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COMPREHENSIVE REPORT

ON

NASA ROCKET MOTOR DEFECTS INVESTIGATION

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SUMMARY

OBJECTIVES

The objective of this National Aeronautics and Space Administration (NASA) program was to reduce the number of fiberglass rocket motors rejected because of various case and/or case-grain interface defects by developing accept/reject criteria and methods of repair for these defects. The development of repair techniques for application in the field was considered highly desirable.

PROGRAM PLAN AND SCOPE

The work performed in this program consisted mainly of the static firing of sixteen X248 rocket motors. The motors were used to evaluate (1) fiberglass defects in the domes and cylindrical section, (2) repair of fiberglass defects in the cylindrical section and (3) separations between the propellant and the motor case. Analytical and laboratory work was performed in direct support of the motor program. The analytical results were compared with static testing results. Laboratory work was concerned with evaluating materials and the technique used to repair the fiberglass and case bond defects. The feasibility of repairing fiberglass domes was also investigated with the use of small filament-wound bottles.

The motors used for the static firings were selected from Government-Furnished Materiel and were thoroughly inspected before their selection for use on this program. All those selected were found to include case bond separations in the forward area beyond limits previously considered flightworthy. Certain of these motors had previously incurred fiberglass damage which had caused them to be rejected for flight use. The program was based on the conservative approach that a single failure was fully indicative but that a single success required confirmation. Tests on fiberglass defects and repairs were performed at chamber pressures approximately 25% above normal operating pressures in order to avoid favorable interpretation of marginal results.

RESULTS AND CONCLUSIONS

Two motors, devoted to evaluating case bond separations in the forward dome area, were fired at normal pressure after centrifuge and spin tests to simulate flight loads during firing of lower stage motors. Results showed that such separations, regardless of size of separated area, are of no ballistic significance if so located that they will not be exposed to the advancing flame front prior to tail-off. This was confirmed by the successful firing of other motors in the program. These tests showed that repair of forward dome case bond defects was not necessary.

Only limited work was done on fiberglass defects in the dome areas of motors. Although large defects were inflicted in dome areas of three motors, no motor failure was induced. The X248 domes are not typical of those of more modern case design, and results indicated that the stress analyses used were not directly applicable to the configuration. Since the design was considered obsolescent, the problem was not pursued. A subscale bottle program to obtain information on damage and repair of elliptical domes was conducted. Feasibility of such repairs was indicated.

The remaining motors were used in the investigation of gouge-type defects in the cylindrical section of the motor. The first test established a longitudinal defect which would result in a failure unless it was repaired. The second test demonstrated that even more severe defects could be repaired and that certain defects could be tolerated without repair.

The next series of four motors was used to investigate longitudinal defects penetrating completely through the motor case wall. These tests consisted of (1) two 2.5-in.-long defects repaired with four-ply patches, (2) a 7.5-in.-long defect repaired with a four-ply patch, (3) a 7.5-in.-long defect repaired with a three-ply patch and (4) a 15.0-in.-long defect repaired with a four-ply patch. All defects were considered to be successfully repaired, even though the last two resulted in failure. These failures occurred at pressures which were more than 25% over the normal operating pressures. The two failures were results of processing variables in fabricating the patch. These variables are believed controllable within acceptable limits.

Circumferential defects in the X248 were considered to be of a less critical nature than longitudinal defects because of the loading conditions and winding geometry. One test was used to investigate the repair of two 7.5-in.-long, complete-penetration, circumferential defects. Results of this test, as expected, indicated that a three-ply patch was adequate for repair of circumferential defects.

The final two tests consisted of investigating combinations of longitudinal and circumferential complete-penetration fiberglass defects. The first test was of 5.3-in.-long and 7.5-in.-long combination defects which formed right angles. These were repaired with four-ply patches. Although a failure resulted because of a patch processing problem, the test was considered successful because pressures 25% above normal operating pressures were attained before failure. The second test was of 5.3-in.-long and 7.5-in.-long combination defects which formed squares. These defects were repaired with five-ply patches. The successful firing indicated that large area defects could be repaired.

This program demonstrated that certain fiberglass defects and case bond separations in the X248 motor can be tolerated and that a field repair technique for fiberglass defects in the X248 cylindrical section can be used to repair defects of large magnitude. However, the application of these data to accept or reject defects and repairs remains subject to an engineering evaluation of each case.

FUTURE WORK

Future fiberglass defect and repair work should be directed primarily towards extending the information derived from this program into an analytical generalization. The objective would be to make the results general enough to afford an insight into defect behavior in other fiberglass applications regardless of configuration.

The available X248 and X259 motors should be utilized to continue the evaluation of propellant and case bond defects and repairs.

SECTION I

INTRODUCTION

A. PROBLEM AND OBJECTIVES

Under contract NAS 1-6367, Hercules Incorporated, Allegany Ballistics Laboratory (HI/ABL) was authorized to conduct a program to evaluate the severity of defects in solid propellant rocket motors. These defects included propellant-to-chamber (case bond) separation, fiberglass damage, and porous propellant.

Fiberglass solid propellant rocket motors are vulnerable to both external and internal defects. External surface damage such as gouges, bruises, and abrasions may occur during motor manufacture or in the field. Field-type damages are more critical, since the motor contains live propellant and cannot be returned to the motor case fabricator for rework. Internal defects consist of either case bond separations or porous propellant. These two defects could cause abnormal burning of the propellant and result in a failure of the motor.

Thus, the basic program objective was to reduce the rejection rate of fiberglass rocket motors due to various case and/or case-grain interface defects by developing accept/reject criteria and methods of repair for these defects.

B. BACKGROUND

A review of completed programs involving chamber damage and repair was made to establish a background of knowledge and to formulate the present program. Culliss' work[1] at HI/ABL included an evaluation of strength degradation as a function of the magnitude, orientation, and location of external defects; development of effective repair methods; and determination of the defect magnitudes for which adequate repair was improbable. The external defects studied in this program were limited to the cylindrical section and repair techniques included the removal of layers affected by the damage followed by rewinding glass in the area. Full repairs were thus limited to defects affecting hoop windings; no compensation for damage to helical windings was provided.

Chamber damage effects and repair techniques were also studied by Burkley[2] at Goodyear. This program dealt with sub-scale cases having induced flaws in the cylindrical section. A notable development from this work was that the most successful technique for field repair involved elastomeric bonding of a fiberglass patch over the cut area. This work also further recognized the influence of layer orientation upon the initial "peel-back" