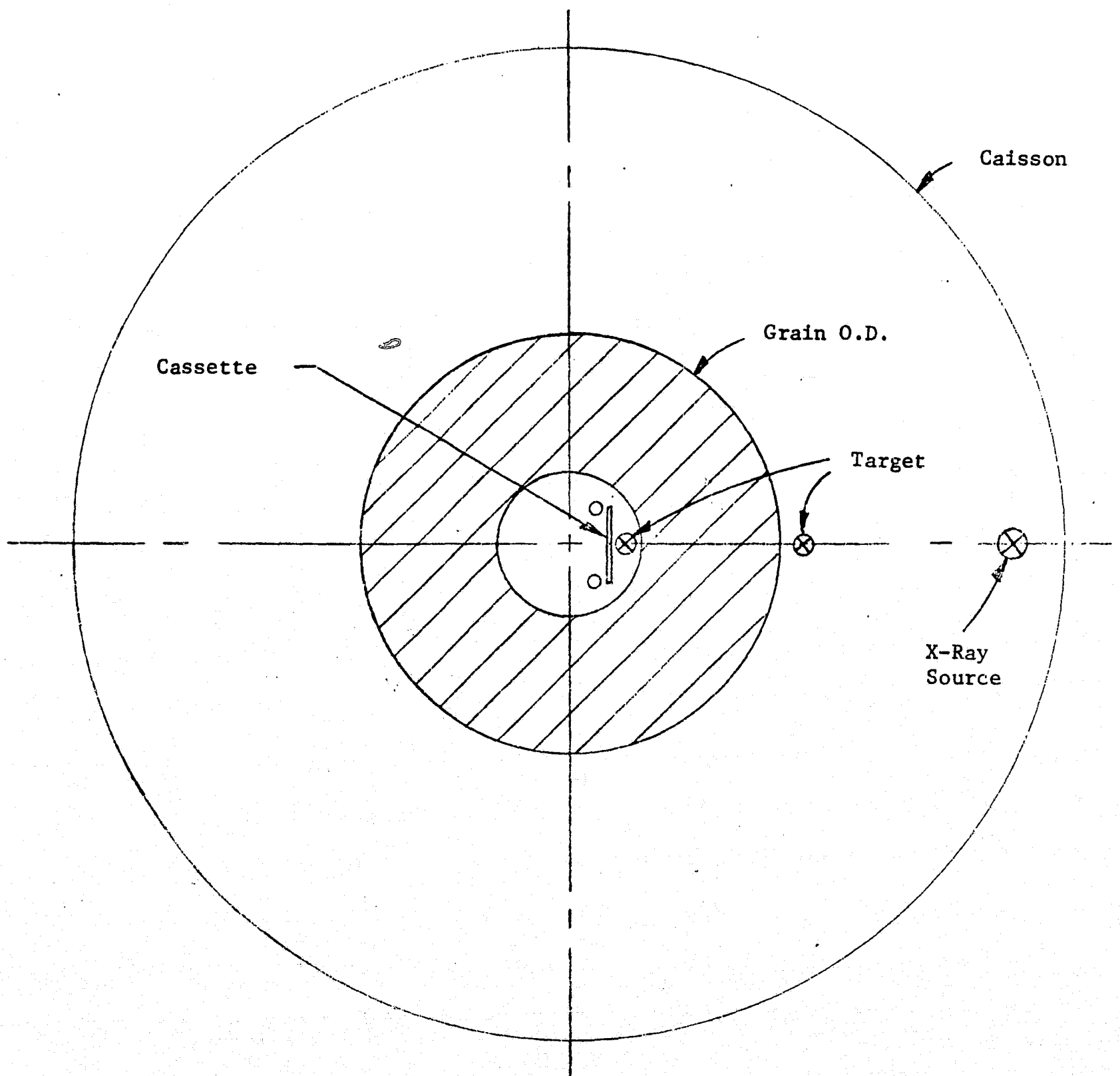


Figure 39. - Source-to-Cassette Initial Alignment

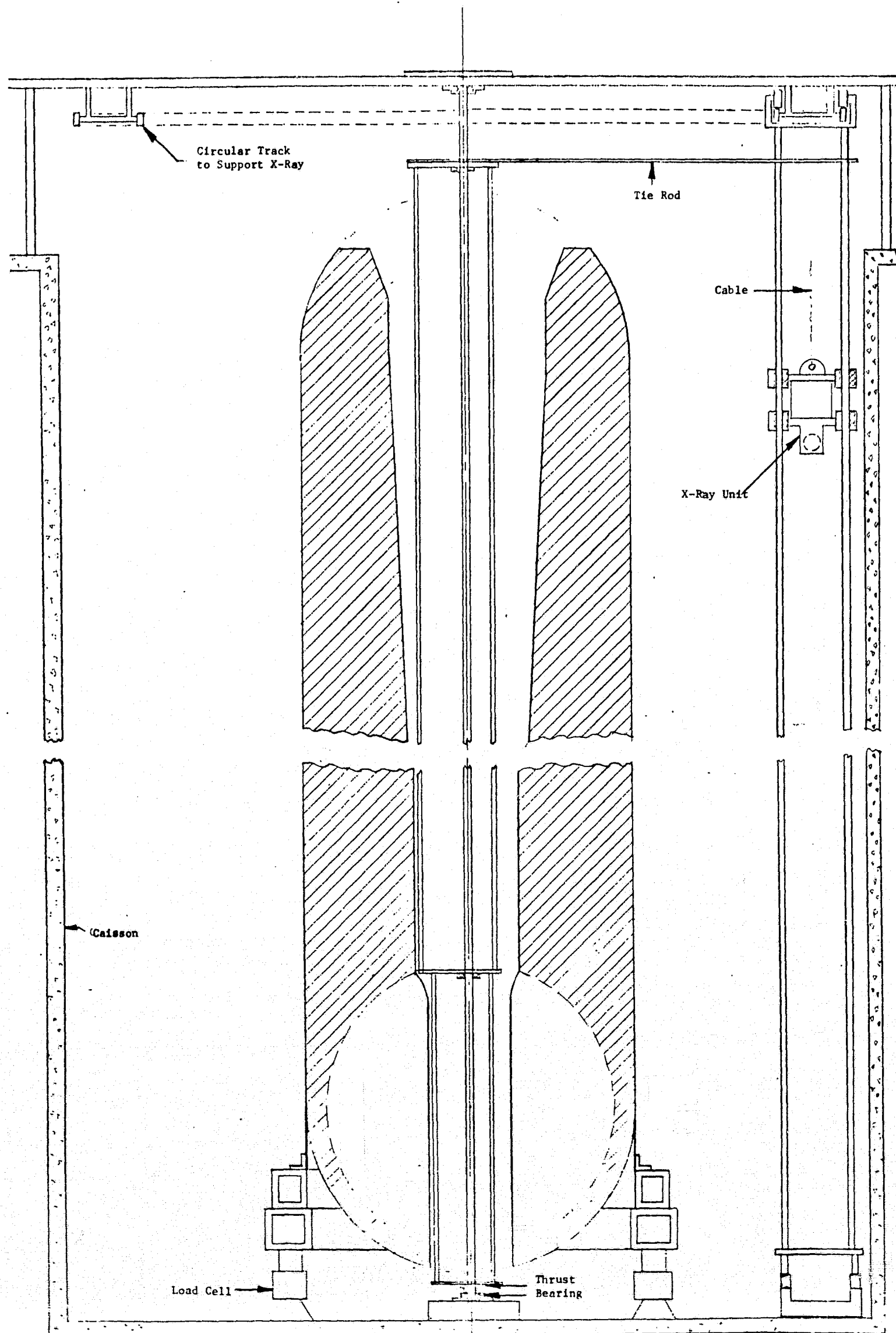


Figure 40. - X-Ray Scanning Mechanism

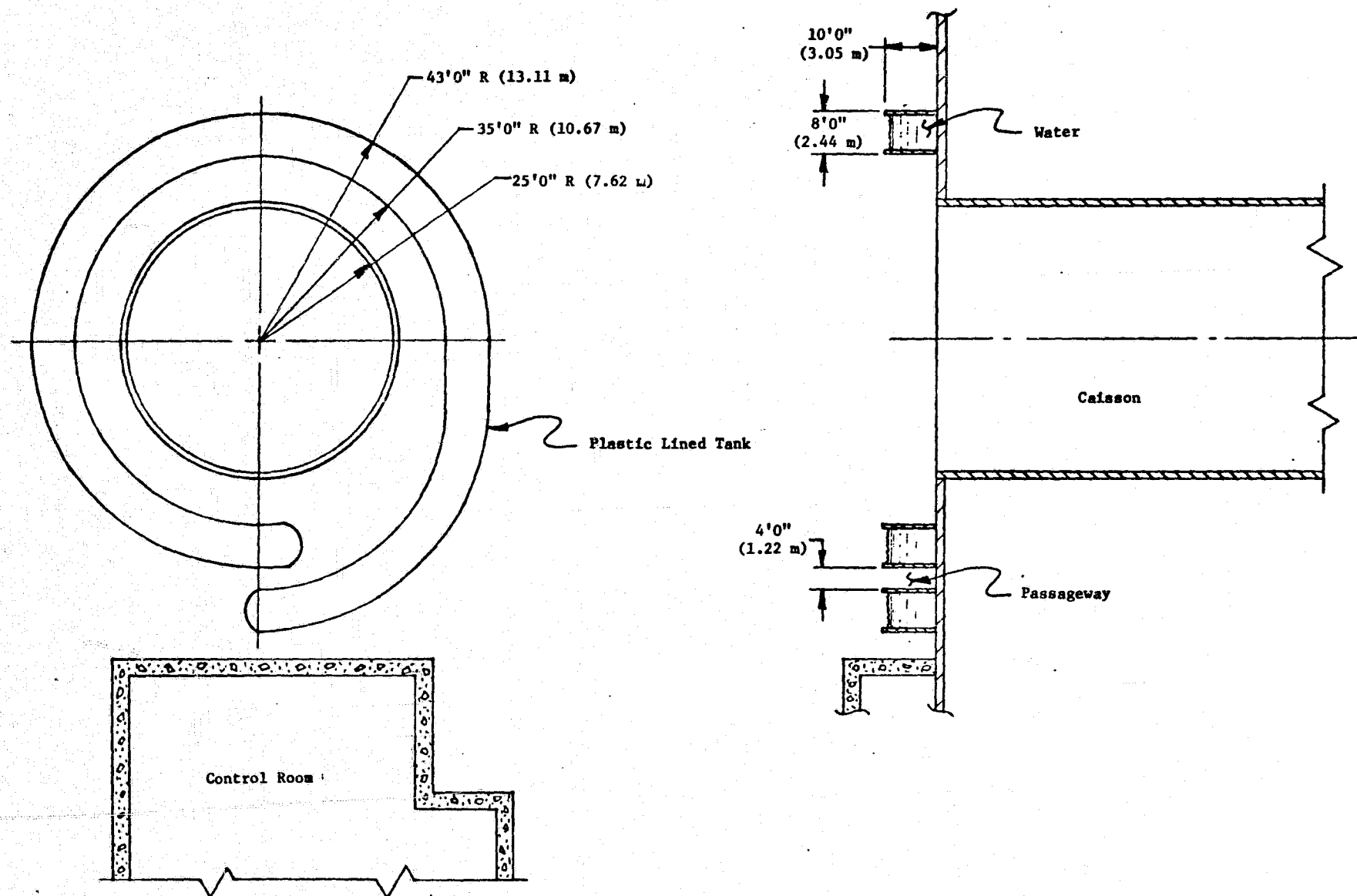


Figure 41.- Radiation Shield

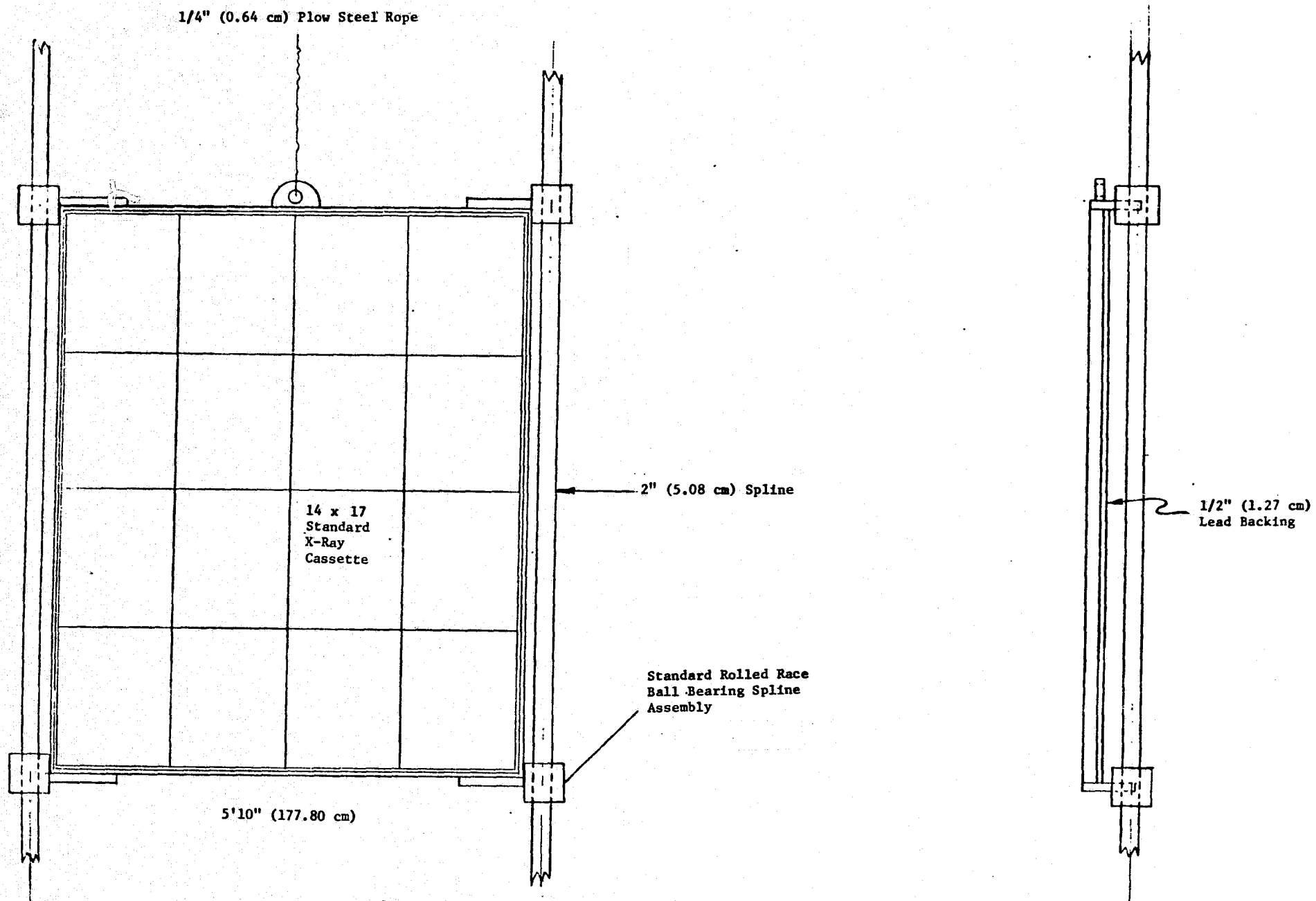


Figure 42. - X-Ray Film Holder

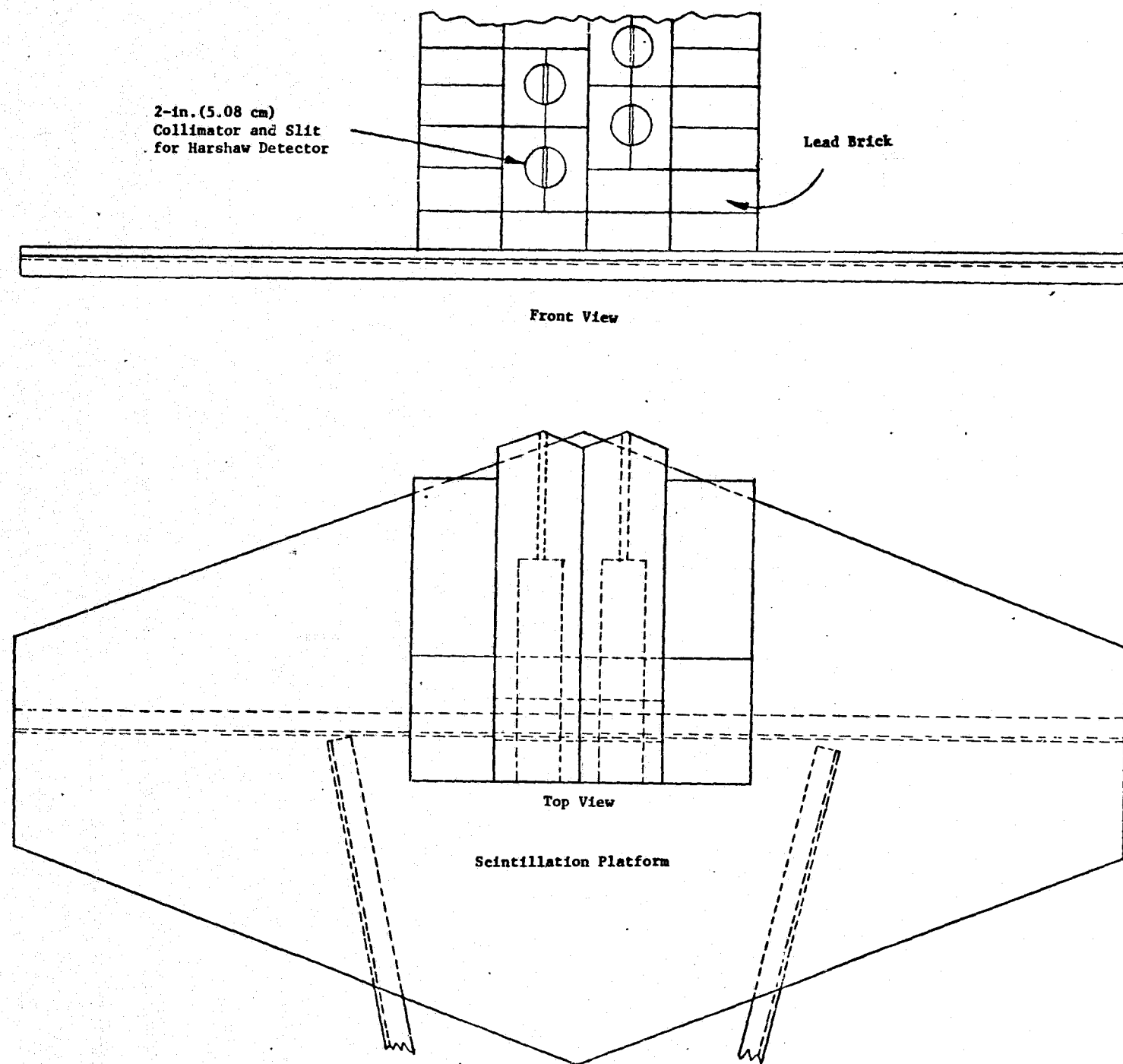


Figure 43.- Scintillation Detector Mounting Platform

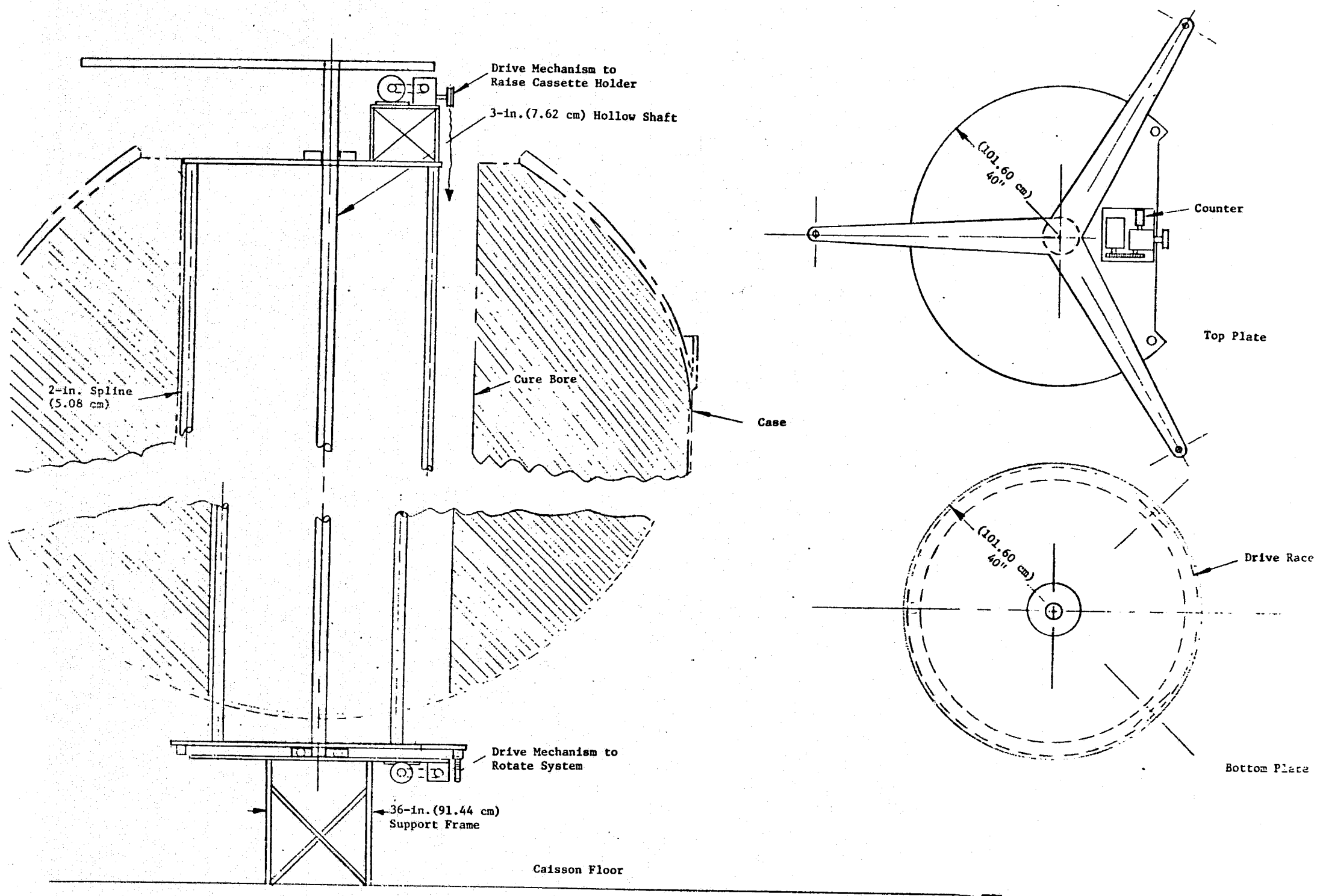


Figure 44.- Cassette Positioning

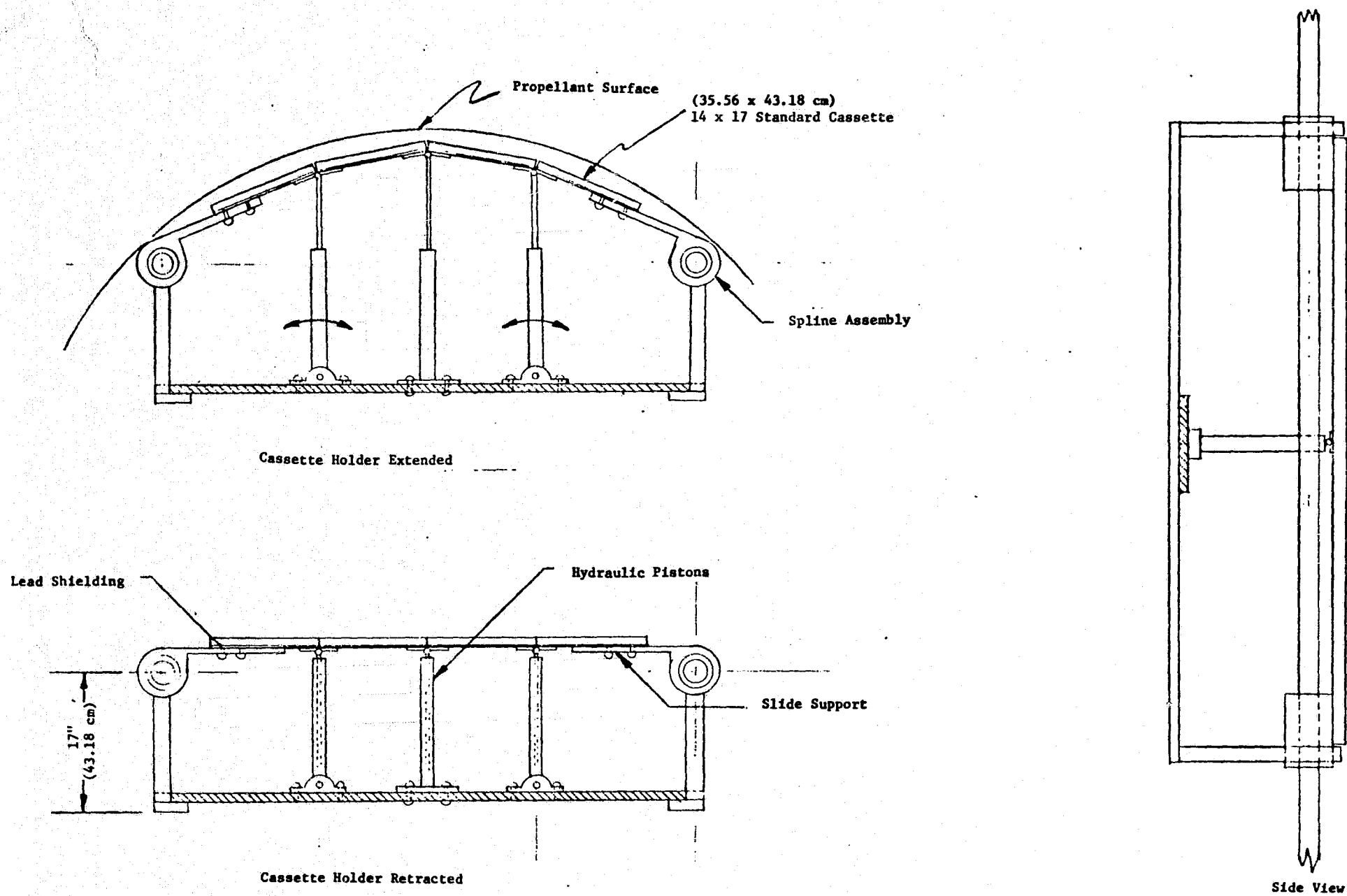


Figure 45.- Cassette Holder Retracted

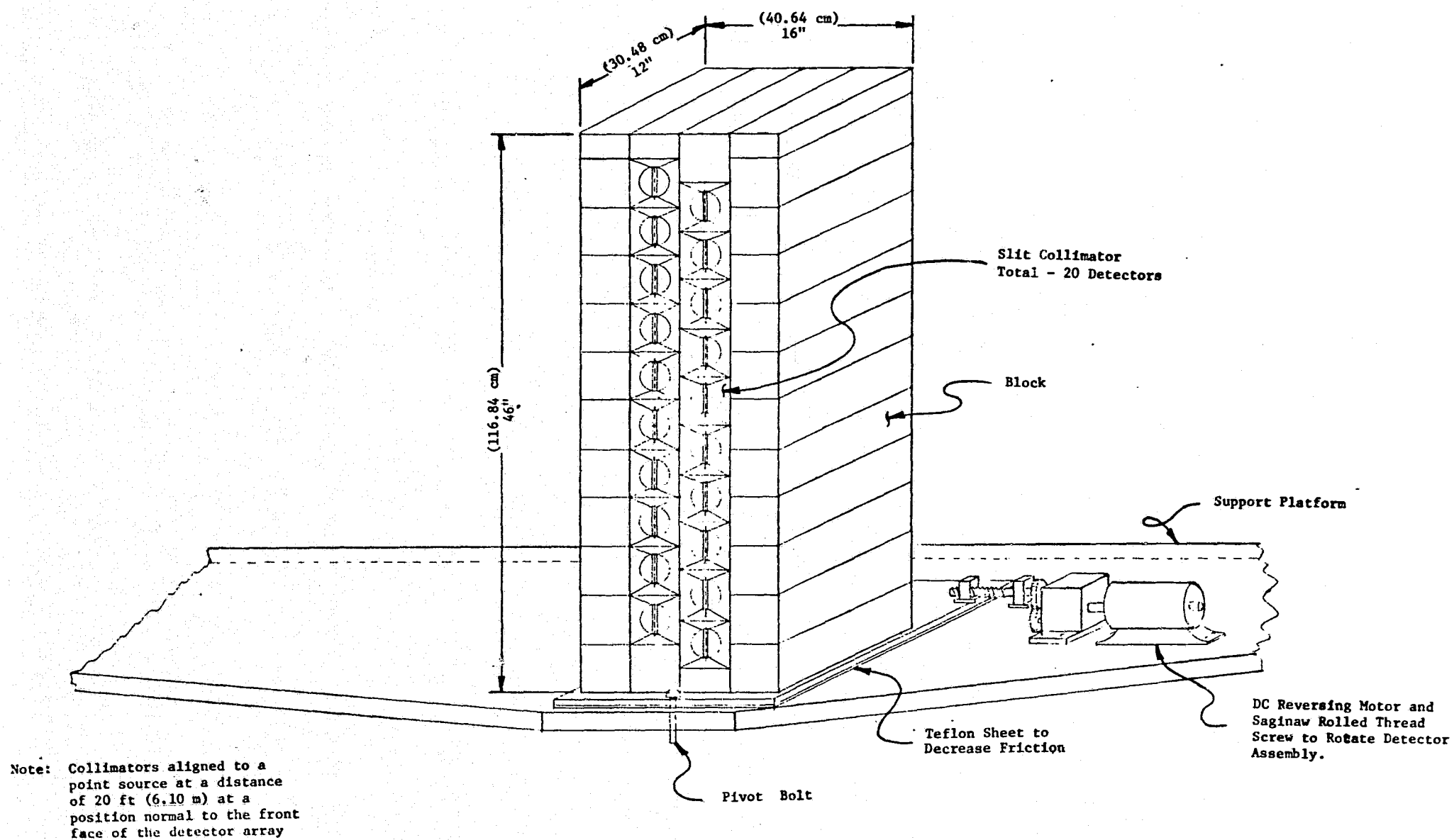
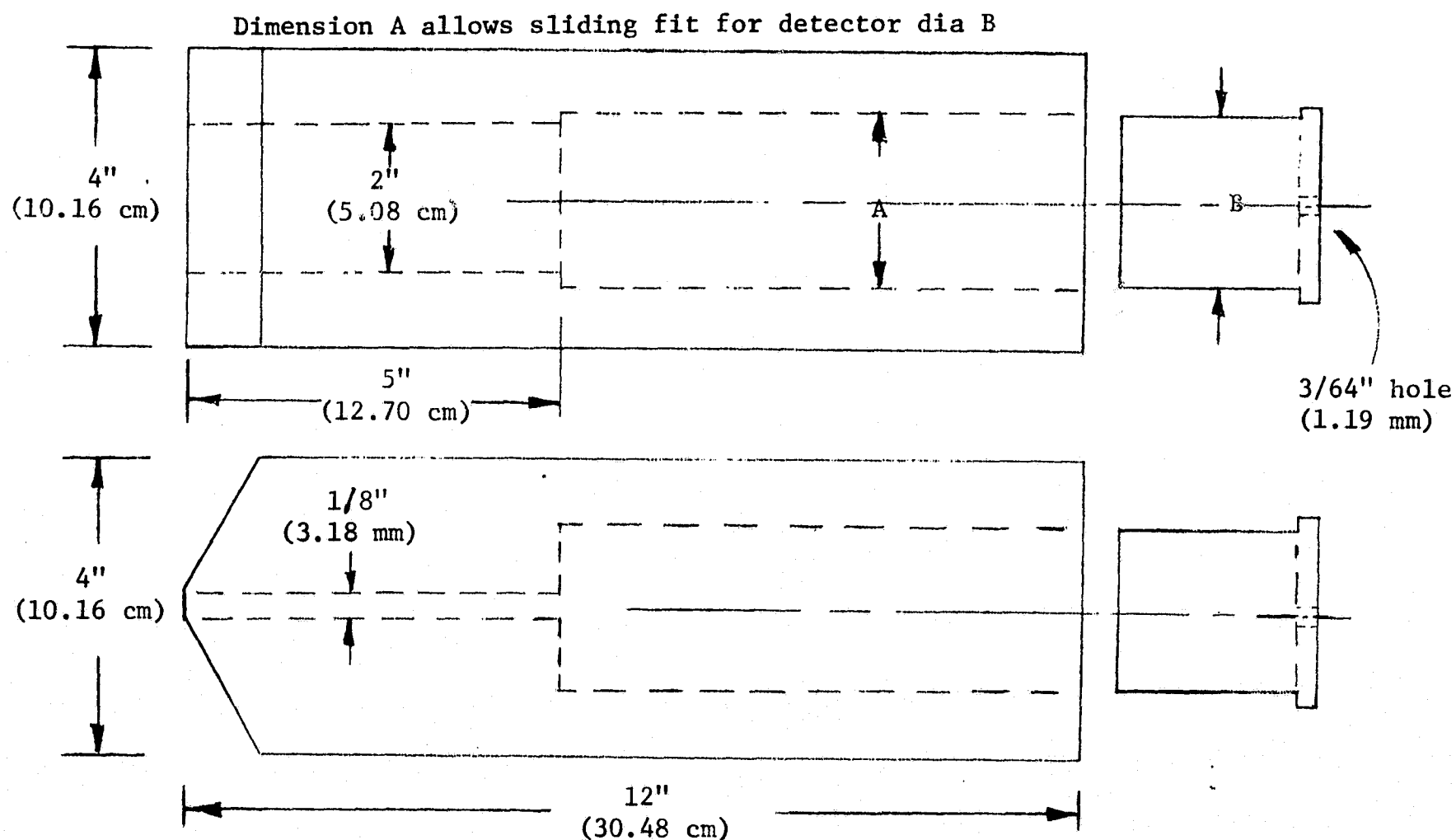


Figure 46. - Scintillation Detector Array



A. Collimator Block and Peepsight

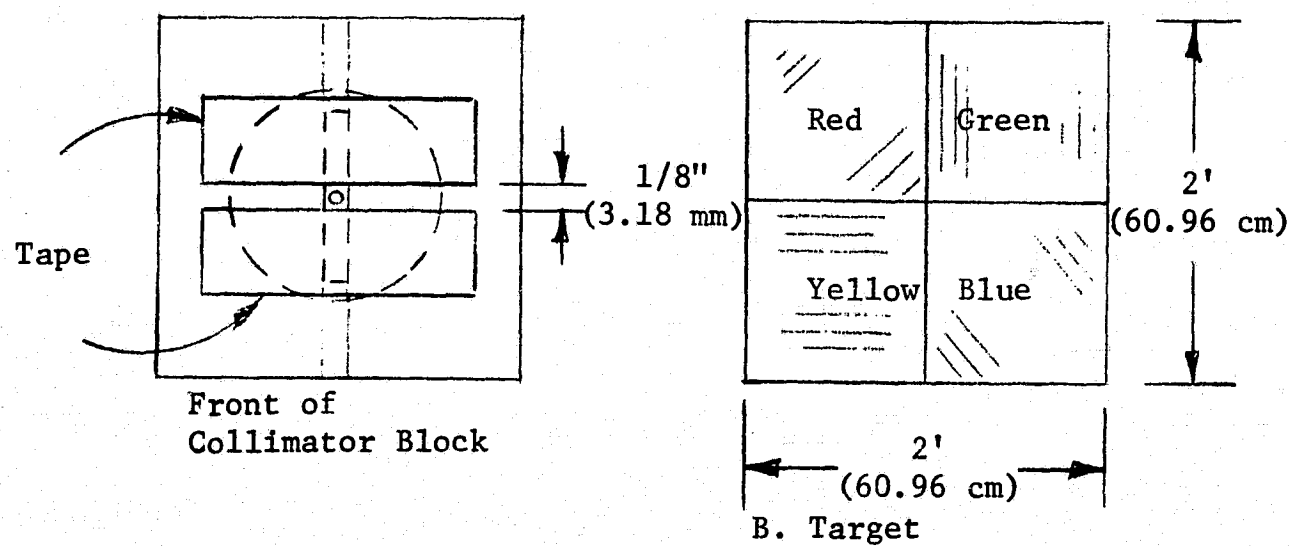


Figure 47. - Accessories for Boresight Alignment of Collimators for Convergence

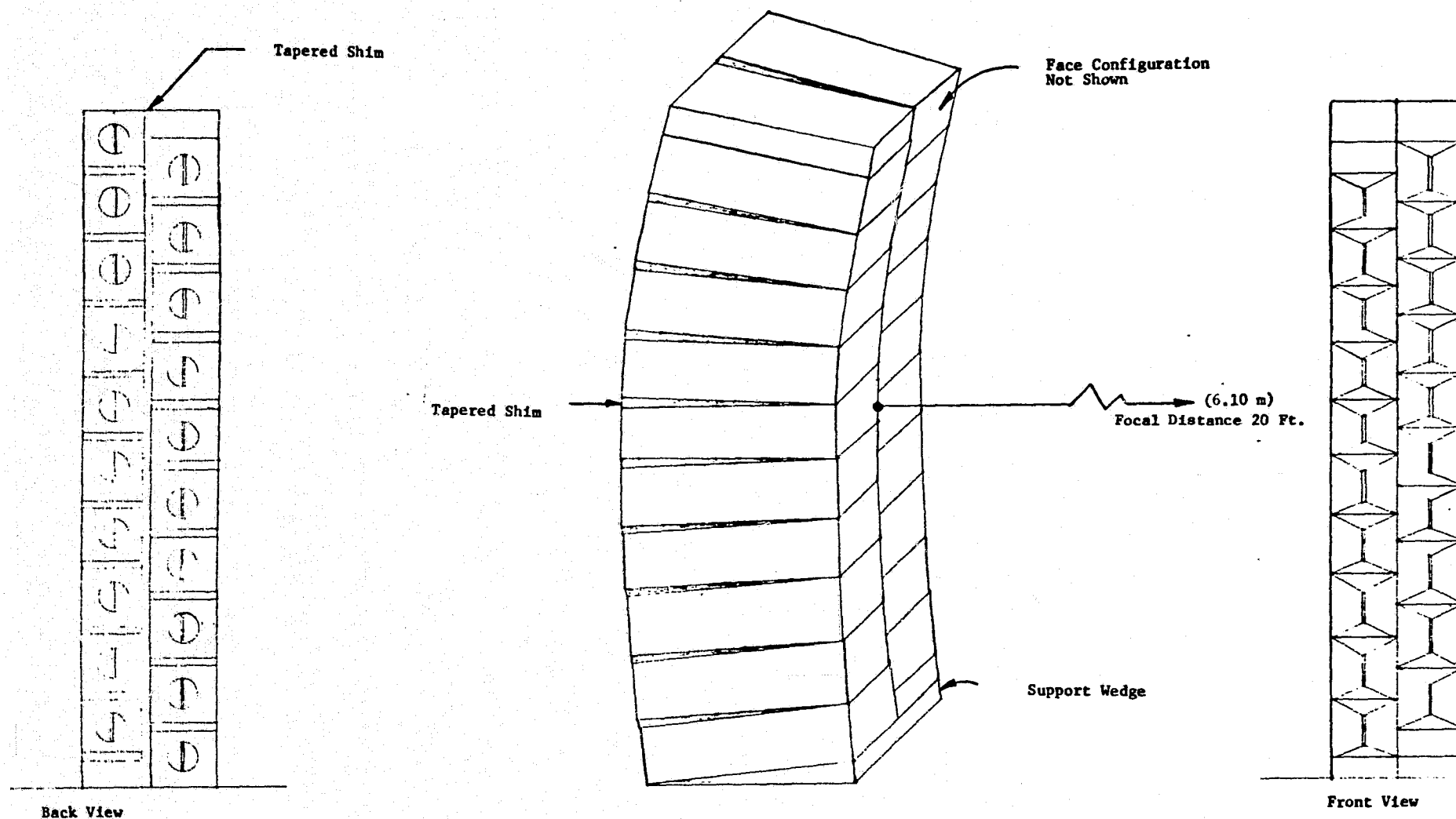


Figure 48.- Collimator Alignment

APPENDIX A

GAMMA AND X-RAY SCANNING SYSTEM ANALYSIS

APPENDIX A

GAMMA AND X-RAY SCANNING SYSTEM ANALYSIS

August 1969

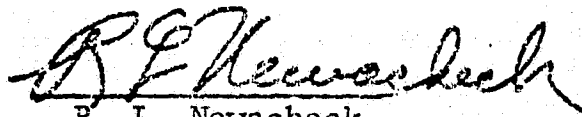
Prepared by:

Steve Kahn
Steve Malmstrom
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Contributions from H. Hefflin of MWS

Interplant Work Authorization No. 105576 by J. M. Amaral

Approved by:



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NUCLEAR DIVISION
Aerojet-General Corporation
San Ramon, California

ABSTRACT

A scintillation scanning system to detect 4-inch cubic voids in the propellant of the 260 inch solid rocket motor is analyzed in this report. A 3000 curie Co-60 source beaming to an array of many 3 in. diameter by 3 in. long sodium iodide scintillation detectors, presents a continuous count rate to a recording system. The source and detectors are arranged on the same horizontal plane while the entire array moves vertically. The propellant thickness between the source and each detector remains the same for the entire 120 foot vertical scan. Voids are easily discernible above a uniform count rate from each detector rate meter channel.

The detection of separations of liner from propellant is analytically feasible for all continuous separations of 0.050 in. or greater. Separations down to 0.020 in. are marginally detectable by the radial scanning technique.

A test program is outlined to verify the engineering parameters assumed in the analysis.

I. INTRODUCTION

Gamma scanning systems have been successfully used for nondestructive inspection of the early Polaris solid propellant missiles. One system, GIGI (Gamma Inspection of Grain Integrity), has been used at the Aerojet-General Sacramento Facilities. Two additional systems were built to inspect the liner-to-propellant interface and to locate separations. One was used at Cape Canaveral and one at the Navy facility at Charleston, South Carolina.

A straightforward extrapolation can be made from the initial Polaris inspection process where a void volume of $1/256$ of a cubic inch could be detected in a 54 inch diameter motor to finding a cube 4 inches on a side in a 260 inch diameter motor. The scaling up of equipment is hindered only by the propellant penetration limits of Co-60 (1.17 and 1.33 mev) gamma photons and/or the spectral output of a 4 mev linear accelerator. The analytical results are discussed along with those tests necessary for verification of the nuclear constants associated with the 260 inch solid rocket propellant.

The Naval Weapons Station at Concord, California is now funded to develop a liner-propellant interface bond continuous gamma scanning system. Their computer program which analyzed 20, 50 and 100 mil continuous separations for the 260 inch problem are summarized in this report.

II. GAMMA SCANNING SYSTEM

A. PROPELLANT INTEGRITY INSPECTION

The activity of the gamma photons (Co-60) should provide a count rate of about 10^5 cpm to the detection system. This provides an adequate number of statistical events for good flaw detection at reasonable scanning speeds. To obtain the maximum sensitivity, the propellant thickness should remain constant over the area scanned. Differences in propellant thickness were established by the method described below.

1. Method

A rough layout was made and the distances scaled to determine the various propellant thicknesses using the following dimensions (see Figure 1).

APPENDIX A

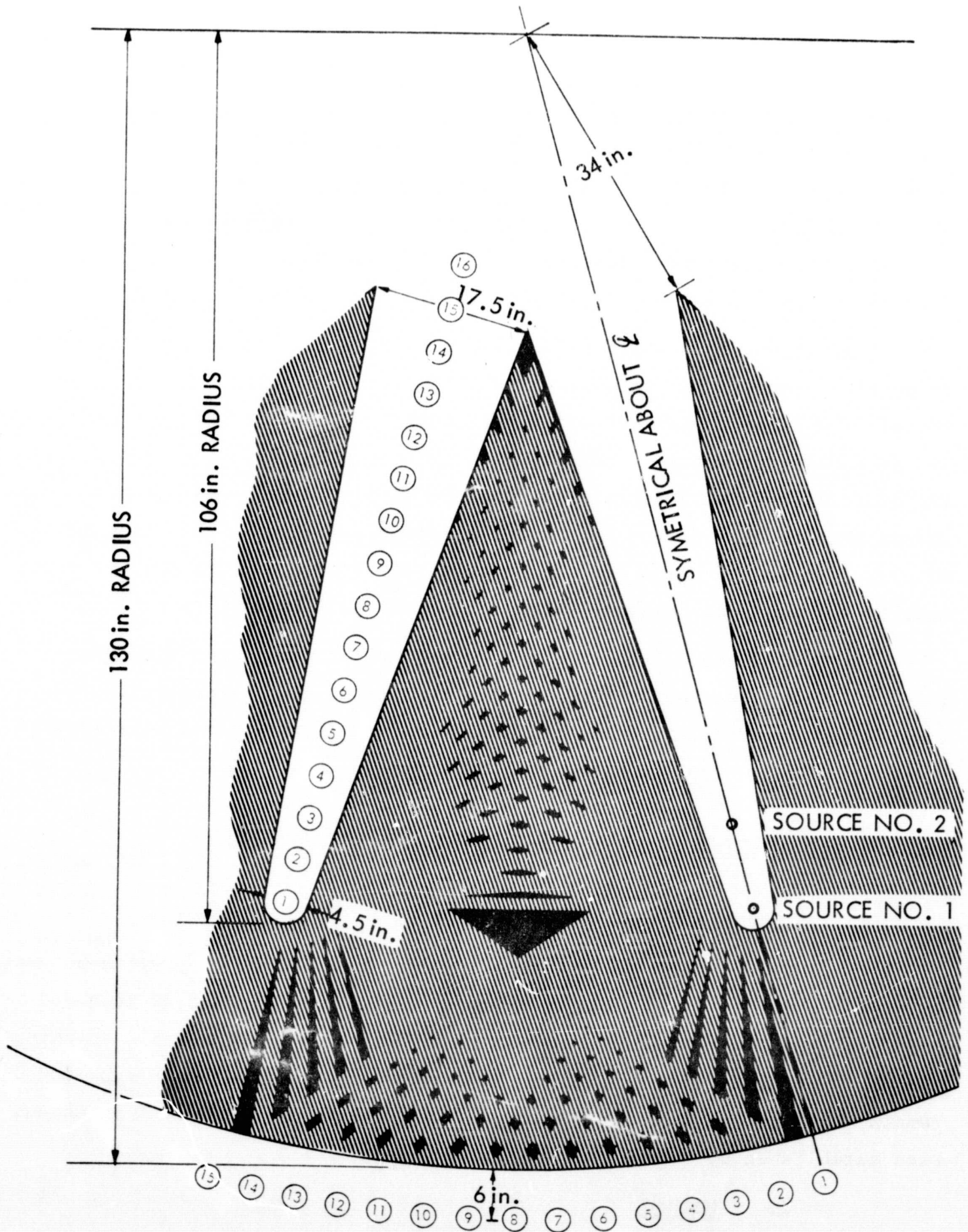


FIGURE 1. ARRANGEMENT OF SOURCES AND DETECTORS

APPENDIX A

4

Motor radius	130 in.
Radius to face of circumferential detector	136 in.
Radius to apex of wedges	34 in.
Inner radius of annular grain sections	96 in.

It was assumed that the sides of the arms (extended) met the centerline of the arms (extended) at the outer circumference of the grain. This gives a maximum and minimum width of the arm of 17.5 and 4.5 in., respectively. All dimensions for source-detector distances (d) and interposed grain thicknesses (t) were measured from the layout with an estimated error of ± 0.4 in.

a. Inspection Times

An arbitrary value of 80 hours (2.88×10^5 sec) was chosen for the total inspection time. Selection of this time was based on using two sources positioned in the center arm; these sources sequentially placed in each of the 12 arms and 120 feet vertical coverage per source per arm. This gives a total travel distance of 2880 feet (3.456×10^4 in.) and a nominal travel rate of 0.12 in./sec. If it is assumed that 10% of the 80 hours is not used for inspection but for such functions as repositioning at the end of each vertical scan, the travel rate will be 0.132 in./sec.

b. Density - Attenuation Coefficient

The value of 0.24 in.^{-1} for μ (linear attenuation coefficient) was based on a propellant density of 1.77 gm/cc and a mass attenuation coefficient of $0.0534 \text{ cm}^2/\text{gm}$.

c. Flaw Size

The required detectable flaw was assumed to be a cube 4 in. on a side. While it is improbable that a flaw will be cube-shaped rather than ellipsoid, the cube was used to simplify the calculations. If smaller voids are of interest slower scanning speeds can be used.

2. Radiation Damage

The dose rate 1 in. from a 1 curie Co-60 source is 1905 R/hr. Based on the above dimensions and treating the one in. long by one in. diameter 3000-curie source as a point source 2 inches from the grain, the dose rate to the grain will be 1.43×10^6 R/hr or 397 R/sec.

Assuming the source is shielded top and bottom with 3 in. diameter by 5 in. long pieces of Mallory metal such that the effective exposed distance on the grain above and below the centerline of the source is 5 in., then the dose at any given point will be 0.471 times that which would have been received at that point if the source had stayed directly in front of the point for the same length of time. At 0.132 in./sec, the time to cover 10 in. would be 76 seconds. Thus the total dose would be $(0.471) (76) (397) = 1.42 \times 10^4$ R.

Since the damage threshold is at 10^6 R*, there is a safety factor of ~ 70 in this proposed system.

3. System Configuration (see Figure 1)

a. Sources

Each arm will have two source positions: No. 1 will be located 2.5 in. from the narrow end of the arm (103.5 in. from the center) and No. 2 will be 12.5 in. from the end of the arm (93.5 in. from the center).

Source No. 1 will be used to inspect the wedge sections; source No. 2 will be used to inspect the annular sections.

b. Arm Detectors

The two arms adjacent to that containing source No. 1 will each have 16.3 in. by 3 in. NaI (Tl) detectors spaced 5 in. apart (centerline to centerline) starting 2.5 in. from the narrow end of the arm.

c. Circumferential Detectors

Starting with a detector placed on the extension of the arm containing source No. 2 and located 136 in. from the center of the motor, there will be 14 detectors placed on either side of this line extension, spaced at 2° intervals, i.e., 4.75 in. apart. All detectors will be 3 in. by 3 in. NaI (Tl) and focused at the source with 6 in. of collimation. The two end detectors will be on the extensions of the centerline of the two arms adjacent to that containing the source.

*"Effects of Ionizing Radiation on Solid Rocket Motor Components", Richard E. Gardner, ARS Journal, July 1962.

APPENDIX A

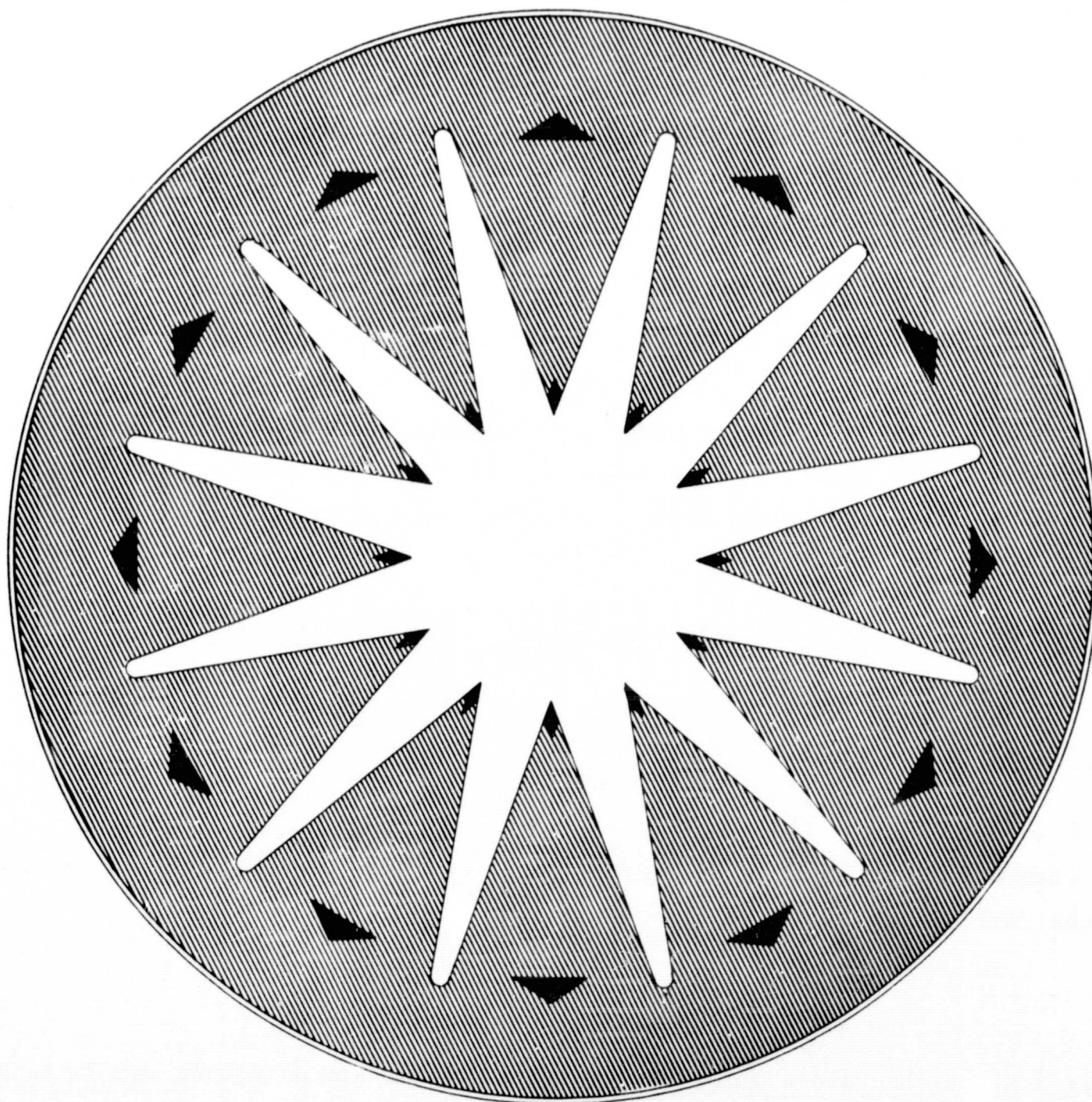


FIGURE 2. VOLUME NOT COVERED BY SCANNING SYSTEM

APPENDIX A

7

4. Coverage

In the above configuration there is only one volume in each wedge which could contain the specified void undetected. This will have an isosceles triangle cross section with the base 14.8 in. and altitude 5.2 in. see Figure 2. The apex will point to the outside surface and be at the intersection of the centerline of the wedge (i.e., the bisector of the wedge internal angle) and the circle described by the narrow ends of the arms (106 in. from the center of the motor).

5. Count Rates and Statistics

Assume a 3000 curie Co-60 source that emits 2 photons per disintegration and a 3 in. by 3 in. cylindrical detector with a 36% detection efficiency for the photopeaks. The actual detection efficiency for a source-detector distance of 40 in. is a factor of 5.6 below the inverse square calculated value. Thus the count rate at a given distance (d) through a given thickness (t) is

$$\text{cps} = \frac{(0.36)(2)(3.7 \times 10^{10})(3 \times 10^3)(\pi)(1.5)^2}{4\pi (5.6)} \left[\frac{e^{-ut}}{d^2} \right]$$

$$\text{cps} = 8 \times 10^{12} \frac{e^{-ut}}{d^2}$$

The standard deviation on a one second count time for a rate meter with a one second time constant will be approximately

$$\sigma = \sqrt{2(\text{cps})}$$

Table 1 gives the values of d, t, cps and σ for the arm detectors and Table 2 gives these values for the circumferential detectors.

The increase in count rate from a 4 inch long void that completely fills the beam path is $e^{(0.24)(4)} = 2.61$ times the no-void count rate.

Depending on the ratemeter circuitry, the count rate should be kept near 2500 cps to avoid coincidence losses which would confuse the data. The standard deviation of this count rate is 2.83% which is about two orders of magnitude less than the change from the 4 in. void.

The detectors listed in Table 1 and 2 having count rates above 2500 cps can be shielded with lead (tenth value layer = 1.65 in.) or some other heavy metal. A possible alternative in the case of source No. 1 would be to reduce the source strength. Since this source is nearest the grain, such a decrease (factor of 3 to 10) would reduce the radiation damage.

The equilibrium time for a change from the base 2500 cps will be 0.14 sec for a 0.05 sec time constant and 0.90 sec for a 0.25 sec time constant.

6. Equipment Required

a. Electronic

The electronic system is shown in Figure 3. Each channel consists of 1) the NaI crystal with its collimator, 2) a photomultiplier detector, 3) a preamplifier or line drive, 4) a count rate meter, and 5) a strip chart recorder. The detector package will be housed using the appropriate radiation shielding.

The optimum sodium iodide crystal size will be determined during the experimental phase. The preamplifier will probably be of Aerojet design to fit the detector package (collimator and shielding) as an integral unit. No extensive development is required to accomplish this. The ratemeter will be selected from commercial equipment to meet the following specifications:

Linear ranges to adequately cover the regions of 10^2 cpm to 10^6 cpm

Input - voltage $\simeq$ 0.25 volts

current $\simeq$ μ a full scale

resolving time $\leq$ 1 μ sec

high voltage = 500 to 3000 V at 0.5 ma

background suppression - 0 to 100% of full scale

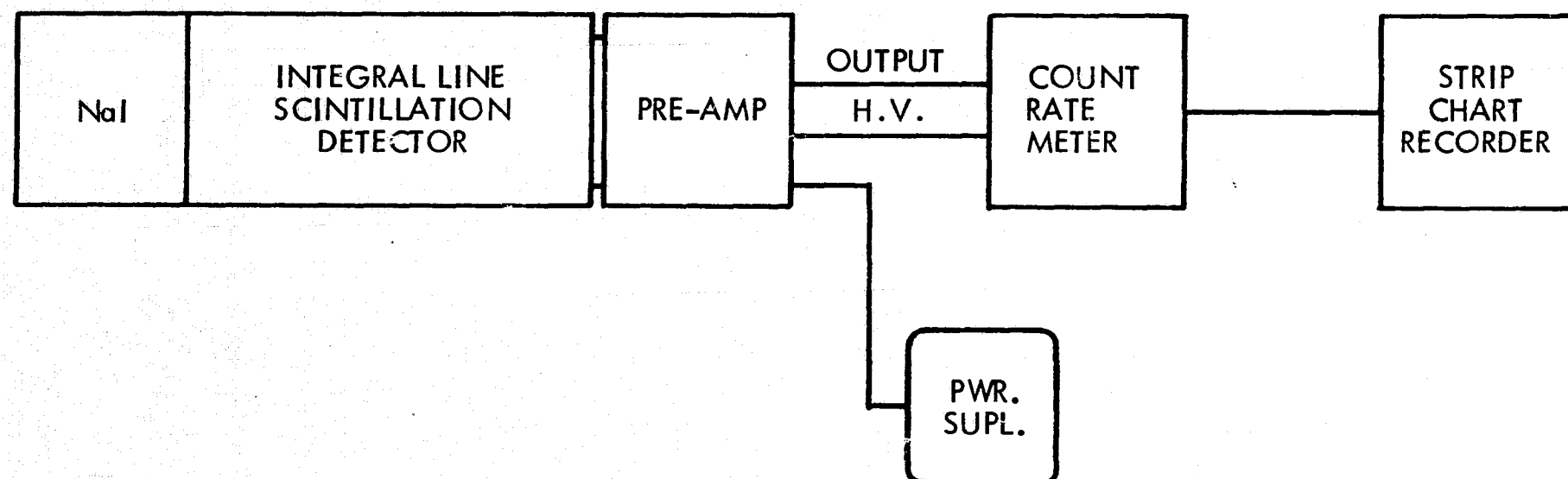
pulse height discriminator - 0 to 100%

calibration - internal

recorder output - compatible with 0 to 1 ma or 0 to 10 mv recorder

The speed of the strip chart recorder will be compatible with the output of the ratemeter. The option of a timing mark to relate chart indications with scan distance would be desirable and can be supplied at a nominal cost. A convenient chart drive speed will be selected

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APPENDIX A

FIGURE 3. GAMMA SCANNING SYSTEM INSTRUMENTATION SINGLE CHANNEL BLOCK DIAGRAM

APPENDIX A

9

TABLE 1 -- ARM DETECTORS, SOURCE NUMBER 1

<u>Position*</u>	<u>d(in.)</u>	<u>t(in.)</u>	<u>cps</u>	<u>% σ</u>
1	54.0	48.8	22500	0.94
2	53.0	47.4	32600	0.78
3	52.4	46.2	44500	0.68
4	52.0	45.6	52400	0.62
5	52.4	45.0	59300	0.58
6	53.4	45.2	54600	0.61
7	54.8	45.4	49400	0.64
8	56.4	46.0	40400	0.70
9	58.2	47.0	29800	0.82
10	60.8	48.0	21400	0.97
11	63.4	48.6	17100	1.10
12	66.4	49.2	13500	1.20
13	69.6	50.0	10200	1.40
14	73.0	50.2	8800	1.50
15	76.6	46.2	20900	0.98
16	80.2	41.4	60200	0.57

*Position 1 is 2.5 inches from the narrow end of the arm.

APPENDIX A

10

TABLE 2 - CIRCUMFERENTIAL DETECTORS, SOURCE NUMBER 2

<u>Position*</u>	<u>d(in.)</u>	<u>t(in.)</u>	<u>cps</u>	<u>% σ</u>
1	45.2	24.0	1.39×10^7	0.04
2	43.2	24.4	1.22×10^7	0.05
3	43.8	27.4	5.79×10^6	0.06
4	44.8	30.6	2.58×10^6	0.09
5	46.2	33.2	1.30×10^6	0.12
6	47.9	35.8	6.50×10^5	0.18
7	49.8	38.4	3.21×10^5	0.25
8	52.2	40.2	1.82×10^5	0.33
9	54.8	43.0	8.80×10^4	0.46
10	57.4	46.0	3.89×10^4	0.71
11	60.4	49.0	1.71×10^4	1.08
12	63.2	51.6	8.40×10^3	1.54
13	66.4	54.8	3.52×10^3	2.38
14	69.6	58.4	1.35×10^3	3.84
15	72.8	61.0	6.62×10^2	5.47

*Position 1 is on the extension of the centerline of the arm containing the source.

APPENDIX A

12

after the scan speed and total scan time are fixed. For a multi-channel system, a multi-channel recorder may be more convenient. Up to ten channels of information can be indicated on a single multi-channel recorder. This would greatly reduce the components required for the overall system.

To reduce the data collection and data reduction time it is possible to have the system operate into a converter-coupler arrangement and to supply the data to a tape compatible with the computer. Multiplexing with such a system further reduces the equipment required.

Equipment for propellant-to-liner separation inspection will be identical to that used for the propellant integrity inspection with the exception of a slight difference in collimator geometry. This difference, however, will not alter the cost per channel of the system.

b. Mechanical

The mechanical equipment will consist of the tube guides, the source and detector collimators and the mechanical powered drive to hold the source and detectors in the same horizontal plane during vertical scanning.

c. Cost (rom)

1. Electronic Instrumentation

The estimated cost per channel of the inspection system using single channel recorders is:

<u>Item</u>		<u>Est. Cost</u>
NaI (Tl) crystal	} integral line	{ \$1,000
Photomultiplier		
Pre-amplifier		300
Count Rate Meter		1,100
Strip Chart Recorder		1,000
Associated Power Supplier		500
Miscellaneous Hardware		100
	Total	\$4,000

2. The mechanical equipment cost would vary greatly depending on the design chosen and therefore is not estimated.

7. Experimental Work Needed

a. The attenuation coefficient for the 260 in. propellant must be verified. A source to detector distance will be chosen and held while known thickness of solid propellant are inserted in the beam. The slope of the results will establish the linear attenuation coefficient.

b. Scanning speeds of 0.12, 0.13 and 0.14 in./sec will be used to verify the dynamic scanning capability of the system.

c. Equipment Required

An experimental system will be set up and tested to determine the validity of the analytical results and to specify the acceptable scanning speeds. The instrumentation arrangement for the test will be similar to that depicted in Figure 3.

Two crystals, 2 x 2 and 3 x 3, will be used to determine the optimum NaI size. Each crystal will be provided with an appropriate photomultiplier tube. The associated collimator will be designed to accommodate either detector. The photomultiplier output will operate into a pre-amplifier which is capable of driving the maximum length of line expected. This will operate into a Tracerlab Model SC-79 precision ratemeters.

The Tracerlab SC-79 Ratemeter is a complete instrument with a precision regulated high voltage power supply. This instrument also features audio circuits to produce either an audible pulse for each count or a tone of changing pitch to indicate changes in the counting rate. The SC-79 has nine ranges with full scale readings from 100 cpm to 1,000,000 cpm. The standard time constants which may be selected are 0.5, 2.5, 10, and 40 seconds. When the range switch is set at one of the two highest ranges, the time constant automatically converts to 0.1 that of the standard value. This provision is made because high rates of counting have better counting statistics and require less smoothing and damping.

The overall accuracy of the instrument is $\pm 3\%$ of the reading. This includes the accuracy of the meter and is a conservative rating. The same rating prevails when the instrument is used with any good recorder. A 1.0 milliamperes full scale signal is delivered to the recorder. The accuracy of the signal independent of the meter and the recorder. The accuracy of the signal, independent of the meter and the recorder, is 0.5%.

The same system will be used to inspect the liner-propellant separation with slight modifications to the collimator. Inserts will be machined and provided to obtain the desired geometry.

An adjustable range-adjustable zero strip chart recorder will be used for these experiments to provide a permanent record of the data.

B. LINER-PROPELLANT SEPARATION

Howard Heffin at the Naval Weapons Station used the following 260 inch motor parameters in the computer program developed for Poseidon.

1. 3000 curies Co-60
2. 72 inch source to detector distance
3. 40% detector system efficiency
4. 0.24 sec time constant
5. Radial velocity of 0.1 in./sec
6. Aperature size 0.1 x 1.0 in.

A random noise signal was incorporated to simulate actual response. The result of the NWS runs are shown in the figures 4, 5, 6 and 7. The detection of the 0.050 and 0.100 in. separations are very clear. A computerized curve comparison process could make the detectability of the 0.020 in. separation quite feasible.

For the experimental work the aperature of the GIGI device will be used. The collimated beam will be stepped in 0.020 in. increments across the test sample. A micrometer adjustment on a 10 foot straight edge will be required to obtain meaningful results.

III. X-RAY SCANNING SYSTEM

This mode of scanning can be established by use of the 9 mev linear accelerator at the Sacramento facility. The areas of uncertainty center around the hardening of the x-ray beam through the attenuating media and the coupling of this beam through the aperature test device. Theoretically the 4 and 9 mev linear accelerators offer some gain over Co-60 as far as flux levels are concerned, but the energy distribution is not clearly known. Therefore, the effectiveness will have to be determined experimentally.

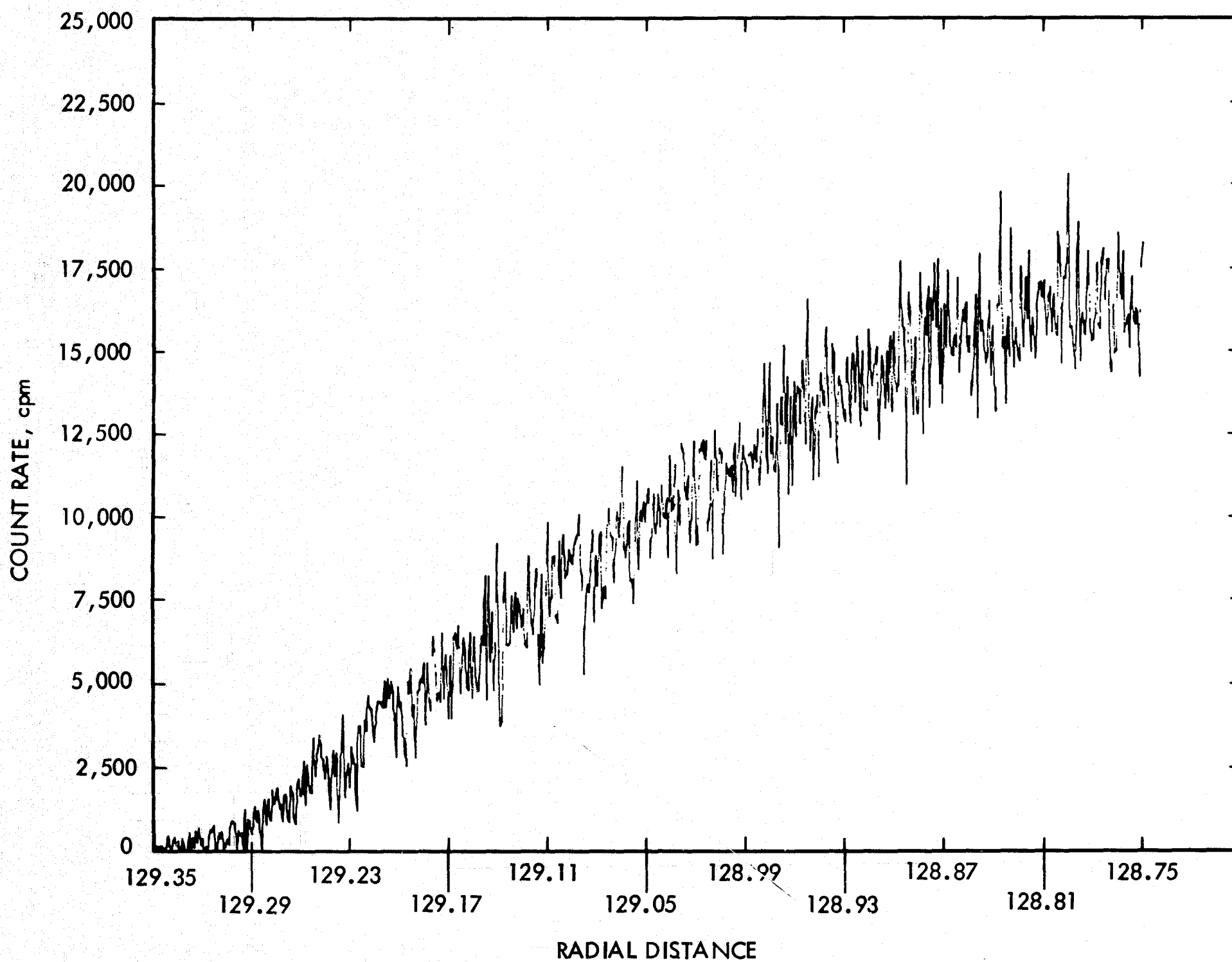


FIGURE 4. STANDARD TRACE - NO SEPARATION

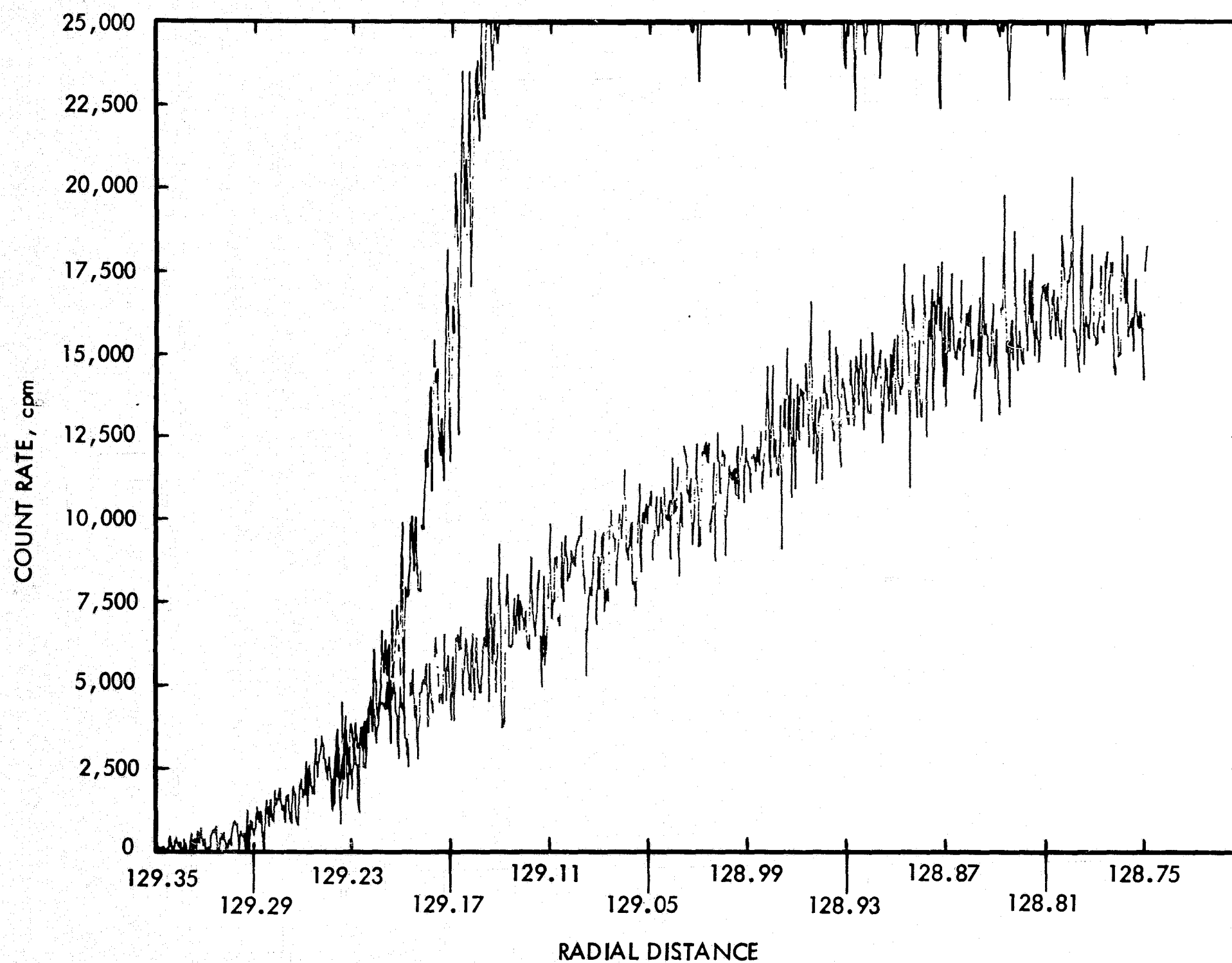


FIGURE 5. STANDARD TRACE COMPARED WITH 0.100-IN. SEPARATION

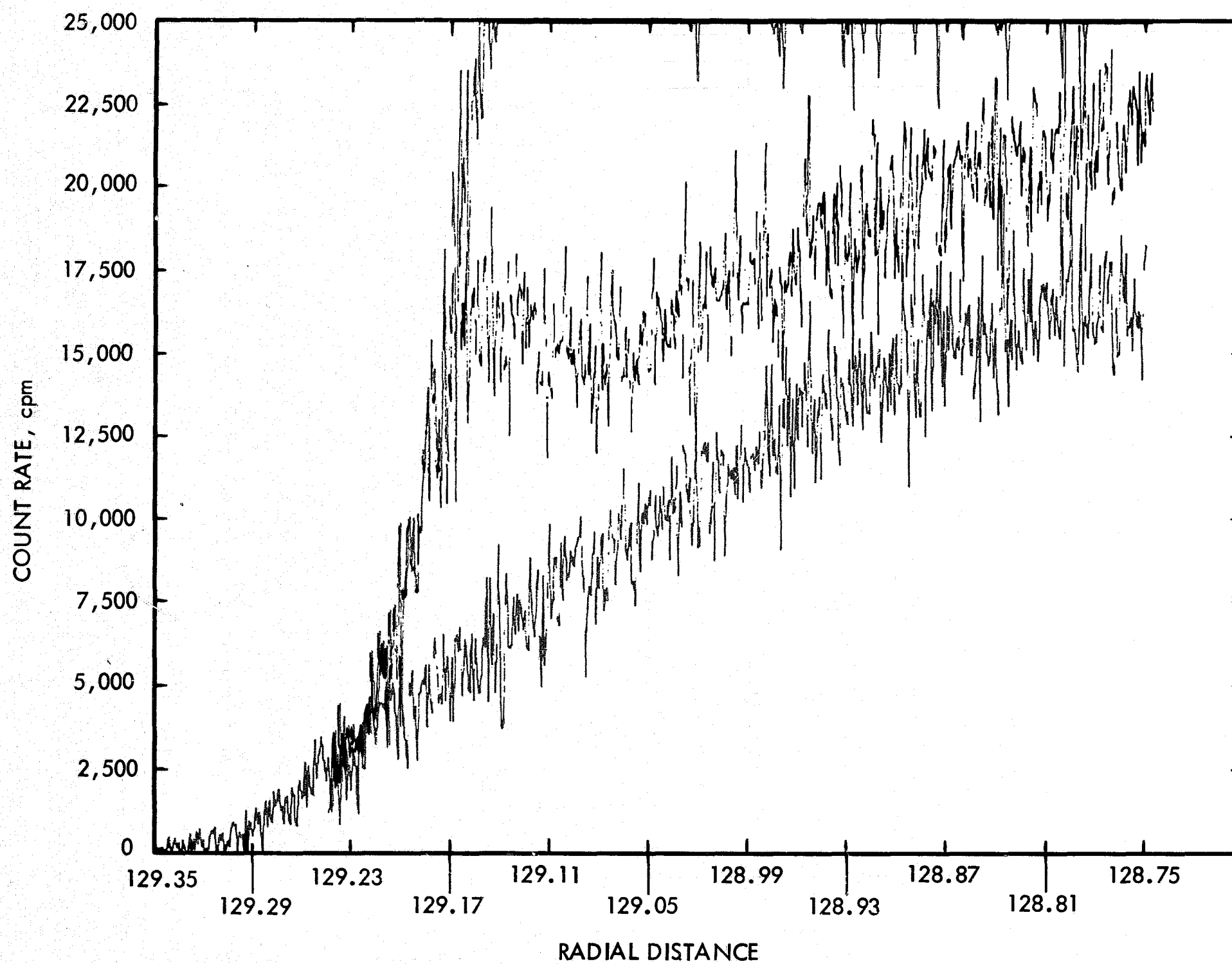


FIGURE 6. STANDARD TRACE COMPARED WITH 0.100 AND 0.050 IN. SEPARATIONS

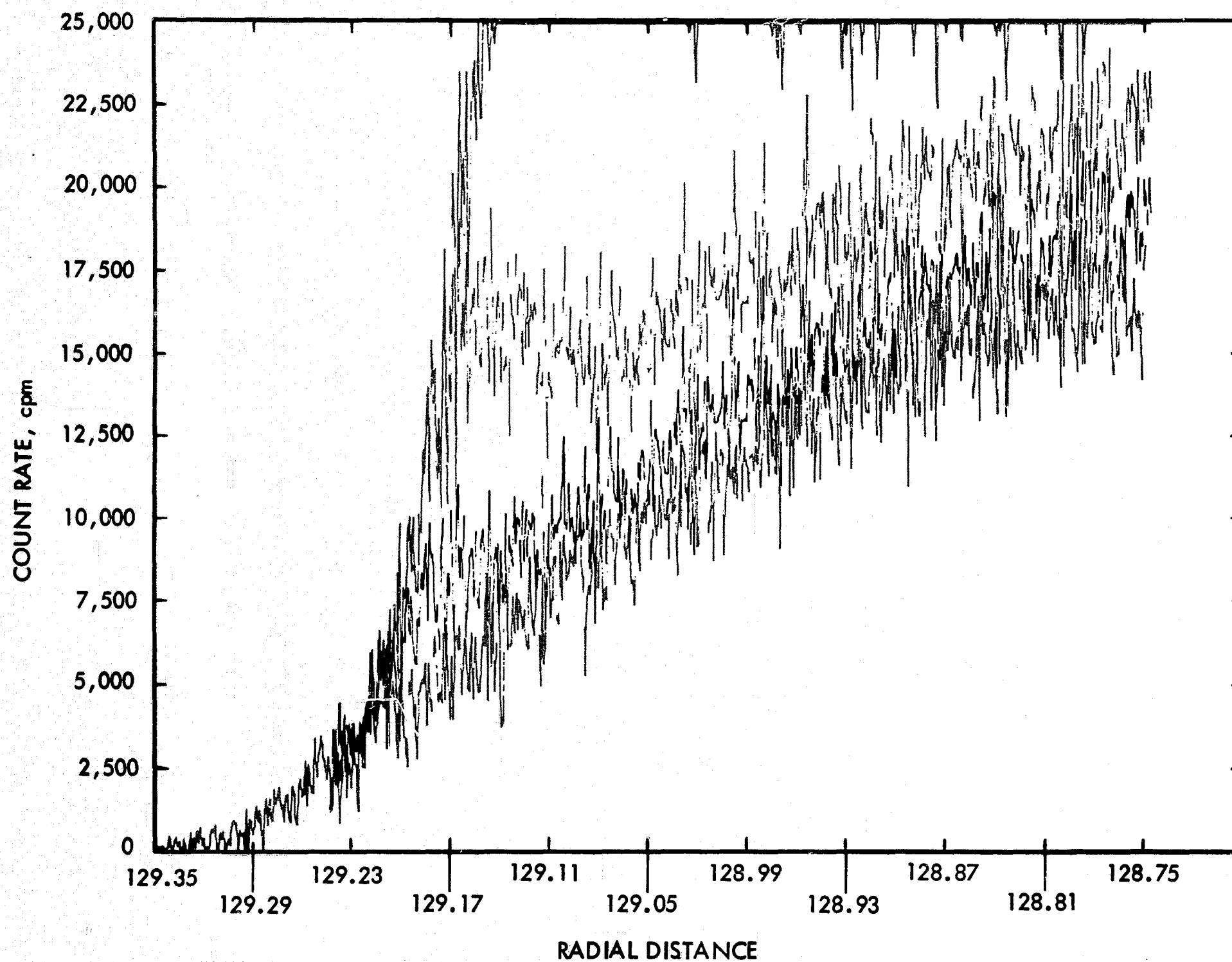


FIGURE 7. STANDARD TRACE COMPARED WITH 0.100, 0.050, AND 0.020 IN. SEPARATIONS

APPENDIX B
FACILITIES SELECTED FOR SURVEY

APPENDIX B

FACILITIES SELECTED FOR SURVEY

<u>Facility</u>	<u>Major Interest</u>
Ohio State University*	General
Magnaflux Corporation*	Ultrasonics
Perkin-Elmer Corporation	Infrared
Automation Industries, Incorporated*	Infrared/Ultrasonic
U.S. Naval Ordnance	Radiograph (Scintillation)
Thiokol Chemical Corporation*	General
U.S. Naval Weapons Station*	Radiography
Microwave Instruments Company	Microwave
Lockheed Missiles and Space Division*	Infrared
Allegheny Ballistics Laboratory	Radiography
Atlantic Research Corporation	Ultrasonics
Boeing Company, Aerospace Group	General
G.C. Optronics*	Holography
Picker X-Ray Corporation*	Radiography
Varian Associates*	Radiography
Rohm & Haas Company	General
Rocketdyne	General
Southwest Research Institute	Neutron Radiography
Modern Controls*	Holography
Electro-Physics Company*	Microwave
Aeronutronics*	Radiograph Enhancement
SHM Nuclear*	Radiography
Aerojet Nuclear Systems Company*	Radiography (Scintillation)
URESCO*	Ultrasonics
TRW*	Holography

* Personal contact scheduled.

APPENDIX C

THERMAL NONDESTRUCTIVE TESTING ANALYSIS (INFRARED)

APPENDIX C

TR 69-60

THERMAL NONDESTRUCTIVE TESTING
OF LINER/PROPELLANT SEPARATION
IN SOLID ROCKET MOTORS

prepared for

Aerojet-General Corporation
Sacramento, California

P. O. No. R-109109-4915
Contract No. NAS 3-12036

by

W. R. Apple
R. E. Robichaud

December 12, 1969

AUTOMATION INDUSTRIES, INC.



MATERIALS EVALUATION GROUP

RESEARCH DIVISION

BOULDER, COLORADO

APPENDIX C

FOREWORD

This report describes the results of an investigation on the feasibility of detecting solid rocket motor liner/propellant separation by a thermal nondestructive testing method. The experimental work was conducted at the Aerojet-General, Sacramento, facilities from 17 November to 21 November 1969 by W. R. Apple and R. E. Robichaud of Automation Industries, Inc., with the cooperation of S. W. Jang and L. G. Swieger of Aerojet-General.

The work described herein was authorized by Aerojet-General's purchase order number R-109109-4915, under Contract NAS 3-12036.



APPENDIX C

SUMMARY

The feasibility of detecting liner/propellant separation by thermal nondestructive testing methods was investigated. A technique that requires water cooling the casing's outside surface was successful in detecting a triangular defect. Minimum detectable defect size diameter is approximately five to six inches. An infrared scanning camera system with facsimile recorder output was used to produce thermographs of the defect indication.



APPENDIX C

TABLE OF CONTENTS

	<u>Page</u>
Foreword-----	i
Summary -----	ii
1.0 INTRODUCTION -----	1
1.1 Purpose of the Investigation -----	1
1.2 The Thermal NDT Technique -----	1
1.3 General Procedure -----	1
2.0 TEST PROCEDURES AND RESULTS, LINER/ PROPELLANT SEPARATION -----	3
2.1 Ambient Cooling -----	3
2.2 Forced Air Cooling -----	6
2.3 Water Cooling -----	6
3.0 TEST PROCEDURE AND RESULTS, CASING/LINER SEPARATION -----	10
4.0 CONCLUSIONS-----	10
4.1 Liner/Propellant Defect -----	10
4.2 Casing/Liner Defect-----	12
5.0 RECOMMENDATIONS -----	12
5.1 Liner/Propellant Defect-----	12
5.2 Casing/Liner Defect-----	14
6.0 APPENDIX -----	14
6.1 System Specifications-----	14



APPENDIX C

TR 69-60

Thermal Nondestructive Testing of Liner/Propellant Separation in Solid Rocket Motors

1.0 INTRODUCTION

1.1 Purpose of the Investigation

The primary purpose of the work described herein was to determine the feasibility of utilizing thermal NDT in detecting a liner/propellant separation in the test sample described in Figure 1. The test results obtained will be utilized in determining the feasibility of thermally inspecting a 260 inch diameter solid rocket motor for liner/propellant separation. Of secondary importance was the detection of any casing/liner separation that may have been present.

1.2 The Thermal NDT Technique

The evaluation of materials and structures for near surface defects by the thermal nondestructive testing technique is well established. Basically, the method involves the inducement of a heat current within the part, perpendicular to the outside surface, and the monitoring of the surface temperature. Any defects such as voids or inclusions within the part will alter the normal heat flow, thus imaging the defect on the surface as a relatively cool or hot area. Due to diffusion effects, it becomes increasingly difficult to image a given size defect as its distance from the surface increases. The minimum detectable defect size grows increasingly larger as its distance from the surface increases.

1.3 General Procedure

The test method utilized consisted of first heating the sample in an oven to 135°F until temperature stabilization within the sample was achieved. The particular temperature chosen was intended to simulate the temperature of the propellant during the curing phase. At the start of a test, the ambient was brought quickly to about 75°F, subsequently, various methods of cooling the casing's outside surface were attempted. Cooling is necessary to induce a heat current from within the sample to the outside casing surface. Defects that attenuate the normal heat flow will result in a slower heat transfer to the surface at that location. Thus a



APPENDIX C

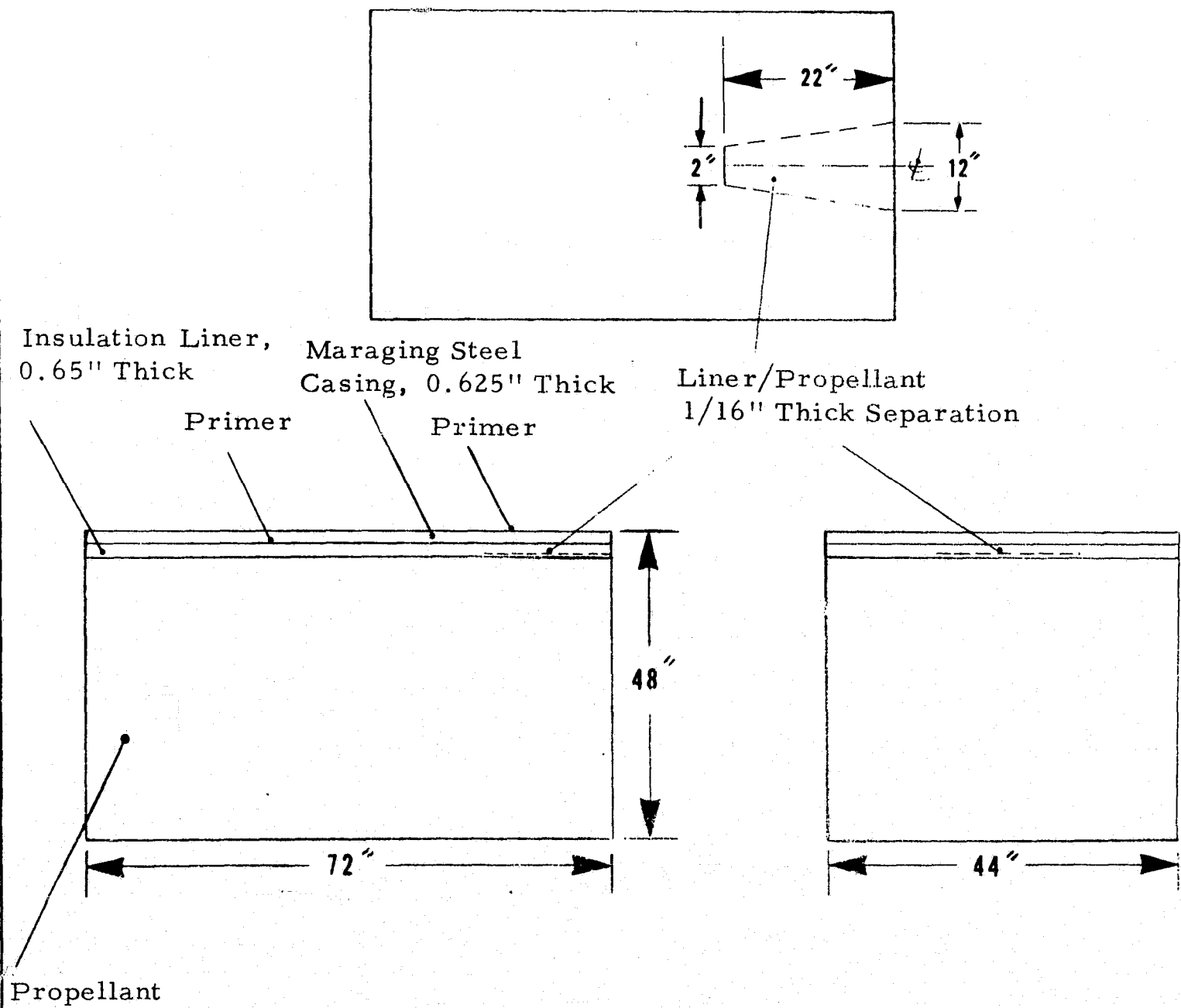


Figure 1. Test Sample

APPENDIX C

separation defect should be imaged on the casing's outside surface as a low temperature area.

Surface temperature distribution was monitored by an infrared scanning radiometer system with oscilloscope signal display and area scan recording capability. Periodic thermal images of the sample's surface were recorded throughout a particular test. Complete specifications on the scanning radiometer system are included in Appendix 1.

2.0 TEST PROCEDURES AND RESULTS, LINER/PROPELLANT SEPARATION

Three distinctive series of tests were run in the attempt to detect the liner/propellant separation shown in Figure 1. Each series is distinguished from the others by the method used in cooling down the casing's outside surface. In each test the sample's temperature was first brought to about 135°F prior to the cool down and surface temperature monitoring phases. The three cooling methods were (1) ambient room temperature cooling, (2) forced air cooling and (3) water cooling.

2.1 Ambient Cooling

This method attempted to induce a thermal current from within the sample to the casing's outside surface by simply letting it cool down at room temperature. This was done by opening the oven's doors and thus suddenly reducing the sample's ambient from about 135°F to 78°F. The general orientation of the infrared scanning camera and sample is shown in Figure 2. During the cooling period, the surface temperature distribution was continually monitored by the infrared scanning system.

A typical facsimile recording of the surface temperature is shown in Figure 3. This particular recording was taken 90 minutes into the test. Warmer areas are darker. Note the streaking present in the recording. This was due to an uneven surface emissivity produced by a variation in the paint coating thickness on the casing's outside surface. The position of the defect is shown by the area outlined with dashed lines.

The casing's outside surface was monitored as described above for a three and one-half hour period. Indications of the liner/propellant separation could not be detected.

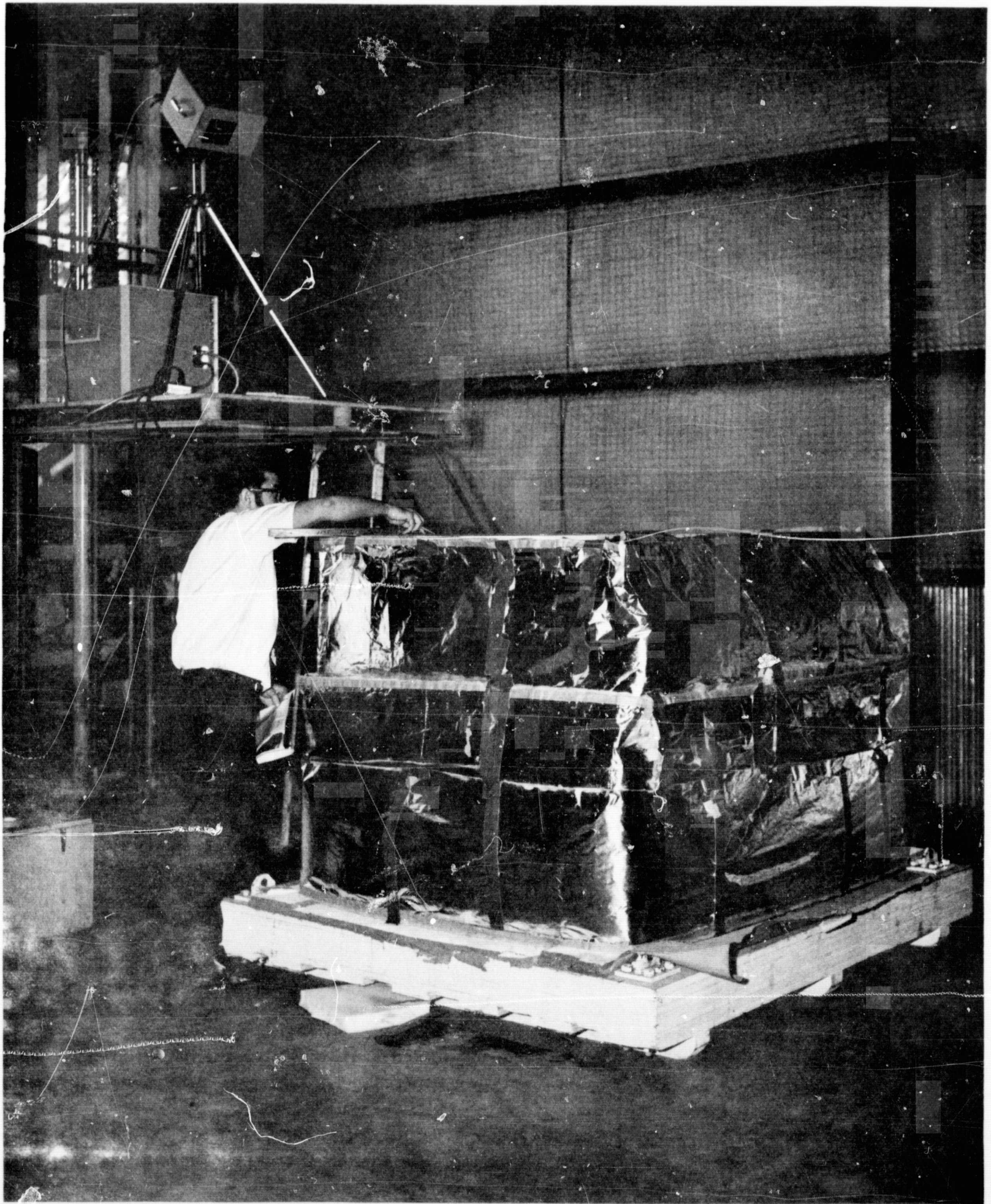


Figure 2. Infrared Camera System and Sample

Change in Surface
Emissivity Streaks

Separation Defect Outline

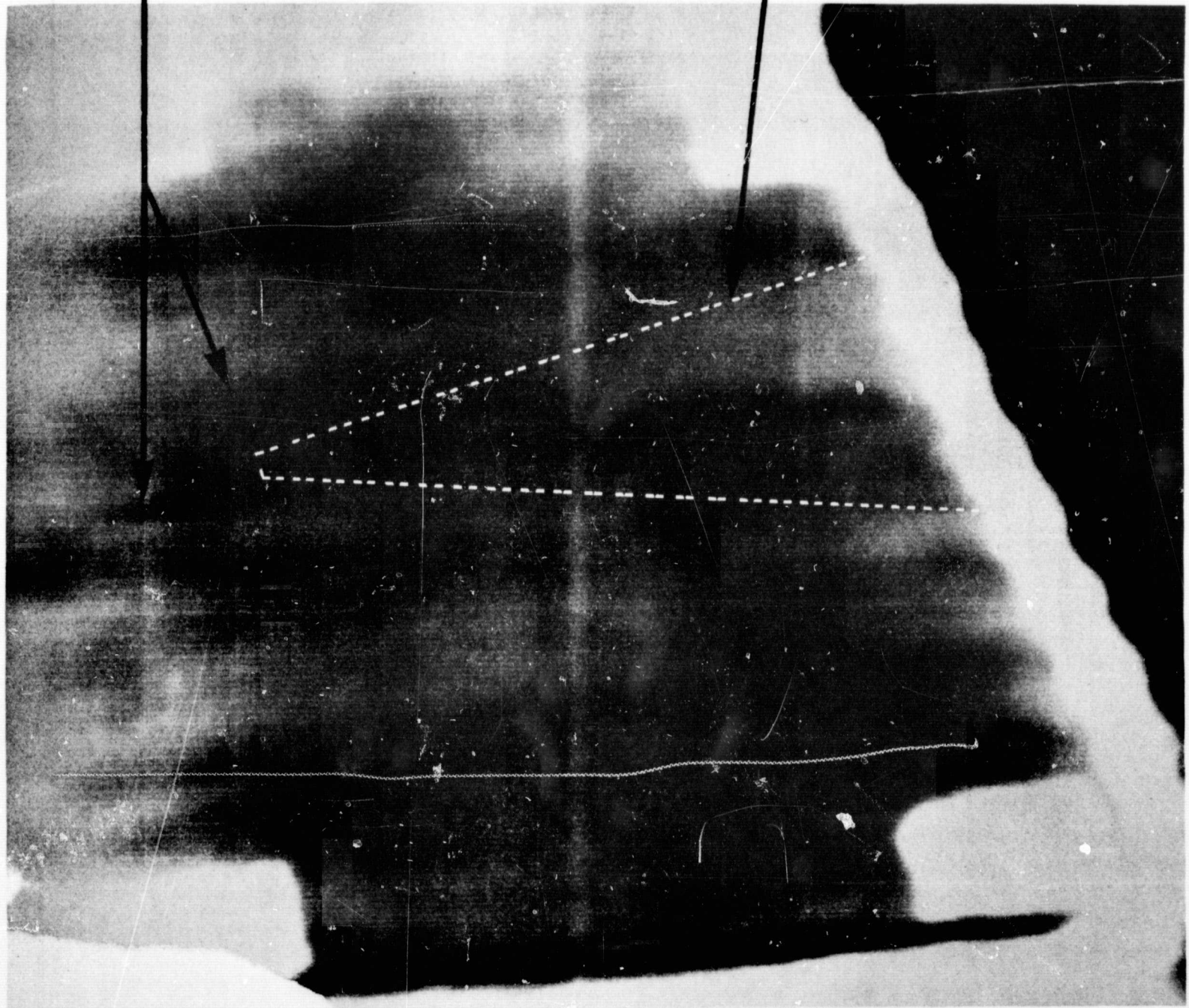


Figure 3. Recorder Output, Ambient Cooling

APPENDIX C

2.2 Forced Air Cooling

This series of tests was very similar to the ambient cooling series but differed in the cooling method. Three fans were utilized to blow air across the casing's surface. It was hoped that this would result in a higher cooling rate than the ambient cooling method. The infrared cameras was also repositioned for this test so that the defect area would be closer to the camera.

Typical results are shown in Figure 4. This was taken at 18 minutes into the test. Note that there is no streaking present as in the ambient cooling test. Prior to this series of tests, the surface of the casing was sprayed uniformly with black paint to eliminate the changes in emissivity across the surface. All subsequent tests were run with the surface painted.

The casing's outside surface was monitored during cooling for a one hour period. Indications of the liner/propellant separation could not be detected.

2.3 Water Cooling

Of the three cooling methods discussed in this report, this was the only one that resulted in the detection of the liner/propellant unbond area.

As in the previously discussed methods, the sample was first oven heated to about 135°F. The oven was then quickly brought to 78°F and the water cooling cycle of the sample's surface started. This was done by inclining the whole sample at about three degrees from the horizontal and allowing a thin sheet of water at 65°F to flow downslope over the casing's surface. After the water cooling period, the surface was wiped dried. Monitoring the surface temperature with the infrared scanning system began at this time.

Three sets of tests, with water cooling, were run. The first set was run with a six minute water cooling period. The other two were run with fifteen minutes cooling periods. The liner/propellant separation was detected in all three sets of tests. Results from the two fifteen minute cool down tests were superior to the six minute cool down test. Only the results from the longer cool down tests will be discussed below.

Results from each of the fifteen minute cool down series of tests are shown in Figure 5 and 6. In each figure, the separation defect location

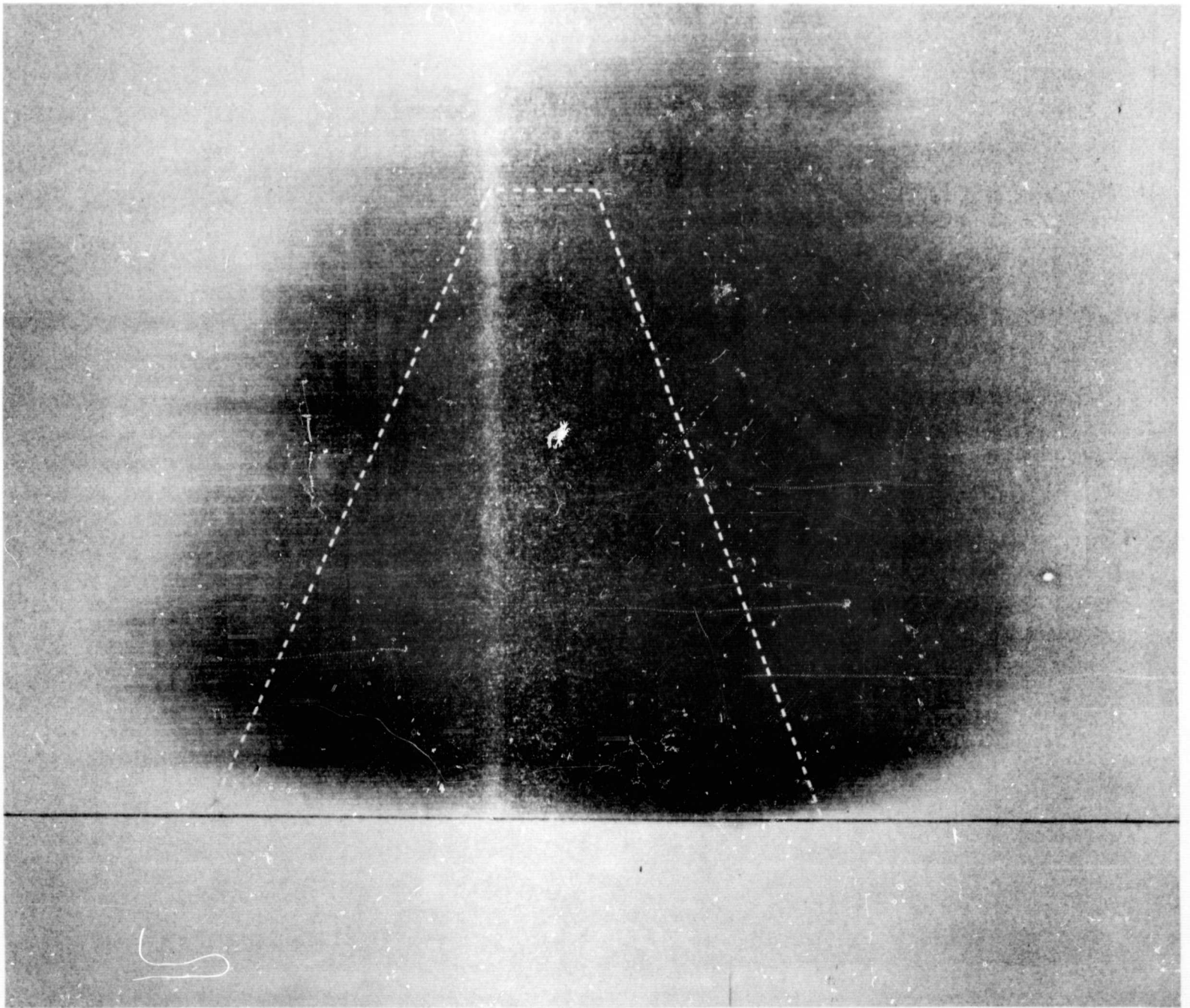


Figure 4. Recorder Output, Forced Air Cooling

Appendix C

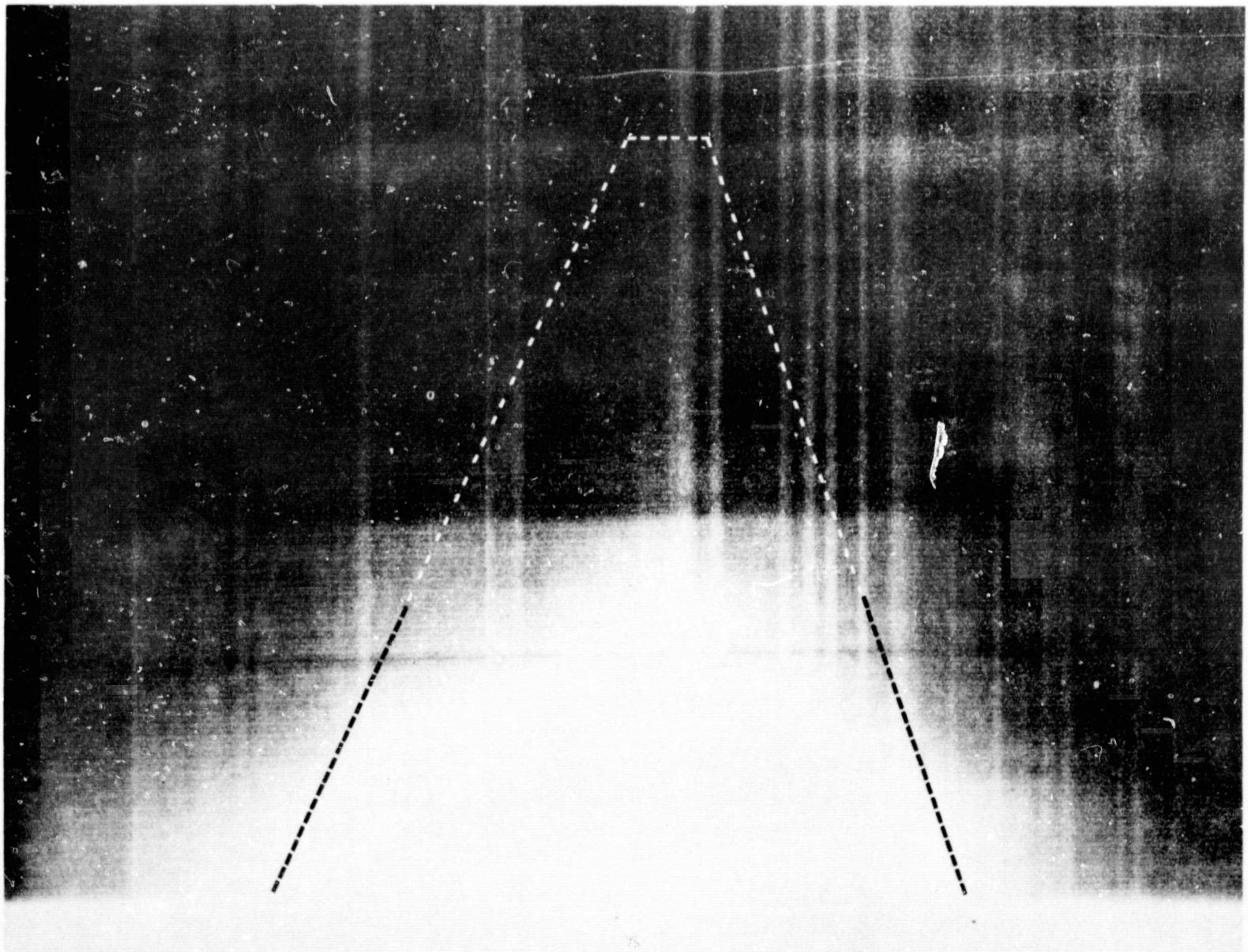


Figure 5. Recorder Output, Water Cooling

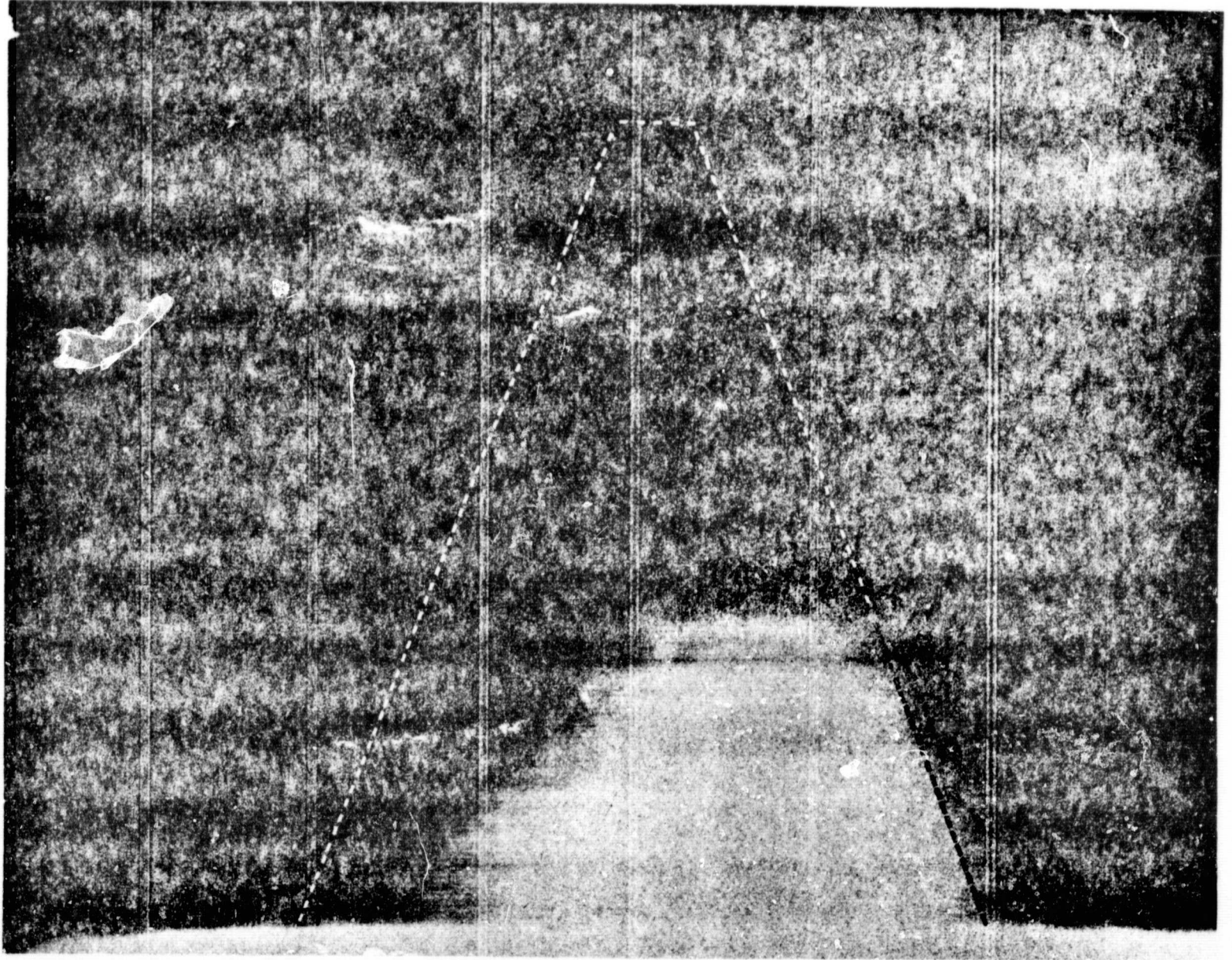


Figure 6. Recorder Output, Water Cooling



APPENDIX C

is noted by the area enclosed by the dashed lines. The straight streak marks noted in Figure 5 were made by an anomaly in the development process of the facsimile recorder. Note that the tip area of the triangular defect cannot be detected. From this data it is estimated that the minimum detectable defect size is about six inches in diameter.

The purpose of running two fifteen minute cool down tests was to determine the repeatability of the test. Each test showed the following general results. Immediately after the fifteen minutes cool down period, another fifteen minute period must be allowed prior to testing. This period allows the separation defect to maximize the defect/nondefect temperature differential and also allows spurious surface temperature variations to vanish. In effect by waiting this period of time the signal to noise ratio tends to be maximized. Another period then follows in which the defect can be detected and recorded. This period lasts about one-half hour. Typical results obtained during this period are as shown in Figures 5 and 6. Figures 5 and 6 were obtained at forty-six minutes into their respective tests.

3.0 TEST PROCEDURE AND RESULTS, CASING/LINER SEPARATION

The bulk of the work performed was channeled towards the detection of the liner/propellant separation defect. One test was run in an attempt to detect casing/liner separation. Figure 7 shows the locations of various casing/propellant separations detected by pulse-echo ultrasonic NDT techniques. A water cooling down period of fifteen minutes was followed by a period of one-half hour in which the surface thermal gradients were recorded. Indications of casing/liner unbonds could not be found.

The above results are in no way conclusive, due to several factors. One is that the sample had not achieved temperature stabilization with the 135°F oven temperature. Surface casing temperature was measured at 115° prior to initiation of the water cooling cycle. Another factor is that the cooling cycle should probably be shorter when attempting to detect casing/liner defects as opposed to liner/propellant defects.

4.0 CONCLUSIONS

4.1 Liner/Propellant Defect

Three methods of testing the sample for the presence of liner/propellant separation were investigated. These methods were distinguished from



APPENDIX C



Figure 7. Location of Casing/Liner Defects Located by Ultrasonic Pulse-Echo Technique



APPENDIX C

each other by the method of inducing a heat current within the sample. The three methods were (1) ambient cooling, (2) forced air cooling, and (3) water cooling. The water cooling method was the only one that yielded acceptable results.

A typical test consisted of cooling down the outside surface with a flowing water sheet for a period of fifteen minutes. A fifteen minute waiting period then followed. The defect area could then be detected during the next one-half hour period.

4.2 Casing/Liner Defect

Casing/liner defect detection was attempted but conclusive results could not be obtained due to the lack of time in performing more exhaustive tests.

5.0 RECOMMENDATIONS

5.1 Liner/Propellant Defect

Even though excellent results were obtained in detecting liner/propellant separation, further work is recommended in order to gain more data on the effect of various test parameters. This data could then be used in predicting the performance of this type of test on an actual missile in the field.

The next series of tests should be done on the same type of sample as utilized in this report. Further testing should strive to simulate possible field testing conditions as closely as possible. Recommendations for further testing are as follow:

A. Vertical Surface Testing

The sample should be oriented so that the casing's surface is vertical. This would be the best simulation of field orientation.

B. Surface Emissivity

The sample's surface finish should be the same as the missile's finish.

APPENDIX C

C. Separation Defect

Unbonds, defined as the lack of bond between liner and propellant without separation, should be simulated. In this case we have physical contact between liner and propellant but without bond. This type of defect should produce different thermal effects than a 1/16" thick separation.

Separation defects should be produced with varying diameters with both unbonds and separation defects. This will be used to determine the minimum size defect that is detectable. Defects should be separated from each other and away from the edges of the sample as much as possible.

The ability of the test to distinguish between casing/liner and liner/propellant separation should be investigated by simulating a casing/liner defect over a liner/propellant defect.

D. Water

The possible use of chilled water should be investigated.

E. Cooling Time

A fifteen minute cooling period was found to produce good results. Varying the cooling period may produce better results.

F. Cooling Rate

Thermocouples should be embedded in the casing, liner and propellant to monitor cooling rates at various depths during the test. These should be placed both in defective and non-defective areas. Data from the thermocouples will furnish valuable data in establishing various parameters such as water temperature and cooling time.

The results of the above program would be a much clearer definition of the effects of various parameters and a gain in confidence in the results under varying conditions.

After the above series of tests, sufficient data should have been accumulated to conduct tests during actual test pouring of missile sections.



APPENDIX C

5.2 Casing/Liner Defect

If the detection of casing/liner separation by thermal NDT is to be pursued, the feasibility study should follow the same general procedure as the liner/propellant study.

6.0 APPENDIX

6.1 System Specifications

Specifications of the thermal NDT system utilized are listed below.

Radiometer Scanner

Radiometer

- Optics - front surface mirrors
- Detector - photovoltaic, indium antimonide, liquid nitrogen cooled; operating time, 4 hours
- Focus - adjustable 18 inches to 24 feet
- Spot Size - 0.080" at 24" focus
- Sensitivity - 0.2°C NET
- Temperature Range - ambient to 100°C
- Vertical Scan Field - 12°
- Vertical Scan Speed - 2°/sec
- Horizontal Scan Field - 12°
- Horizontal Scan Speed - 40 scans/sec
- Target Sighting System - permits operator to rapidly focus and aim radiometer on the target
- Vertical Switch - ON-OFF switch for vertical sweep motor
- Horizontal Switch - ON-OFF switch for horizontal sweep motor
- Cont. Switch - disables trigger every other vertical sweep, used in conjunction with scan test mode

Tripod

Heavy Duty - adjustable



APPENDIX C

Control Console

Control Panel

Main Power ON-OFF Switch - applies line voltage to the system

System Power ON-OFF Switch - energizes radiometer, rotating mirror motor, heat source, recorder and oscilloscope

Recording Signal - Level Control adjusts threshold writing level of recorder;

Sensitivity Control gain adjustment for radiometer signal;

Normal-Alt Switch - provides for AC or DC coupling of radiometer to recorder and oscilloscope;

(+) and (-) Switch - reverses polarity of radiometer output signal; (+) causes recorder to write darker for increasing temperature, (-) causes lighter writing for increasing temperature;

Meter displays input voltage to recorder.

Monitor Oscilloscope

Benrus Model RA-850 allows continuous monitoring of target temperature information independently of the recorder.

Recorder

Century Model 1522, intensity modulated, scan width 8", paper roll length 250 ft.

Power Requirements

115 volts, 60 cycle AC, 7 amps maximum



APPENDIX D

HIGH ENERGY RADIOGRAPHY ANALYSIS

APPENDIX D

FINAL REPORT
HIGH ENERGY RADIOGRAPHY
OF
260" SOLID ROCKET GRAIN
AEROJET P.O. NO. G-109269-4915
L-2089 13 April 1970

HIGH ENERGY RADIOGRAPHY
OF
260" SOLID ROCKET GRAIN

- I. Introduction
- II. Experimental Program
- III. Experimental Data
 - A. General Comments
 - B. Sensitivity
 - C. Minimum Detectable Flaw Estimation
 - D. Extrapolation to Sections > 65"
 - E. Analysis of Tapered-Thickness Radiographs
- IV. Relation of Data to the 260" Grain
- V. Radiography of the 260" Grain
- VI. Discussion
- VII. Summary

APPENDIX D

HIGH ENERGY RADIOGRAPHY OF 260" SOLID ROCKET GRAIN

I. INTRODUCTION

This document is the final report of an analysis of high energy radiographic techniques for the detection of critical defects in large solid propellant grains, with specific application to the 260" grain being studied by Aerojet. The analysis was carried out by Applied Radiation Corporation in cooperation with Aerojet, under Aerojet P.O. No. G-109269-4915.

The analysis consists of a preliminary study,¹ an experimental program carried out by Aerojet based on the initial study, the analysis of the experimental results, and conclusions and recommendations. This final report embodies the latter two phases of the effort.

1. Superscript numbers refer to the list of references appended.

II. EXPERIMENTAL PROGRAM

The gross outlines and some details of an experimental program designed to use the Aerojet 10 MeV linacs as x-ray sources to test the conclusions of the initial study¹ were outlined in that study. For mechanical reasons certain modifications in the proposed program became desirable and these were worked out with Aerojet project personnel prior to the actual experiments. The work itself was carried out by Aerojet project and radiographic personnel, and credit is due them for the excellent and expeditious manner in which the work was done as well as for the good results (see below). Brief but comprehensive notes of the experimental exposures were taken by the Aerojet project engineer and some of what is stated below is quoted from these notes.

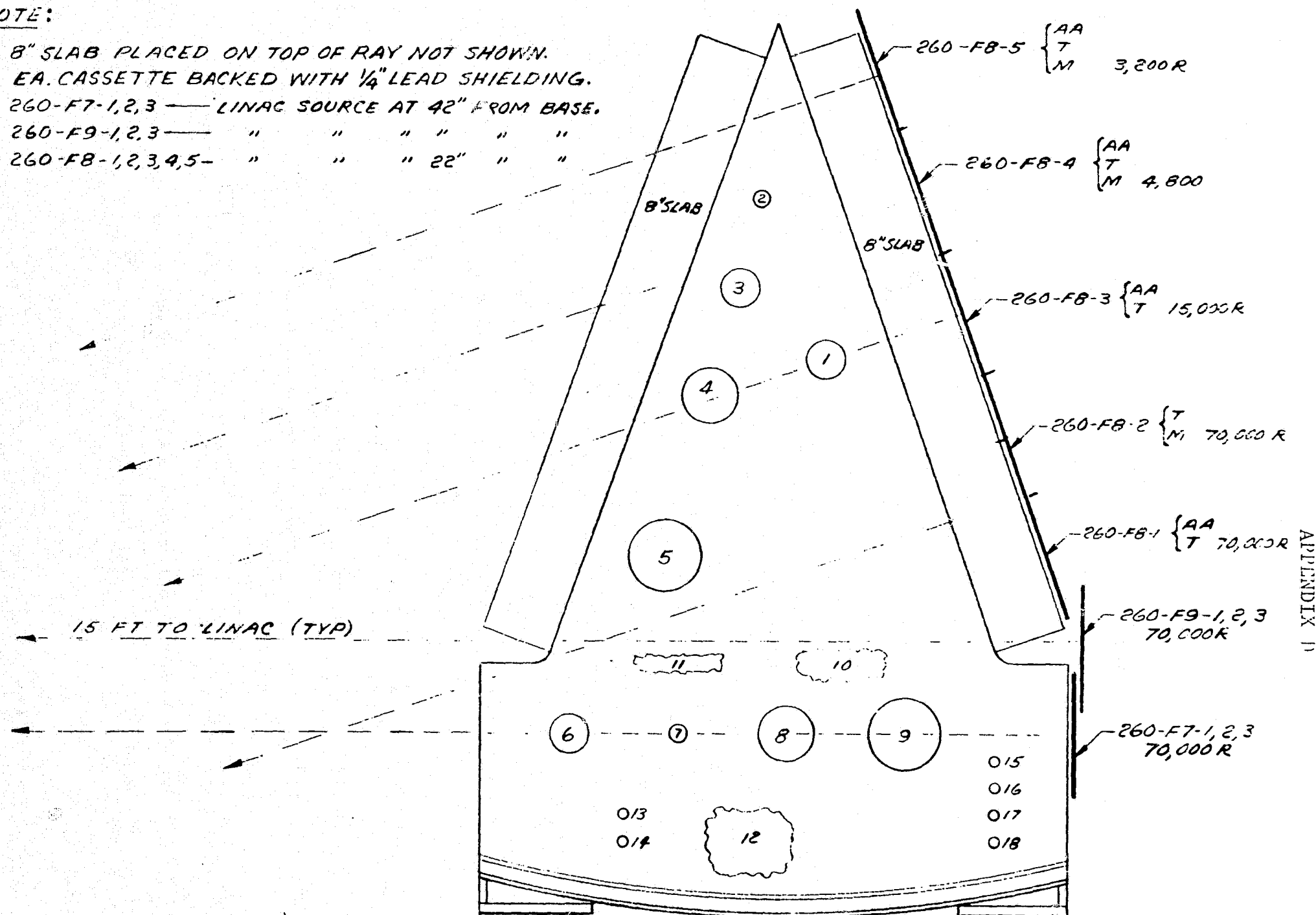
The setup for the experiments is shown in figure 1, taken from an Aerojet sketch. In addition to the two 8" propellant slabs placed along the tapered ray section a third slab, not shown in the figure, was placed atop the ray section to reduce scattered radiation from the upper surface of the section, to permit examination for flaws near that surface, and to more nearly simulate scattering conditions in the interior of the main body of the actual grain.

All cassettes for the program were loaded with multiple films and incorporated lead screens 0.010" thick in front of and 0.040" thick behind the films. A first exposure in the F7 area (see the figure) revealed that considerable scattering from the walls etc. of the radiographic room could reach the films from behind, and $\frac{1}{4}$ " back lead filters were added to eliminate this problem. All exposures were carried out using a TFD of 15 ft. (4.57 meters).

The first exposure, F7-1, 2 and 3, was made primarily to view the 4" void through 65" of propellant. A penetrometer was also placed on the film intended to receive the image of the void (F7-2) and additional films F7-1 and F7-3 were placed adjacent to F7-2, to view additional areas of 65" thickness above and below the area containing the 4" void. Film F7-3 was so placed as to test the detectability of a 2" void.

NOTE:

1. 8" SLAB PLACED ON TOP OF RAY NOT SHOWN.
2. EA. CASSETTE BACKED WITH 1/4" LEAD SHIELDING.
3. 260-F7-1,2,3 — LINAC SOURCE AT 42" FROM BASE.
 260-F9-1,2,3 — " " " " " "
 260-F8-1,2,3,4,5 — " " " 22" " "



DEFECT GRAIN SAMPLE - TOP VIEW

FIGURE 1

APPENDIX D

II. EXPERIMENTAL PROGRAM (Contd.)

A series of exposures was then made along the tapering ray section as modified by the additional slabs of propellant (F8-1 to 5) with the purpose of exploring the capability of covering a broad thickness range, in a single exposure, through the use of multiply-loaded cassettes in which the various films are of different speeds. Consideration of the speeds of available film types indicate the possibility of covering a range at least as great as 3 hvl's by this method. If this could be done in fact, a portion of the aft end of the ray section of the grain could be inspected if other methods were not available. Penetrameters were so placed as to assist in the evaluation of the coverage of the films.

The final exposure was designed to reveal the "crack" simulation defects. It also covers a wide thickness range, from 65" down to 50", because of the taper and the additional slabs of propellant.

Table I, taken from the Aerojet data, lists the complete series of exposures, with the film loading, the dosimeter reading of exposure in R, whether any penetrometer was used on each film, and the film identification symbols.

The penetrameters were of the step type fabricated of "Apocast" (sp. gr. ~1.7), 1" wide; the three thickest steps were 0.5", 0.35", and 0.25" thick respectively, and each step included a 1T hole (ASTM E-142 terminology)².

APPENDIX D

TABLE I

<u>IDENTIFICATION</u>	<u>FILM USED</u>	<u>(R) EXPOSURE</u>	<u>PENETRAMETER ON FILM</u>	<u>NUMBER OF FILMS IN CASSETTE</u>
260-F7-1	AA	70,000	NO	2
260-F7-2	AA	70,000	YES	2
260-F7-3	AA	70,000	NO	2
260-F8-1	AA+T	70,000	NO	2
260-F8-2	T+M	70,000	YES - 2	2
260-F8-3	AA+T	15,000	YES - 2	2
260-F8-4	AA+T+M	4,800	YES - 2	3
260-F8-5	AA+T+M	3,200	YES	3
260-F9-1	AA	70,000	YES	2
260-F9-2	AA	70,000	YES	2
260-F9-3	AA	70,000	YES	2

III. EXPERIMENTAL DATAA. General Comments

Before proceeding to details of the data derived from the program, a few general comments are offered to characterize the overall experimental effort. In the first place, the overall results must be described as truly excellent. Although H&D densities of some of the films were somewhat lower than optimum, nevertheless the series constitutes a highly searching examination of those sections of the ray which were radiographed. The artificial spherical flaws, 8", 6", 4" and even 2" in diameter, are clearly and unequivocally delineated on the films, as are a number of unplanned actual flaws a number of which are considerably smaller than the 2" artificial flaw. One of these latter is approximately an ovoid $3/4" \times 1/2"$. Several of the penetrameter holes, which though geometrically designed as "sharp" flaws are nevertheless smaller even than the small unplanned flaws detected, are also clearly visible. Penetrameter sensitivity, and even sensitivity estimated on the basis of the smallest actual flaw, is below 1% for the 65" thickness. In consideration of the limited capabilities of the Aerojet linacs (see below also), this is quite remarkable performance and the Aerojet personnel who conducted the experiments are to be commended in the highest terms. Table II, also supplied by Aerojet, lists the exposures and the significant details revealed on each film.

B. Sensitivity

The "sensitivity" of the films through the 65" section may be estimated in a variety of ways. Detection of the required 4" void requires a "thickness sensitivity" or "contrast sensitivity" of $\sim 6.2\%$, approximately equivalent to 4.3% as defined in ASTM E-142,² wherein the basis of sensitivity estimation is a "2T" hole in a 2% thick penetrameter. In our opinion, to provide maximum assurance of detection of the 4" void it is preferable to plan for detection of a 2" void, for a contrast sensitivity of $\sim 3.1\%$, or $\sim 2.2\%$ by E-142.

In order to assist in the estimation of sensitivity, H&D density measurements were made on a number of the films, in areas of flaw images as well as in "background" areas. An attempt was also made to measure density increments in and around penetrameter hole images. In these latter cases the density differences

APPENDIX D

TABLE II

<u>FILM NUMBER</u>	<u>SIGNIFICANT DETAILS</u>
260-F7-1	No penetrameter - no defects.
260-F7-2	Penetrameter, 4" void No. 6, flat cracks 11 and 10 (edge only) and one unidentified void.
260-F7-3	No penetrameter, 2" void No. 7, 6" void No. 8, edge of 8" void No. 9.
260-F8-1	Clear - no penetrameter.
260-F8-2	Penetrameter (2) clear.
260-F8-3	Penetrameter (2) clear.
260-F8-4	Penetrameter (2) not clear, numerous small indications.
260-F8-5	Penetrameter, very severe density changes, small indications.
260-F9-1	Penetrameter, very severe density changes.
260-F9-2	Penetrameter, 4" void No. 6 visible, at least six separate unplanned voids visible.
260-F9-3	Penetrameter, part of 2", 6", 8" voids visible.

III. EXPERIMENTAL DATA (Contd.)

were near the precision of the instrument (a MacBeth Quantalog Model TD-100A Densitometer) as well as the visibility threshold; but the measurements are consistent with those made on the flaw images and are considered reasonably indicative.

The densitometric measurements, and visual examination of the films, confirm that sensitivity is clearly better than required. Although "background" densities of the films measured varied between ~ 1.3 and ~ 1.9 , even in the lighter films two penetrameter holes were visible ($0.35" \times 0.35"$ right circular cylinder). This indicates without doubt that the requirement to detect the 2" spherical void is more than met. And in the darker films (H&D 1.6 - 1.9) three penetrameter holes were visible through the full 65" thickness ($0.25" \times 0.25"$ right circular cylinder) (film F7-2). To check this a number of Aerojet radiographers were independently asked for their assessments. All reported "no trouble seeing the third hole". Aerojet project personnel, though not trained radiographers, also confirmed this. The density difference ΔD thus observed is in the neighborhood of 0.01, corresponding to a "sharp" (cylindrical) defect of 0.25" diameter, or a penetrameter sensitivity about 0.39% on a contrast basis, or about 0.27% on the ASTM basis. Since the best reported penetrameter sensitivities in the radiography of solid propellant are in the range of 0.25-0.3% ASTM, the outstanding quality of these films is obvious. On the other hand, since the 260" requirement relates to detection of spherical voids, it is reasonable to anticipate that the minimum detectable ΔD would be ~ 0.02 rather than 0.01. This figure is used in the estimations below.

When we come to consider the images of both the artificial and the unplanned "natural" flaws, the conclusions above are well substantiated. The required 4" void is quite obviously depicted in several films, with a density difference ΔD averaging conservatively ~ 0.2 , not only through the 65" thickness (film F7-2), but also through a considerably lesser thickness, $\sim 50"$ (film F8-3). This is not an unusual circumstance in high energy radiography. The 2" void

III. EXPERIMENTAL DATA (Contd.)

is revealed through the full thickness in films F7-3 and F9-3, with $a/\Delta D$ in the range of 0.1. A small unplanned void, the 1/2 x 3/4" ovoid cited earlier, shows through the full thickness in film F9-2, with $a/\Delta D$ of ~ 0.035 . Since its configuration appears to be not unlike that of a 2T hole, one can deduce an ASTM sensitivity, as shown by this actual flaw, of $\sim 0.77\%$, comfortably better than 1%. Such an image on the film is probably a more real indicator of sensitivity to the type of flaws of interest in this study than even the penetrameter images.

C. Minimum Detectable Void Estimation

Based on the data taken from the films and quoted above, it is possible to make a rough estimate of the size of the minimum detectable spherical void. In consideration of the penetrameter images, one could conclude that a very small void, perhaps $\frac{1}{2}$ " in diameter or less, could be observed. Other estimates can be based on the flaw images, taking into account the fact that film characteristic curves, when plotted as density vs relative exposure rather than log relative exposure, are not far from straight lines, over the density range of interest here. This is illustrated in Figure 2, in which the characteristic curve of Type AA film has been so replotted. It is noticeable also that the density differences, ΔD , due to void images on the experimental films are approximately linear with void size. Combining these two facts, and recalling that we have estimated a ΔD of 0.02 necessary for detection of a spherical void, then from the ΔD of the 4" void - (~ 0.2) one can deduce that a flaw about one-tenth that size, 0.4" in diameter, could probably be detected. From the ΔD of the 2" flaw (~ 0.1) the same conclusion follows. From the ΔD of the 1/2" x 3/4" ovoid (~ 0.035), one may estimate that a flaw near 0.3" in diameter could be detected. In any case it is clear that voids slightly smaller than $\frac{1}{2}$ " diameter could be detected and that this is about the limit of sensitivity for such voids ($\sim 0.77\%$ contrast, $\sim 0.54\%$ ASTM) in these films. These considerations will be important in extrapolating the results to thicker sections.

CHARACTERISTIC EXPOSURE-DENSITY DATA (KODAK TYPE AA FILM)

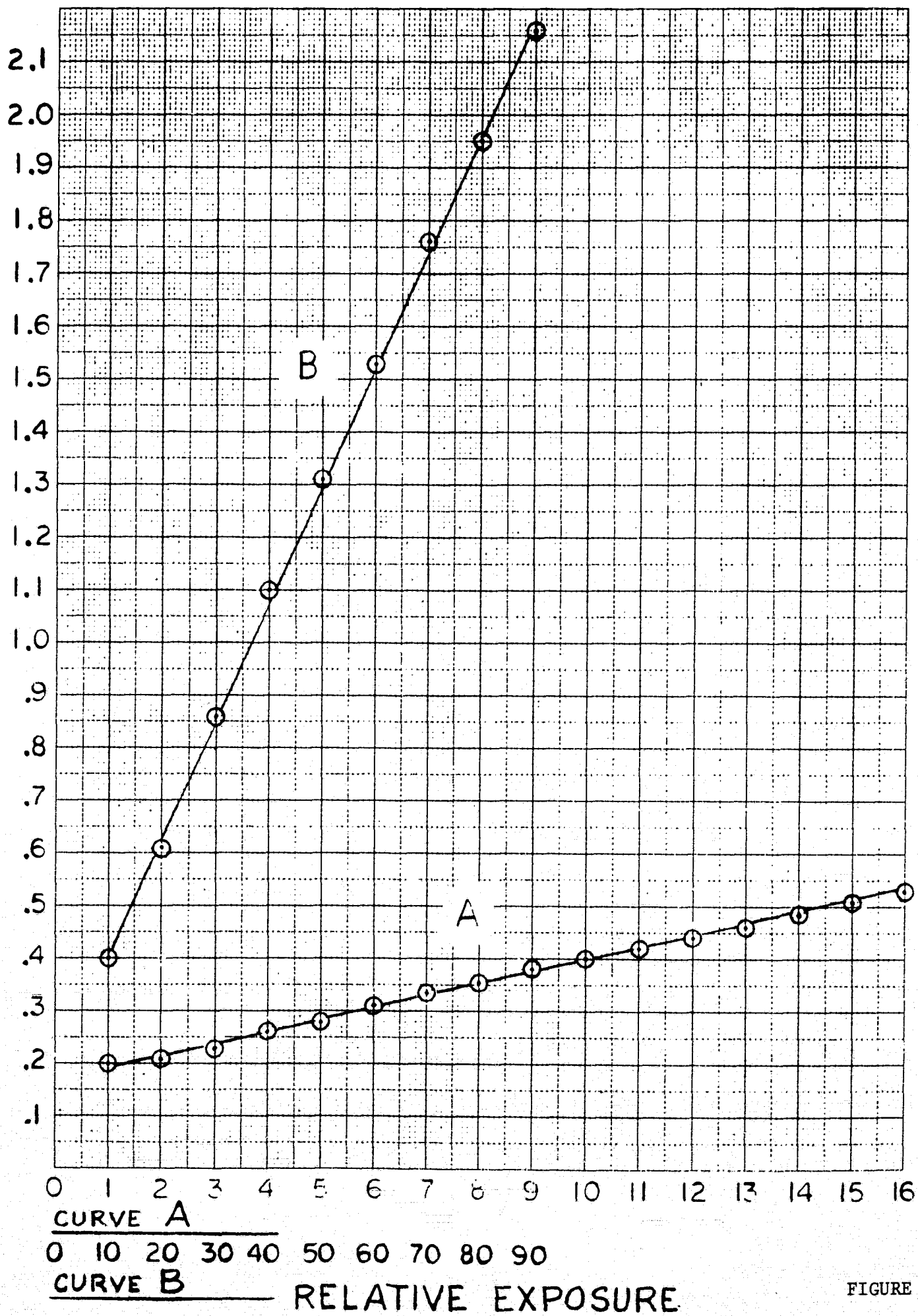


FIGURE 2

APPENDIX D

II. EXPERIMENTAL DATA (Contd.)

D. Extrapolation to Sections > 65"

Since the experimental results in the 65" thickness are so much better than the requirements for the 88" thickness of the 260" grain, it appears relevant to consider what minimum performance could be expected from an Aerojet-type linac, perhaps with a higher output capability, in sections thicker than the 65" of the present ray sample. For this evaluation the actual performance, in terms of energy and half-value layer (hvl) should be closely examined to assure that the extrapolation is reasonable.

The Aerojet linacs operate at a nominal energy of 10 MeV. The dose required for the 65" section was indicated by the dosimeter as 70,000 R at 1 meter. The TFD was 15 ft (4.57 m), which leads, by the inverse square law, to a dose of 3350 R at the film (attenuated however by the object). From the densitometric data an average gross density minimum of 1.7 through a flawless 65" thickness may be inferred. Consultation of characteristic curves and exposure requirements for given density levels on AA film³ leads to the conclusion, taking into account a minimum intensification factor of 2 for the lead screens, that the dose actually received at the cassette was ~1.5 R. Thus the attenuation introduced by the object was a factor of ~2235, corresponding to ~11.1 hvl's. Thus the apparent hvl was ~5.85". Consulting figure 2 of the initial study¹, one would infer an actual energy of the linac of only ~7.5 MeV, which is almost certainly too low for a nominal 10 MeV machine. It would appear that the linac dosimetry is reading high. As a matter of fact there is some evidence⁴ that (a) the linac energy is indeed low, in the range of 8-9 MeV, and (b) that the dosimeter does indeed read high, of the order of 5% but less than 10%. Making allowances for the dosimetry leads to a hvl near 6", corresponding to an actual energy of 8 MeV, with the total 65" thickness thus representing ~11 hvl's. These values appear reasonable to consider for the extrapolation below.

The dose of ~70,000 R at 1 meter requires already a rather long exposure at the Aerojet exposure rate of ~500 R/min at 1 meter. If one is to consider greater

III. EXPERIMENTAL DATA (Contd.)

thicknesses than 65", one can scarcely plan a TFD less than the 15 ft used in these experiments. For reasonable exposure times, then, one should consider increased output, to permit exposures comparable with these. The "next larger size" linac would have an output in excess of 4 times that of the Aerojet machines, and would therefore be capable of penetrating two more hvl's (total 13) in about the same time as the present 65" exposures.

We now consider whether such an exposure could be expected to have adequate sensitivity to the voids of interest. At 11 hvl's and 8 MeV, the scattering ratio¹ is about 7.7, and at 13 hvl's this ratio has a value near 9.1. If the 13 hvl thickness were exposed to the 11 hvl dose, ~70,000 R, the films would be hopelessly underexposed, with an average density less than 0.5. In view of the scattering ratio values, it is clear that when the exposure is quadrupled to bring the film density up to ~1.7, most of the additional density will be contributed by scattered radiation. For conservatism we are justified in basing our calculations on the assumption that all of the additional density will be from scattering. On that assumption, the data of figure 2 tell us that the ΔD 's due to the flaws present will be divided by 4 (although this descriptive analysis is oversimplified, it is useful since it leads to conservative results). Thus the ΔD due to the 2" spherical void will be about 0.025 rather than 0.1. On the basis of the films actually taken ΔD 's of this level and even less are revealed in the penetrameter images; a ΔD not much larger is revealed in the image of the 1/2" x 3/4" ovoid; and we have already concluded that a ΔD of about 0.02 would suffice for detection of a small spherical flaw. It is conservatively clear then that we should expect to detect the 2" void in the 13 hvl thickness, and that the required 4" void would be reasonably obvious, under the conditions given.

One can conclude then that the required inspection sensitivity could be achieved, using a linac of ~8-10 MeV and at least 2000 R/min at 1 meter, through a thickness not less than 77" and possibly somewhat more, but probably not through the 260" grain's 88" sidewall thickness.

III. EXPERIMENTAL DATA (Contd.)E. Analysis of Tapering-Thickness Radiographs

The series of films F8-1 through 5 were made in the tapering section of the ray. Their primary purpose was to show experimentally the thickness range which could be covered in a single exposure, by multiply-loaded cassettes. The actual maximum thickness range covered by any one exposure in the F8 series was about 12", due to the taper angle, and film images of the penetrameters do indeed confirm that this thickness range can be covered easily. Thus a range of 3 hvl's, contemplated by the initial study¹, has not been demonstrated. On the other hand the F9 series films, loaded only with Type AA, show quite severe density variations the dark areas of which have been explored with high-intensity viewers. It would appear that, had slower films also been used in the cassettes, a thickness range of 15"-17" would have been demonstrated. While this does not confirm the planned range of 3 hvl's, it is considerably more than 2 hvl's, and it is our opinion the 3 hvl range is a reasonable maximum to consider. The application of this conclusion to the 260" grain is discussed below.

IV. RELATION OF DATA TO THE 260" GRAIN

Turning now to the problem of the 260" grain itself, and specifically to the radiography of the 88" wall thickness, the experimental program has developed the following two conclusions, when considered in relation to the initial study¹.

1. The minimum x-ray unit which could make a minimally acceptable exposure through the 88" wall (without considering exposure time at this point), would have an energy such that the wall thickness represents not more than 13 hvl's, and an output not less than 2000 R/min at 1 meter. The corresponding hvl is $88/13$ or 6.77" and the required minimum energy is 11 MeV¹. Since scattering ratios at 11 MeV or more are less than for the Aerojet machines, some slight additional conservatism is thus added to the analysis to provide assurance that the 2" spherical void would be detectable and the 4" void relatively obvious. Since in seeking the minimum unit one would wish to avoid a specially developed machine, it is clear that commercially-available linacs rated at 12-13 MeV and 2500 R/min at 1 meter fit this requirement nicely, although they would exhibit overly long exposure times for the entire 260" production inspection job (~2 hrs or more for each exposure, depending on the required film density).

2. The optimum x-ray machine would be a compromise among the various factors of energy, coverage, degree of flattening required, etc. However for high quality inspection, similar to that demonstrated by the experimental program discussed herein, the energy should be high enough so that the 88" wall constitutes no more than 11 hvl's (the same as in the experiments). The corresponding hvl is 8" and the required energy is ~25 MeV. In addition, for reasonable exposure times the output should be in the range of 10-15000 R/min or more at 1 meter, flattened over the area of the film array to be used. Even so, exposure times will be ~10 min or more¹. It is clear that for complete radiography of the main body of the grain in a reasonable time, the high energy/high output

APPENDIX D

IV. RELATION OF DATA TO THE 260" GRAIN (Contd.)

machine is essential. But since meaningful films can be made with less ambitious equipment (if time is available), it is necessary to keep both conclusions in mind in coming to ultimate decisions.

We believe that the above conclusions confirm the findings of reference 1 with regard to the main body of the 260" grain, and that attention can be given now to exploring the actual inspection in more detail, in Section V below.

Some final comments may be made at this point relating the experimental program to inspection of the ray section of the grain. In the program, no attempt was made to develop data concerning a technique for the major portion of the ray section. The initial study¹ conclusions, that this geometry per se is basically not suited for radiographic inspection, are in our opinion sufficiently clear not to require further substantiation. Some consideration was indeed given to inspection of the extreme aft end of the ray section by using film arrays placed around the radius of the ray points, as though these points constituted an ID, compensating for the extreme thickness variations by use of cassettes multiply-loaded with films of various speeds. This tour-de-force technique could suffice for, at most, the aft 39"-40" of the rayed area; also the poor scattering geometry would degrade sensitivity; it is probable that in some areas the 4" void would be only marginally detectable. The experimental data quoted in III E above appear to support this view, since a thickness range between 2 and 3 hvl's was covered with reasonable evidence of adequate, if not optimum, sensitivity.

However, given the powerful x-ray generator postulated earlier, the entire ray section can be radiographed using the ancient radiographic technique of section equalizing (it is our understanding this suggestion was first made by Aerojet personnel, who are deserving of high commendation). By this technique the spaces between rays would be filled with plastic sections cast to the contours of the ray sections; the plastic must have approximately the same density as propellant and should preferably be clear so it may be visually inspected for voids, lest its use introduce spurious flaw indications. Alternatively the plastic

APPENDIX D

IV. RELATION OF DATA TO THE 260" GRAIN (Contd.)

sections can be radiographed before installation. They can presumably be produced by techniques developed for the fabrication of the core around which the propellant is poured in the manufacture of the motor. When they are all in place the cross-section of the head end becomes circular throughout its length, with a uniform ID of 60". The OD is also uniform down to the point where the hemispherical nose of the motor intersects the cylindrical section. To that point the radiography is a straightforward extension of the work on the main body. The maximum film array, due to the increased curvature of the smaller ID, is now 3x3 films of the 14x17 size. Due to geometric considerations, 40 (rather than 30) exposures are required around the circumference (assuming still a 20 ft. TFD). Three such setups will approximately cover from the "end" of the main body to the intersection with the nose curvature. The next such setup will require only 50% exposure as the thickness begins to decrease toward the nose. The fifth setup will require the use of more than one film type, and some multiply-loaded film holders, to cover the varying thickness. Due to the rapidly-increasing thickness gradient toward the nose, and the location at the bottom of the caisson, radiography from here on will probably be possible of only one 17" film length at a time (but the array of 3 films circumferentially should still be feasible). Thus three more complete circumferential "scans" of 40 exposures each, will probably be required. This effort represents a significant addition to the main body radiography, involving no less than 320 more exposures and ~2500 films (making an allowance for the additional films to be used in multiple loads). The maximum thickness is ~100", or 12.5 hvl's at 25 MeV. Using a density of 3.5 to allow for the change in thickness toward the edges of the film array, the exposure is slightly less than 30 minutes for setups 1-3, decreasing to ~15 minutes for the fourth series. Then, in the nose area, exposure time decreases rapidly to <1 minute.

Consideration of the analysis of sensitivity on Page 8 above, modified for the larger linac, the higher energy, and the maximum thickness of 12.5 hvl's rather than 13, indicates that the required inspection sensitivity will easily be achieved.

APPENDIX D

IV. RELATION OF DATA TO THE 260" GRAIN (Contd.)

However the validity of the analysis must also be considered in relation to the back-scattering problem presented by working in the relatively restricted space of the 60" ID. Recent measurements⁵ have shown that backscatter is a serious problem in the radiography of 12 hvl's of stainless steel at 10 MeV, in a geometry such that the film must be placed in an essentially cylindrical cavity of ~36" diameter. The back-scattered radiation, even filtered through a thickness of 1/2" of lead, was still an important fraction of the total radiation on the film.

A survey of the radiographic literature does not reveal quantitative investigations of these aspects wherewith to extrapolate from the situation given to the situation of the 260" motor. Qualitatively, it is clear that the additional thickness of the motor in hvl's (12.5 vs 12) is an unfavorable variance. Conversely the inverse square law (60" diameter vs 36") provides a favorable variance near a factor of 3. Backscatter calculations⁶ do indicate a favorable variance near a factor of 2 in comparing 10 MeV to 25 MeV. In addition, although the forward scattering ratio in the motor is greater than in the steel, the difference in average atomic number should make for a favorable variance in backscatter ratios. It is our estimate that the backscatter x-ray field at the film will be, for the 260" motor ray section, approximately 4 times less intense than for the stainless steel case quoted above, and will have an energy slightly less also. This would imply that an excellent radiograph would require no more than 1/2" lead backing. Since the weight of such a back filter is appreciable, an experiment on the actual rocket is desirable to determine whether its thickness could be reduced, or whether perhaps a lighter multi-layer back filter (e.g. lead, copper and aluminum combined in the proper order and thickness) might not be suitable. In any case, we believe the above extrapolation shows that no serious effect on the sensitivity of the procedure need be anticipated; the required flaws will still be capable of detection.

APPENDIX D

V. RADIOGRAPHY OF THE 260" GRAIN

Having now determined that the required inspection is technically feasible, some further consideration is due of the details of such an inspection, beyond what was included in the earlier study.¹ It is clear that if conventional film radiography of this entire motor is chosen as the inspection method, the 26 MeV, 15-20,000 R/min (flattened) x-ray unit contemplated earlier is the unit of choice. Film placement, exposure times, array details etc. are as originally postulated, with additional effort for the ray section, as described above. In addition, the hemispherical section at the aft end will require techniques similar to those described above for the nose section. However, the reduced thickness will ameliorate the problem.

It now appears that a total of more than 800 exposures yielding more than 10,000 films will be required for the complete inspection. Some consideration must be given to the mechanization of the process, since the film arrays will be invisible from the x-ray generator and vice versa; in addition, the large number of basically similar setups cries out for a process study. Although such a study is not, strictly speaking, a part of this analysis, a few comments would seem to be in order.

Present plans are for the motor to rest vertically, forward end down, on load cells. It will not be feasible, initially, to rotate it. Therefore, the x-ray equipment and the film arrays must be capable of being located anywhere about the 360° circumference of the caisson wall and the motor ID respectively. In addition, they must be capable of traversing the vertical length of the motor. Means of indexing the arrays and the linac must be provided so that the films are properly centered on the area being irradiated for each exposure.

Before considering specific mechanical means of accomplishing the inspection, one must decide a basic question: should the inspection raster be vertically or horizontally oriented; i.e., will one make a series of exposures traversing the vertical length of the motor, then index in angle to the next position, or would it be preferable to make a 360° traverse horizontally and then index

V. RADIOGRAPHY OF THE 260" GRAIN (Contd.)

vertically? Since both the linac and the film array must be capable of being positioned everywhere around and in the motor (respectively), the question might appear to be trivial. However, in traversing vertically the different thicknesses, film loadings, array sizes etc. must be considered for each traverse; whereas in traversing around the motor horizontally all of these factors remain constant for a single traverse. For this reason, we prefer to traverse horizontally, then index vertically. Further, the inspection must be carried out in a caisson which for other activities must contain other equipment. It appears to us easier to plan a completely-removable setup for horizontal traverses.

The actual arrangement should in our opinion be worked out in a separate study by a process engineer, but some possible system concepts can be described briefly.

For linac positioning, a system of guide rails on the ID of the caisson, with an overhead support system of telescoping members, is an approach which attempts to exploit present radiographic linac flexible mount technology. However, the extreme length of lift, and the requirement for rotary rather than straight-line movement, would make such a system extremely costly. In addition the rail system in the caisson appears less than desirable. A more suitable solution is the annular elevator proposed by Aerojet - San Ramon.⁷ This elevator is stabilized in angle by vertical guide rails keyed to slots in the caisson ID, and the linac rests on rails on the elevator platform. It progresses on these rails around the 360° traverse at each level, stopping every 12° for the main-body exposures and every 9° for the ray-section films. A penetrameter array would also be supported on the elevator and positioned mechanically, automatically, for each exposure.

The film array positioning system is a more difficult problem; in fact, when and if the motor were to be produced in quantity, a whole Pandora's box of important questions must be faced in the process engineering sense. For

V. RADIOGRAPHY OF THE 260" GRAIN (Contd.)

example, can a reasonable way be devised to place a larger number of films than a single array at one time (e.g., all the films for one traverse), with shielding to permit exposure of only one array at a time? Is in-motion radiography a practical way of reducing setup time (we have a priori doubts)? Could roll film find a place in this inspection? Since there is no doubt that type KK film would reveal flaws of the required size, is it appropriate to save exposure and inspection time by its use? (We propose that for the first motor it would be preferable to maintain a rather high inspection quality to provide relatively detailed data on the internal structure). Obviously these questions go beyond the purview of this study. Our conceptual considerations have, however, led to the following comments regarding film positioning.

Consider a circular platform or elevator slightly less than 5 feet in diameter, so as not to touch the propellant when in the smallest ID of the motor cavity. On this platform will be mounted the film array holder (different holders will be required for the different arrays, 4 x 4, 3 x 3, 1 x 4 and 1 x 3). This holder will be jointed vertically at the points where the individual film holders meet, so that it may be set at the proper "curvature" to match the motor ID for each horizontal series of exposures. It will incorporate necessary back filters, segmented so as to follow the holder "curvature", as well as "strip" filters behind the joint areas. The entire array, after loading with films, identifying numbers, and any necessary front filters, and after positioning in vertical height and azimuth by the platform, will be moved radially by a pneumatic piston to a position in close proximity to the grain ID. It will remain in that position for the duration of the exposure and then retracted to prevent rubbing against the propellant during the reloading cycle. The exposure position will be controlled by an air gage to prevent undue pressure of the holder assembly against the ID. Consideration should be given also to incorporating in the holder a remotely-adjustable automatic exposure "timer" to terminate the exposure when the preset dose has been received. This would eliminate the need to establish an extensive library of exposure

APPENDIX D

V. RADIOGRAPHY OF THE 260" GRAIN (Contd.)

settings for the entire job, since the setting would remain the same for the same type film, irrespective of variations in grain thickness or small variations in TFD as the inspection proceeds.

The elevator can be supported and positioned vertically by either existing bridge crane in the movable building which can be placed over the caisson; however, positioning automation must be provided to assure the correct vertical position corresponding to the linac position. Azimuthal positioning and control are also required to assure the angular setting of the film array with respect to the linac position. Positioning could be controlled by closed-loop servo systems, connected with the linac positioning system. However, if the complete inspection is programmed in advance, it would be desirable to consider an open-loop system such as the numerical control digital positioning systems used on machine tools with positioning by, e.g., Slo-Syn motors, perhaps with hydraulic amplifiers for moving the linac. Such a system would probably have superior reliability and lower cost as compared with a closed-loop servo system; it would require less preliminary engineering effort; and it can be purchased as a complete unit from a single responsible source.

The actual configuration of the internal rotary elevator platform is constrained by the requirement that it be not only positioned in elevation and azimuth, but also stabilized in both respects to prevent contact with the motor ID and maintain a fixed correct position during exposures. We have given brief consideration to this problem, and we find it to require careful engineering effort to attain all these objectives. The following suggestions are illustrative of the tradeoffs which must be considered.

Since stability must be attained without contact with the motor, a basic internal stabilizing member appears necessary. For this purpose we have considered a standard 12" heavy-wall steel pipe which could extend down the axis of the grain. This appears to be about the maximum size pipe which

APPENDIX D

V. RADIOGRAPHY OF THE 260" GRAIN (Contd.)

could be used, since considerable apparatus must be on the relatively small platform. The elevator would ride up and down the pipe on spring-loaded trucks, supported by the hoist cables. For maximum stability the pipe should be supported from overhead, in a rotary bearing; the lower end would be constrained by a similar bearing which would not support the weight of the pipe (4 tons), and there would be provision for expansion and contraction at that point. An "inverted keyway", welded on the pipe, would provide for rotation, and for azimuthal stability. Since the hoist cables could not rotate if lift is to be provided by existing bridge cranes, the platform would require to be a rotary turntable supported on a stationary one (an alternative solution is to support the elevator from its own rotary overhead platform keyed to the pipe, with its own hoist on the platform; since the elevator weight is only ~1-2 tons this option may actually be less expensive). In order to prevent variations in keyway alignment from affecting the azimuthal positioning, rotation will be accomplished after the elevator is lowered to the proper level, with control and adjustment via an external reference. A laser beam from the elevator to a scale at ground level would be a suitable visual reference, or automatic positioning can be effected by using sets of photocells (one set each for the 12° and 9° intervals). Using the visual system, remote positioning from the control bunker can be accomplished by closed-circuit television observation of the scale.

It should be noted that even this "stabilized" system is rather sensitive to transverse forces, especially when the elevator is at mid-level. Also, it will be important to maintain the load axial to prevent a couple stress being imposed on the pipe. For these reasons it is proposed that the film array weight be counterbalanced by a similar weight at the 180° position from the array; the counterbalance should move via its own pneumatic piston in synchronism with the array (to prevent the couple developing). If it too approaches close to the grain ID, and is controlled by an air gage, the air-flow through both sides can be continuous during the exposure and will act

APPENDIX D

V. RADIOGRAPHY OF THE 260" GRAIN (Contd.)

to "brace" the whole assembly gently against the ID without actually touching it and without undue pressure.

The conceptual description above is believed to suffice to indicate basic requirements for the design and development of the actual radiographic film handling system. A bridge arrangement across the caisson at ground level will provide access to the elevator platform for unloading, reloading, adjusting, and replacing the film arrays.

Under the above conditions, the minimum operating crew would appear to be four men. One of these would operate the linac and the positioning systems. Two men would be required for loading and unloading the films on the film elevator, placing and removing film identification, delivering to the processing room, etc. With automatic processing the fourth man would be kept busy handling this phase alone (if the "dead time" between exposures can be sufficiently reduced, two men will be required for this duty). In addition to the operating crew two film readers would be required (to spell each other), one of whom could be supervisor of the entire operation.

The total exposure time would appear to be about 140 hours, taking into account the shorter exposures toward the ends. Normally, even with some degree of mechanization, one would expect the dead time between exposures, for setup, to be of the same order as the exposure time. However in this case, the setup times will be increased relatively due to waiting time not only for the exposures but also for the cycle time of the positioning system. Our estimates of setup times lead to an overall setup time of 295 hr., or slightly more than double the total exposure time. This estimate includes also an allowance of 20% on the overall time for night shift inefficiencies, start-up times, "non-productive" time, and completion of final film evaluation after completion of the exposures. Thus, the total cycle time for the complete grain inspection is ~ 435 hr., or ~ 55 shifts.

In view of the various possibilities inherent in the question of how many grains

APPENDIX D

V. RADIOGRAPHY OF THE 260" GRAIN (Contd.)

are to be inspected, it is difficult to make meaningful cost estimates. Man-hours and material (film, etc.) required can of course be estimated from the above comments. The data given earlier¹ on linac costs are still considered valid. The two elevator systems, with their rather special cabling, precise indication of position, and the linac and inner elevator rotating and indicating systems, are not likely to cost less than $\sim \$200,000$, including the stabilizing system for the inner elevator. A tape-controlled open-loop control system programmed for all positioning functions is estimated at $\sim \$50,000$. In addition is the cost of a shielded bunker for the system control and the dark-room, with processor and other accessories, carts, etc. for facilitating film handling. A budgetary figure for this portion of the system would be $\sim \$100,000$. Thus the complete system would carry a budgetary ball-park capital cost estimate of \$1.35-1.5 million.

The shielding problem for the bunker has been considered on the basis that the linac direct beam is always aimed toward the motor in such fashion that the entire cross-section of the beam strikes the object or, alternatively, the far side of the caisson; i.e., no part of the direct beam escapes above ground level. Under these conditions, several factors are relevant: (1) leakage radiation from the linac (assumed to be 0.1% of the forward beam), (2) scattering from the object, and (3) scattering from the far wall of the caisson. Consideration of all three indicates that the governing shielding problem is the leakage radiation (0.1% or 58 R/min) from the linac. Assume the linac is positioned on the side of the caisson adjacent to the control bunker with a scattering object or source just above it in "ideal" position to scatter x-rays toward the bunker. Under these conditions, with no assumptions regarding workload factor (percentage on-time), and without consideration that the linac spends most of its time at a more distant place (either around the circumference or lower down in the caisson), a bunker shield thickness of $\sim 12"$ is indicated. If a ceiling for sky-shine protection is needed, $1/4"-1/2"$ of lead might suffice. Although a registered x-ray physicist should be consulted on this point, the above data are

APPENDIX D

V. RADIOGRAPHY OF THE 260" GRAIN (Contd.)

believed to be reasonable or conservative. Of course, it would not be possible to do other work on the grain while the radiography was in progress.

VI. DISCUSSION

The overall study thus far has shown the feasibility of high energy film radiography of the 260" grain, has determined the system required, and has considered briefly some relevant details of the specific process. To complete the effort it is deemed desirable to consider further the general void detection problem in this grain, with particular relation to the comments in Section V, Advantages, Limitations and Alternatives, of the prior study¹.

A priori, the general discussion of the method, given earlier, remains valid, and has been amplified somewhat in Section V above. However, some further study of the alternatives mentioned has generated the additional comments below.

Regarding non-film imaging systems, to eliminate the cost, in both materials and labor, of using conventional x-ray films, and at least potentially to speed up the process, there has come to our attention an image-intensifier system which may have promise for this inspection. The so-called Delcalix-Isocon system, distributed in this country by General Associates, Inc., 1231 Main Avenue, Cleveland, Ohio, 44113, employs an external fluorescent screen and a small light intensifier viewed by a closed-circuit television system. The screen is rather large (12-1/2" diameter) and since it is external to the associated equipment it can readily be modified to be optimized for the particular x-ray energy in use. Experimental work with low kilovoltage x-ray sources has shown superior contrast sensitivity and the ability to perform a given inspection at lower kilovoltage than other image intensifier systems. This presumably reflects a response to a lower order of x-ray intensity than other systems. As a matter of fact, the distributor claims an image can be formed at 100kV by only 5 μ R/sec or 300 μ R/min. In changing energies from 50kV to the high energy region the required increase in dose for a given density on film is a factor between 11 and 39, depending on the film type (reference 3, pp. 16-17). Assuming a factor of 40, one would estimate that 12m R/min might suffice for an image at 25 MeV, especially if the screen were modified specifically for good response to high energy x-rays. Since the linac being postulated will deliver more than 75m R/min from 6 meters distance

APPENDIX D

VI. DISCUSSION (Contd.)

through 100" (12.5 hvl) of propellant, the method would appear worth looking into. The distributor is planning experimental work in March-June 1970 to develop data on these subjects. Since his planned experimental program will transcend the time limitations of this study, it is recommended that project personnel follow up the work.

As of this writing, the proposed experiment to check the Szepesi amplifier's performance using cobalt 60 radiation has not been carried out -- no new data is available regarding this system, nor concerning the Anger camera. The general comment is still valid, that none of these systems, including the Delcalix-Isocon, even though a saving in time and material costs would accrue, would provide a record or any means of checking later for human errors of interpretation. However the Delcalix-Isocon system could be combined with videotape to eliminate this problem, but at considerable expense.

In view of Aerojet's recent experimental results, further consideration of x-ray scanning would appear to be in order. It is our understanding that scanning experiments with cobalt sources have not been successful at propellant thicknesses above about 40". The data are believed to indicate that for cobalt scanning of the 260" grain a source of the order of 50 kilocuries would be necessary; we understand this has been judged impractical. On the other hand there has been considerable preliminary success at greater thicknesses, using an Aerojet linac as the source. Electronic means of integrating the detector signal to provide an "average current" indication have overcome the problems related to the pulsed nature of the linac output. Detection of the 4" void unequivocally, and a reasonable indication of the 2" void, have been accomplished, through the 65" section, at ~500 R/min/m. The reasoning developed in III D and IV above, concerning extrapolation of results to greater thicknesses, and determining the minimum "acceptable" linac, is directly applicable here except with relation to scattered radiation; the collimation used in scanning goes far toward reducing the effect of scattering; the dose rates to be expected at the detector using a 12 MeV, 2500 R/min linac penetrating 88" rather than 65" would be slightly greater than present dose rates

APPENDIX D

VI. DISCUSSION (Contd.)

using the Aerojet linac through 65", under comparable conditions; and the magnitude of indication to be expected would be reduced only about in proportion to the increased hvl at the higher energy; the broad-beam scattering situation is not applicable. However the 10-foot source-to-detector distance used for the 65" thickness is not considered realistic for the greater thickness. Twenty feet would be a better distance (and is about the maximum available) to minimize magnification of flaw "images." This tells us that the "minimum" linac for scattering 88" thicknesses should have a dose rate of 10,000 R/min/m at 12 MeV. Since now we must also consider the additional thickness at the forward end the required dose rate at 12 MeV becomes $>30,000$ R/min/m. And if the beam is to be flattened over 10° ($\pm 5^\circ$), as indicated in reference 7, the necessary unflattened dose rate is ~ 43000 R/min/m. From the initial study¹ we can conclude this is not a viable option unless a two-klystron linac is considered. The 26 MeV machine described therein would, on the other hand, deliver more than 20,000 R/min/m flattened $\pm 5^\circ$. Although reference 7 indicates a requirement for 32000 R/min/m, this is based on the assumption that the attenuation coefficient for propellant does not change between 10 MeV and 25 MeV. Broad-beam hvl data¹ tend to cast doubt on this assumption, and in fact consideration of these data would indicate that if 32,000 R/min/m is required on the assumption of an unchanged attenuation coefficient, then in fact probably 8000 R/min will be adequate. Such broad-beam information may however be applied to the scanning case only with extreme caution. Elementary attenuation constants, (e.g. for magnesium) calculated on a narrow-beam basis, appear to justify a reduction in the coefficient of only 5-10% between 10 MeV and 25 MeV. Such a difference would suffice to make the expected output adequate; but in fact it may be advisable to reduce slightly the width of the scan proposed in reference 7 so as to have an adequate reserve of sensitivity.

We note that the scanning method does depend in an important way on the stability of output of the linac; and in fact the detection of the 2" void in the experiment cited was substantially impeded by lack of stability of the Aerojet linac. For ultimate success, either (1) the linac output must be stabilized to the order of

VI. DISCUSSION (Contd.)

1% or better, or (2) a signal from the linac dose rate circuit must be used to modify the detector response in such a way as to cancel the effect of any dose rate variations. Both approaches are considered feasible; clearly the first is more direct; the second has the advantage that even in case of minor malfunction in the linac the scanning probably need not be interrupted. The design of the Aerojet machines, as well as the hardware itself, is relatively old. A more modern linac, even "free-running", is far more stable (in the range of 1-3%) than the Aerojet units. Stabilizing circuits to assure output stability to 1% and even better are available if the measured actual stability is insufficient. With regard to the second alternative, modern control electronics design concepts would surely find this a simple problem.

The above considerations lead one to postulate an interesting "combination" inspection system. If scanning can indeed be used, automatic signalling of flaw detection above a given level becomes feasible. The human error element is essentially eliminated, given "fail-safe" electronics (which are surely feasible). A permanent record, if required, can be made by a simple strip-chart recorder. It is quite probable that scanning rates etc. could be such as to save considerable overall inspection time as well as film and attendant costs. The scanning hardware would probably be less expensive than the mechanized radiographic hardware -- but in case of doubt regarding any specific area, a high quality radiograph could be made. (It should be noted that stability problems in the internal elevator require further engineering attention in the scanning case, since the elevator platform must rotate continuously and uniformly for success. The great sensitivity to lateral forces, especially in mid-level positions, may require additional stabilizing means).

It is recommended that, in Aerojet's overall planning, the scanning-with-radiographic-capability method, using the 26 MeV linac discussed herein, be given consideration as the potential method of choice for the detection of voids in the 260" grain.

APPENDIX D

VI. DISCUSSION (Contd.)

For the detection of flaws in the propellant-insulation bondline, the discussion in the initial study is still considered valid, except that the Aerojet development of x-ray scanning makes it possible to consider further this method, provided that studies of other methods of bondline inspection do not develop an acceptable method. In that case a critical comparison of gamma-ray vs x-ray scanning should be made to determine the better method. And in any case, conventional film radiography is still considered impractical, though technically feasible, due to the extremely large number (thousands) of exposures required.

APPENDIX D

VII. SUMMARY

In a theoretical and experimental analytical study of the detection of critical defects in large solid propellant grains, specifically in the proposed 260" motor grain, a suitable high energy radiographic system has been determined and described. The basic radiation source is a 26 MeV electron linear accelerator, optimized for use of the full power of the high-power version of the SLAC-type klystron and packaged in a special radiographic configuration for this inspection problem. A system for conventional film radiography, with brief consideration of necessary auxiliary equipment and the inspection process itself, is proposed. This radiographic system is suitable for examination of the entire grain; the ray section requires section equalizing, as proposed in reference 7, to make feasible the inspection. The work did develop a "minimally acceptable" radiation source (a commercially-available 12-13 MeV, 2500 R/min at 1 meter linac) which is not suitable for the production inspection problem because of the long exposure times required, but would be capable of making a film which could reveal the required defects.

Consideration of non-film imaging systems did not lead to a method of eliminating conventional film radiography, although the "Delcalix-Isocon" image intensifier system shows promise. If the system can be developed for this inspection, it is visualized that the large linac source will still be required; use of any such system instead of film does involve risk of undetectable human error through lack of a record, unless the expensive videotape recording method is adopted.

Recent success at Aerojet in the experimental evaluation of an x-ray scanning system indicates that a "combination" inspection system for the grain body may be feasible. The 26 MeV linac source mentioned above would suffice for the scanning system, though output stabilization or special detector circuitry may be needed. Void detection could be automatized to eliminate human error; a record of the scan could be produced by a strip-chart recorder if desired; and when areas of doubtful interpretation occur, the linac would be able to produce a high quality radiograph, to permit direct visual examination of the questionable area.

APPENDIX D

VII. SUMMARY (Contd.)

This "combination" system should be less expensive in capital cost and faster in inspection time than conventional film radiography, even with some degree of mechanization to minimize radiographic setup time.

APPENDIX D

REFERENCES

1. High Energy Radiography of 260" Solid Rocket Motor Grain, Aerojet P.O. No. G-109269-4915, Applied Radiation Document No. L-2088 dated 15 December 1969.
2. Standard Method for Controlling Quality of Radiographic Testing, ASTM E142-68, May 1969 ASTM Standards, Part 31, Page 572.
3. Radiography in Modern Industry, Supplement No. 2, Eastman Kodak Company, 1959, pp. 10 and 17.
4. W. Sells, private communication, 1970.
5. G.C.Wheeler, private communication, 1970.
6. R.D.Evans, "Gamma Rays", Section 8f, American Institute of Physics Handbook, Second Edition, McGraw-Hill, 1963 (note especially fig. 8f-4).
7. I.E.Lamb and S.Kahn, Recommended NDT of 4-inch Voids in 260-inch Motors, Aerojet-San Ramon Memorandum to P.Underhill dated 13 March 1970.
8. Attenuation Coefficient Tables, Nondestructive Testing Handbook, R.C.McMaster, Ed., (Ronald Press Co., New York, 1959), Vol. I, Sec. 27, p. 27.16.

FIGURES

1. Defective Grain Sample -- Top View.
2. Characteristic Exposure -- Density Data (Kodak Type AA Film).

TABLES

1. Film used on each exposure, R level, film identification.
2. Significant details of the various films.

APPENDIX E

RADIOGRAPHIC FILM ENHANCEMENT

APPENDIX E



Philco-Ford Corporation

Aeronutronic Division

Ford Road
Newport Beach, California 92663

21 November 1969

Aerojet-General Corporation
Nimbus, California 95809

Attention: Mr. A. Schweiger
Solid Rocket Division

Reference: P.O. Number R-107986-4915

Final Report Task #1

The technical objective of Task #1 was to apply the Aeronutronic Color Derivation Extraction of Radiographs, hereafter referred to as: CODE-R, to five customer furnished radiographs of successively thicker specimens of propellant containing known defects.

The input radiographs were of good quality and were found to be compatible, in regard to photographic density range and contrast, with the CODE-R technique.

It was assumed that the minimum extractions giving objective indication regarding the defects (voids) would be desirable. It was expected that the study would yield data related to the expected outcome of future tests with greater propellant thicknesses.

In all radiographs, average densities were read for (a) propellant background, (b) penumbra of void, and (c) void. The respective densities are shown in Figure 1.

The next step was to determine the effect of propellant thickness penetrated upon the density differences of the previously measured densities (a, b, and c). The calculated density differences are shown in Figure 1.

By plotting two density differences (Δ_{D_v} = void density minus propellant density and Δ_{D_u} = void density minus penumbra density) against the relative

propellant thickness or number of propellant blocks penetrated (see Figure 2), one can conclude that these density differences level off with increasing propellant thickness. It is estimated that the ΔD_v levels off at $\Delta D \approx 0.20$ and ΔD_u at $\Delta D \approx 0.05$. Both density differences are well within the sensitivity range of the CODE-R technique. This assumes input radiographs of equal photographic characteristics as the tested ones.

Using all previously determined densities as guide points, the following extraction program evolved. In order to facilitate easy interpretability, it was decided to print two CODE-R prints from each radiograph, one in black and white showing minimum radiographic densities of the propellant, masking out all densities corresponding to the void and penumbra. Figures 3 and 4 relate the radiographic densities of the input radiographs to the respective black and white extraction print. Density variations of the propellant are enhanced while penetrometer detail and certain anomalies (spots which may correspond to "star" configurations) become visible. The other extraction print from each radiograph was in color. The five color extraction prints were programmed to print out the average void density as red, while the average penumbra density was coded cyan (dark blue). Referring to Figures 3 and 4, the densities and density differences are recorded according to print color for each CODE-R print. In interpreting the prints, it should be borne in mind that the density levels chosen had a certain overlap.

For instance, let us interpret the color extraction print of Radiograph 260-2.* The void seen as bright red is printed with no notable distortion. The black looking zone surrounding the void is caused by the over-printing of red on cyan dye and corresponds, according to Figure 3, to a radiographic density of $D = 3.18 \pm 0.02$ (the density of 0.02 is a reasonable tolerance for a broad density band extraction). The surrounding dark cyan zone corresponds to the average penumbra density of $D = 3.00$. The lighter shades of cyan correspond to densities ranging from $D = 2.30$ to $D = 2.79$ and reveal penetrometer detail as well as irregular densities in the propellant. It could be suggested to check the dark cyan spot in the lighter surrounding area and verify the cause of this anomaly. A small void is suspected. No attempt was made to color code other densities than those previously discussed. It was reasoned that unnecessary colors would confuse the interpretation.

It has been proven that even the thickest specimen's radiograph could be extracted to print bright red in the void area.

It is therefore concluded that the application of CODE-R to the detection of critical voids in propellants via radiography is feasible and offers

*The black and white radiographic print is included as Figure 5; the color extraction print of Radiograph 260-2 is shown in Figure 6.

objective and reliable density information. In view of the results of this study, it is reasonable to expect that even greater propellant thicknesses can be inspected using this technique.

The five input radiographs and ten extraction prints were shipped under separate cover (Aeronutronic Ref. G081-AD-69-1638).

Report prepared by:

Karl-Heinz Lohse

Karl-Heinz Lohse, Supervisor
NDT and Photo-Science

KHL:po

Attachments: Figures 1 - 4

APPENDIX E
AERONUTRONIC

AEROJET GEN. IDB

11-17-69

FIGURE 1. MEASURED DENSITIES

	260-2	260-4	260-6	260-7	260-8
PROPELLANT	2.42	2.32	1.84	1.86	1.74
PENUMBRA	3.00	2.68	2.03	2.05	1.88
VOID	3.29	2.78	2.09	2.10	1.94

DENSITY DIFFERENCES

$$\Delta D_v = D_{\text{VOID}} - D_{\text{PROP.}}$$

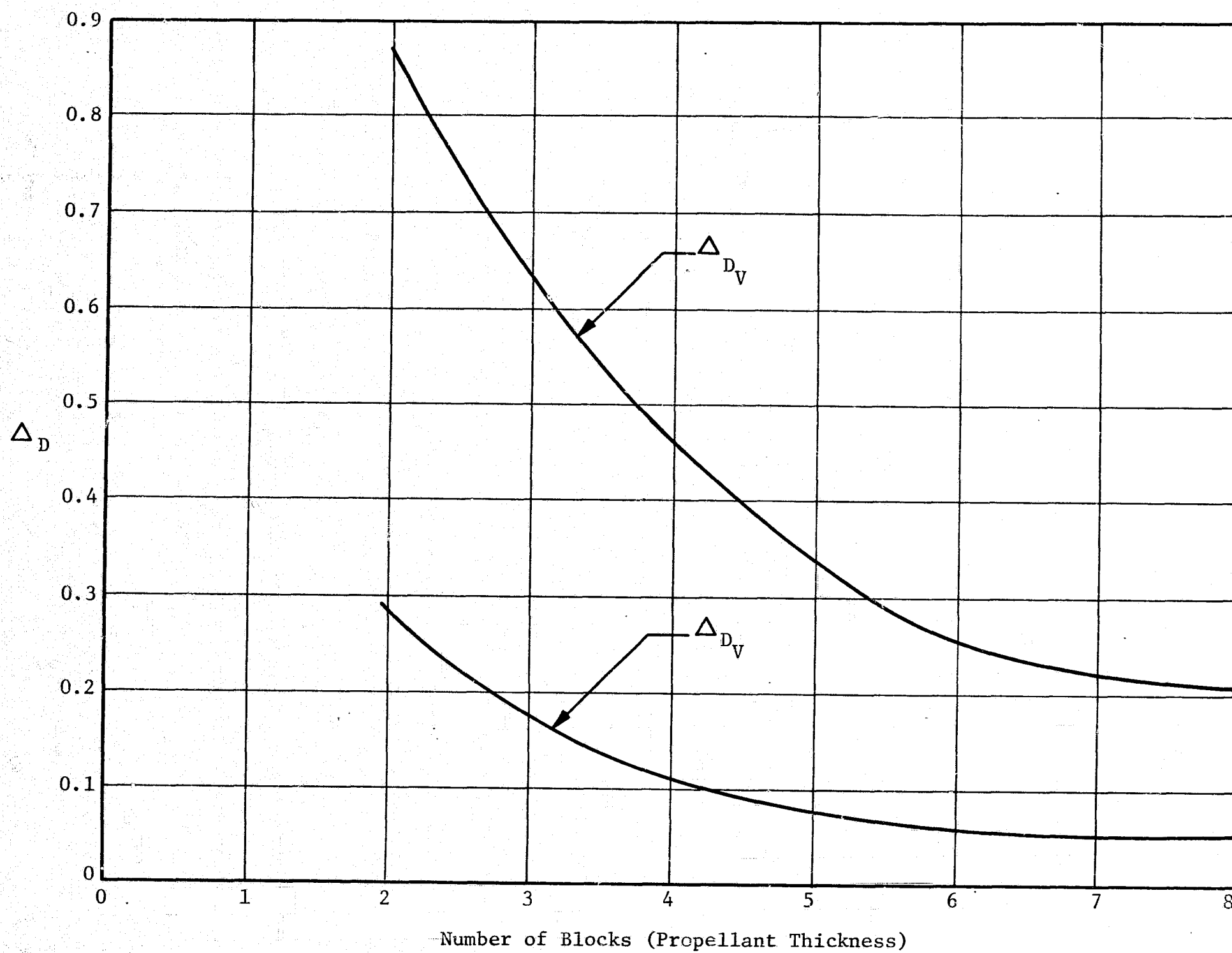
ΔD_v	0.87	0.46	0.25	0.24	0.20
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$$\Delta D_v = D_{\text{VOID}} - D_{\text{PENUMBRA}}$$

ΔD_v	0.29	0.10	0.06	0.05	0.06
--------------	------	------	------	------	------

$$\Delta D_p = D_{\text{PENUMBRA}} - D_{\text{PROPELLANT}}$$

ΔD_p	0.58	0.36	0.19	0.19	0.14
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Effect of Δ_D Change with Propellant Penetrated

APPENDIX E
AERONUTRONIC

AEROJET GEN. JOB

11-18-69

512

FIGURE 3. EXTRACTION PROGRAM

X-RAY	NEG	D	POS	D	DERIV	D	AD	COLOR
<u>260-2</u>	1	2.22						
			1	2.22				
	2	2.30	2	2.30	1	<2.30		B&W
	3	2.40	3					
	4	2.82	4		2	2.79	0.78	CYAN
	5	3.00	5					
	6	3.18	6	3.18	3	>3.18		RED
<u>260-4</u>	1	2.22	1	2.22				
	2	2.30	2	2.30	1	<2.30		B&W
	3	2.40	3					
	4	2.52	4		2	2.63	0.47	CYAN
	5	2.70	5					
	6	2.87	6	2.87	3	>2.87		RED
<u>260-6</u>	1	1.79	1	1.79				
	2	1.84	2	1.84	1	<1.84		B&W
	3	1.88	3					
	4	2.01	4		2	1.96	0.35	CYAN
	5	2.06	5					
	6	2.14	6	2.14	3	>2.14		RED

APPENDIX E
AERONUTRONIC

AEROJET GEN. 1013

11-18-69

FIGURE 4. EXTRACTION PROGRAM (CONTINUED)

X-RAY	NEG	D	POS	D	DERIV	D	ΔD	COLOR
<u>260-7</u>	1	1.79	1	1.79				
	2	1.84	2	1.84	1	<1.84		B&W
	3	1.88	3					
	4	2.01	4		2	1.95	0.22	CYAN
	5	2.06	5	2.06	3	>2.06		RED
	6	2.14	6					
<u>260-8</u>	1	1.68	1	1.68				
	2	1.79	2	1.79	1	<1.79		B&W
	3	1.84	3					
	4	1.88	4		2	1.80	0.24	CYAN
	5	1.92	5	1.92	3	>1.92		RED

Appendix E

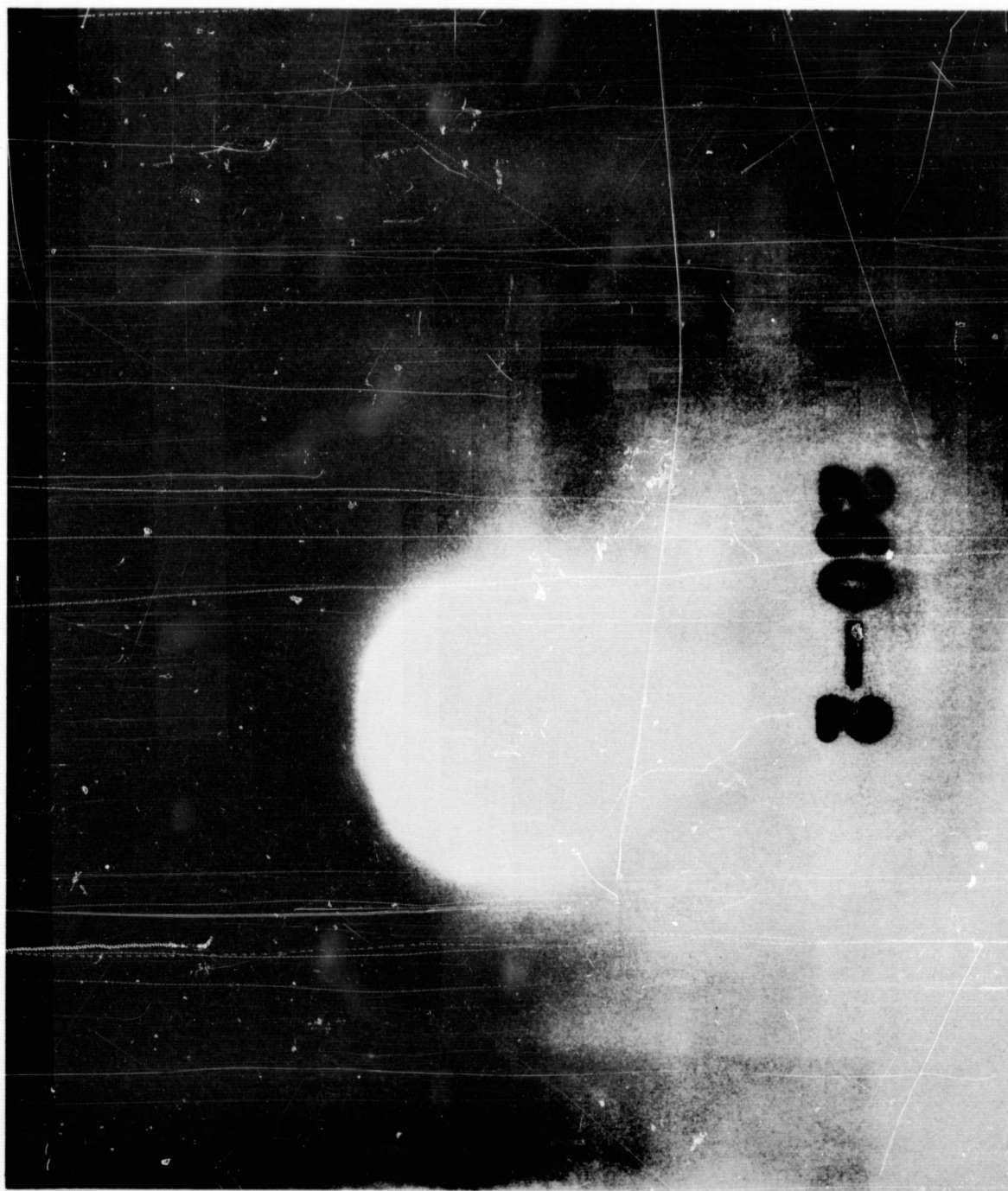


Figure 5 Black and White Print of Radiograph 260-2



AERONUTRONIC
X-RAY PHOTO-DERIVATION TECHNIQUE

Color Extraction Print of Radiograph 260-2

Figure 6

APPENDIX F

QUALITY CONTROL PROCEDURE

APPENDIX F

AEROJET SOLID PROPULSION COMPANY

Page 1 of 4

Number

QUALITY CONTROL PROCEDURE

Issue

Date

Supersedes Issue

SUBJECT: RADIOGRAPHIC INSPECTION USING A 26 MEV LINEAR ACCELERATOR
ON 260" MOTOR

1. SCOPE

This standard defines the use of one type of X-ray equipment in detecting and evaluating internal propellant discontinuities. The specific detail of an inspection technique for the 260" motor configuration is outlined in this standard.

2. EQUIPMENT

2.1 Applied radiation 26 million electron volt (26 MEV) Linear Accelerator (Linac). This piece of equipment has a focal spot size of approximately 3 mm with an uncompensated central axis X-ray intensity greater than 30,000 rads per minute at 1 meter.

2.2 Kodak X-Omat Industrial Film Processing Unit. This unit completely processes film ready for reading in 13 minutes.

2.3 Radiographic Film.

2.3.1 Radiographic film shall be of the extra fine or very fine grain, high contrast and high definition type unless otherwise noted.

2.3.2 All radiographic film shall be safety film.

2.4 Radiographic Penetrameters.

2.4.1 Radiographic penetrameters shall be of material of the same composition as the material to be radiographed.

2.4.2 The thickness of the radiographic penetrameter shall be two percent (2%) of the thickness of the material to be radiographed.

2.4.3 All radiographic penetrameters shall conform to MIL-STD-453 unless otherwise noted.

2.5 Various cassettes, screens, film identification holders, normally used in radiographic inspection are incorporated in a 4 x 4 cassette holder to be placed in the center of the motor.

APPENDIX F

AEROJET SOLID PROPULSION COMPANY

Page 2 of 4

Number

QUALITY CONTROL PROCEDURE

Issue

Date

Supersedes Issue

SUBJECT: RADIOGRAPHIC INSPECTION USING A 26 MEV LINEAR ACCELERATOR
ON 260" MOTOR

3. POLICY

- 3.1 The 26 MEV Linac is generally used on (but not necessarily limited to) motors 260 inches in diameter.

4. PROCEDURE - General

- 4.1 The 260" motor will be inspected at the firing silo. Nondestructive testing personnel perform an inspection which includes:
- a. Visually inspecting the motor or closure for possible transportation damage.
 - b. A safety check of all motor or closure tie downs.
 - c. Assure the presence of all inspection documentation.
 - d. Assure cassette holder positions properly installed.
 - e. During periods of possible inclement weather, assure that the motor or closure is completely covered.
- 4.2 The 26 MEV Linear Accelerator (Linac) will be positioned normal to the motor surface at the 0° position.
- 4.3 The cassette holder will be loaded and centered at the 0° position. The holder will be lowered till the X-ray beam is centered on the cassette holder.
- 4.4 The 26 MEV Linear Accelerator will be activated until an average film density of (H&D 2.0) is realized on the center films.
- 4.5 The cassette will be retrieved, cassettes removed and the holder reloaded.
- 4.6 Both cassette holder and X-ray unit will be indexed 12° clockwise around the motor and steps 4.2 through 4.5 repeated.
- 4.7 Steps 4.2 through 4.6 will be repeated until 360° have been completed. The unit will then be returned counter-clockwise back to 0°.

APPENDIX F

AEROJET SOLID PROPULSION COMPANY

Page 3 of 4

Number

QUALITY CONTROL PROCEDURE

Issue

Date

Supersedes Issue

SUBJECT: RADIOGRAPHIC INSPECTION USING A 26 MEV LINEAR ACCELERATOR
ON 260" MOTOR

4.8 The cassette holder and X-ray unit are then raised 68 inches and steps 4.2 through 4.7 repeated until completion.

5. NON-ACCEPTABLE DEFECTS

The following defects or questionable areas, which appear on the radiographic film as high or low density areas, shall be considered as non-acceptable and will be cause for rejection.

5.0.1 The maximum allowable defect size required to initiate case burn-through is the minimum size defect that must be detected by NDT. It has been determined to be a single 4.1-in.-dia.-spherical void or an accumulation of smaller defects so aligned as to produce a 4.1-in. flame front advancement. The complete criteria for the motor is as follows:

<u>Failure Mode</u>	<u>Minimum Single Defect Size that Must be Detected to Meet Failure Criteria</u>
Case Burnthrough	4.1-in. flame front advancement. This could be either a single spherical void 4.1-in. in diameter or a propellant/propellant separation, etc., that would advance the flame front 4.1-in. The extent of propellant liner separations would vary depending upon longitudinal locations as follows: Fwd Head No limit Fwd cyl. section 12-in. to 64.5-in. Aft cyl. section 160-in. to 297-in. Aft head 4.1-in.
Propellant Ejection	36.2-sq.in. decrease in throat area. This could come from a single 6.5-in. by 6.5-in. propellant/propellant or propellant/liner separation which resulted in propellant ejection.
Abrupt Chamber Pressure Increase	2800-sq.in. increase in burning surface. This could come from a single 31-in.-dia spherical void; a 39-in. by 39-in. propellant/propellant separation or a 55-in. x 55-in. propellant/liner separation.
Grain Structural Failure	None. Although small voids may cause small local cracks, the crack will not propagate unless entire section fails due to inadequate propellant mechanical properties.

Summary of Minimum Defect Limits

APPENDIX F

AEROJET SOLID PROPULSION COMPANY

Page 4 of 4

Number

QUALITY CONTROL PROCEDURE

Issue

Date

Supersedes Issue

SUBJECT: RADIOGRAPHIC INSPECTION USING A 26 MEV LINEAR ACCELERATOR
ON 260" MOTOR

5.1 Acceptable Defects

Unless otherwise specified, all defects not exceeding the Failure Mode Analysis criteria will be considered acceptable and shall not be cause for rejection. However, all defects or questionable areas will be noted and reported as acceptable or non-acceptable.

5.2 Any condition that is within the limits as specified in the previous rejection criteria of this procedure.

100% Inspection (except as noted above)

Others: _____

Results _____

Inspector _____

Process Inspection Engineer _____

Date _____

Date _____

APPENDIX F

AEROJET SOLID PROPULSION COMPANY

Page 1 of 2

Number

QUALITY CONTROL PROCEDURE

Issue

Date

Supersedes Issue

SUBJECT: NON-FILM RADIOGRAPHIC INSPECTION OF 260" MOTOR PROPELLANT GRAIN

I. PURPOSE:

- A. To establish criteria for non-film radiographic evaluation of 260" motor.

II. PROCEDURE:

A. Non-Film Radiographic Equipment

1. 26 MEV - 30,000 R/M/M Linear Accelerator
2. AGC developed multichannel detector
3. AGC developed multichannel recording system
4. AGC developed scanning system

B. Calibration of Equipment

1. The non-film radiographic equipment shall be calibrated by initially aligning the detector-collimator-source system by using a small radio isotope source to replace the X-ray unit. The alignment will be made prior to placing motor case into position.
2. After motor is cured and core is removed the detector mounting will be assembled and tie rod connected to X-ray unit.
3. The detector assembly will be vertically positioned and rotated for maximum output.
4. A 4-inch diameter propellant sphere will be passed through the X-ray beam. The decreased current output must be within 1% of theoretical.
5. The non-film radiographic equipment shall be calibrated to the reference standard prior to each days inspection.

APPENDIX F

AEROJET SOLID PROPULSION COMPANY

Page 2 of 2 Number

QUALITY CONTROL PROCEDURE

Issue Date

Supersedes Issue

SUBJECT: NON-FILM RADIOGRAPHIC INSPECTION OF 260" MOTOR PROPELLANT GRAIN

C. Scanning Procedure

1. The evaluation of the motor shall be performed by automatically scanning around the motor clockwise a complete 360 degrees for each scan.
2. At the completion of each scan, the equipment will be returned counterclockwise to the zero position.
3. The X-ray unit and detector assembly will be raised 20 inches and steps 1 and 2 repeated until the entire motor is covered.

D. Grain Integrity

1. The propellant grain quality level shall meet accept-reject specifications as outlined by the Failure Mode Analysis criteria.
2. All acceptable defect indications shall be recorded in the non-film radiographic report.
3. All non-acceptable defects will be noted, marked on the motor case and recorded in the non-film radiographic report.
4. All non-acceptable defects will be checked with film radiography.

E. Personnel Certification

1. The non-film radiographic personnel shall be certified in accordance with AGC standards and Solid Propulsion Company Quality Control Procedures prior to performing grain integrity evaluation.

F. Reports

1. A Non-Film Radiographic Report (Sheet A) shall be filled out after each evaluation. This report shall contain information as specified in the Solid Propulsion Company Quality Control Procedures.
2. All recordings will be attached to a copy filled in the Inspection Office.
3. One copy of the non-film radiographic report shall be included in the motor log and one copy filed in the inspection office.

AEROJET SOLID PROPULSION COMPANY

Page

Number

QUALITY CONTROL PROCEDURE

Issue

Date

Supersedes Issue

SUBJECT: Sheet A

SECTION III (C)

NON-FILM RADIOGRAPHIC INSPECTION REPORT

REPORT NO. _____

SPECIFICATION:

Tentative

Date: _____ P/O _____

DESCRIPTION:

Propellant Integrity

PURPOSE:

Non-Film Radiographic inspection for the detection of voids in propellant grain according to specification.

EQUIPMENT:

26 MEV - 30,000 R/M/M Linear Accelerator and AGC developed 20 channel detector and recording system.

DETECTOR:

Harshaw Integral Line Detector

CALIBRATION:

AGC specimen to be manufactured.

SEARCH PATTERN
AND OVERLAP:

Automatic scanning at approximately 6" per minute travel speed covering 20" wide per scan.

100% Inspection (except as noted above)

Others: _____

Results _____

Inspector _____

Process Inspection Engineer

Date _____

Date _____

APPENDIX F

AEROJET SOLID PROPULSION COMPANY

Page 1 of 2

Number Tentative

QUALITY CONTROL PROCEDURE

Issue 1

Date

Supersedes Issue

SUBJECT: ULTRASONIC BOND EVALUATION OF 260" MOTOR PROPELLANT/LINER INTERFACE

I. PURPOSE:

- A. To establish criteria for the ultrasonic evaluation of 260" motor.

II. REFERENCES:

- A. General Specification for Ultrasonic Inspection.
- B. Quality Levels for Ultrasonic Inspection of Adhesive Bonds.
- C. Qualification of Equipment, Procedures and Personnel for Ultrasonic Inspection.
- D. General Procedure for Ultrasonic Inspection.

III. PROCEDURE:

A. Ultrasonic Inspection Equipment

- 1. Krautkramer US1P10W ultrasonic flaw detector. (Modified)
- 2. 50K or 100K straight beam longitudinal type transducer.
- 3. Krautkramer couplant solution or equivalent.

B. Calibration of Equipment

- 1. The ultrasonic equipment shall be calibrated by "setting up" the equipment, using the through-transmission method, to determine the difference between the bonded and unbonded portions of the reference standard.
- 2. The ultrasonic equipment shall be calibrated to the reference standard prior to each days inspection.

C. Scanning Procedure:

- 1. The evaluation of the motor shall be performed by automatically scanning in a horizontal direction for 6 feet then indexing the transducer vertically ninety percent of its width and scanning in the opposite direction. This should be continued until the entire scanning area is covered.

APPENDIX F

AEROJET SOLID PROPULSION COMPANY

Page 2 of 2

Number Tentative

QUALITY CONTROL PROCEDURE

Issue 1

Date

Supersedes Issue —

SUBJECT: ULTRASONIC BOND EVALUATION OF 260" MOTOR PROPELLANT/LINER INTERFACE

2. The transducer shall be positioned in such a manner to insure contact between the transducer and the center case at all times during the evaluation.
3. Twelve transducers will be mounted in a horizontal plane around the motor. They will be held in intimate contact to the core of the motor by the vacuum fixture.
4. The automatic scanning fixture will be moved successively around the outside of the motor case until the complete motor is covered.
5. The transducers located in the core will be centered normal to the outside scanner prior to initiation of each seam.

D. Bond Quality Levels

1. The propellant-to-liner bond quality levels as specified by Aerojet-General Corporation Specification QCS-SRP-E-1-3(R) shall be used as acceptance or rejection criteria.
2. Multiple train patterns, which indicate questionable or spotty bonds but fall within acceptable limits, shall be noted in the Ultrasonic Inspection Report.

E. Personnel Certification

1. Ultrasonic inspection personnel shall be certified in accordance with AGC standards and Solid Propulsion Company Quality Control Procedures prior to performing bond evaluation.

F. Reports

1. An Ultrasonic Inspection Report (sheet A) shall be filled out after each evaluation. This report shall contain information as specified in Solid Propulsion Company Quality Control Procedures.
2. One copy of the Ultrasonic Inspection Report shall be included in the motor log and one copy shall be filed in the Inspection Office.

Originated by:

Chief of Quality Control

APPENDIX F

AEROJET SOLID PROPULSION COMPANY

Page of

Number

QUALITY CONTROL PROCEDURE

Issue

Date

Supersedes Issue

SUBJECT: Sheet A

SECTION III (C)

ULTRASONIC INSPECTION REPORT

REPORT NO. _____

SPECIFICATION:

Tentative

_____ Date: _____ P/O _____

DESCRIPTION:

Bond quality level propellant to liner interface.

PURPOSE:

Ultrasonic inspection for the detection of non-bond areas between propellant and liner and according to specification.

EQUIPMENT:

Krautkramer USIP-10W ultrasonic flaw detector. (Modified)

TRANSDUCER:

Straight Beam 50K, 1" Diameter, Longitudinal Wave.

CALIBRATION:

AGC specimen to be manufactured.

SEARCH PATTERN
AND OVERLAP:

Automatic scanning at approximately 1/4" transducer overlap at 6" per minute travel speed.

100% Inspection (except as noted above)

Others: _____

Results _____

Inspector _____

Process Inspection Engineer

Date _____

Date _____

APPENDIX G
TOOLING COSTS

APPENDIX G

TOOLING COSTS

I. ULTRASONICS

- A. Scanning Fixture - a 6' x 6' surface area of the motor case will be inspected at one setting. The scanning fixture will be attached to the motor case by vacuum seats. Sperry wheels will scan the surface. \$ 12,000
- B. Transducers - 50-100 KHz custom designed incorporating Sperry wheel construction.
- Aerojet estimate 2,950
- C. Transmitter-Receiver Instrumentation - Will require custom design to provide unique circuitry.
- Electro-Physics-Aerojet joint estimate 13,500
- D. Recorder - 3 needed. X-Y Hewlett-Packard Model 7005B.
- Catalog Price 3,585
- Total \$ 32,035

II. FILM RADIOGRAPHY-FILM AND NON-FILM

- A. Linear Accelerator (26 MEV, 20,000 R/min/m flattened $\pm 5^\circ$, custom designed unit for 260-in. application to include revolving head and stability compatible to scintillation scanning system (1% or better)
- Applied Radiation estimate \$1,000,000
- B. Positioning Fixture - Provide 360° travel around the motor for the X-ray unit for the complete length of the motor. Precision travel at a fixed rate of speed and specific indexing both vertical and rotational are necessary.
- Applied Radiation estimate \$200,000

APPENDIX G

- C. Film Holder - a sixteen cassette holder complete with precision positioning mechanisms and easy retrieval to facilitate cassette replacement.

Aerojet estimate \$ 16,000

- D. Tape Control System - to provide automatic indexing of both X-ray unit and the film holder.

Applied Radiation estimate \$ 50,000

- E. Shielded Control Room

Applied Radiation estimate \$ 45,000

- F. Revetment - the unique requirements of casting facility will require a removal revetment and still provide radiation safety while inspecting the motor.

Aerojet estimate \$ 19,000

- G. Automatic Film Processor - the large number of films to be processed dictates an automatic system.

Picker Model B processor with replenisher and manual rack crane.

Picker X-Ray estimate \$ 16,320

- H. Miscellaneous Film Processing Equipment

40 Cassettes Cat. No. 200118	\$1,980
Chemical pump	\$ 60
Automatic film feeder Model 5K	\$2,025
Silver recovery unit	\$ 620
80 - .030-in. Lead Screens	<u>\$ 420</u>

\$ 5,105

APPENDIX G

I.	Positioning fixture modification to improve alignment to meet specification imposed for the gamma scintillation systems.	\$ 80,000
J.	Detector Holders, Platform & Electronics	
	Aerojet estimate	\$ 15,000
K.	Recording System	
	Aerojet estimate	<u>\$ 40,000</u>
	Total	\$1,486,425

III. MICROWAVE SYSTEM

A.	Frequency Domain Interferometer	
	Electro-Physics estimate	\$ 40,000
B.	Scanning System	
	Aerojet estimate	\$ 80,000
C.	Recording System	
1.	Hewlett-Packard Model 141A long persistence scope	\$ 2,050
2.	3 X-Y Recorder Hewlett-Packard Model 7005B (cost included under ultrasonic task).	\$ 3,585
3.	Position Monitoring Horn Location	
	Aerojet estimate	<u>\$ 2,500</u>
	Total	\$128,135

APPENDIX H
LIST OF REFERENCES

APPENDIX H

REFERENCES

1. Investigation of Defects by Microwave Holography, Contract NAS7-759, Electro-Physics Co.
2. Final Report, Contract NAS7-572, 260-Inch Motor Reliability Study, dated November 1968.
3. Final Phase Report, 260-SL-3 Motor Program, Vol. IV, Contract NAS 3-7998, 31 July 1967 (NASA CR-72284).
4. Development of Ultrasonic NDT Inspection Techniques for Large Solid Propellant Grains, Contract NAS7-367, Phase II.
5. NAS-367, Final Report 0948, Phase I, Development of Microwave NDT Inspection Techniques for Large Solid Propellant Rocket Motors, Cribbs, Lamb, Lucian, dated 6 May 1966.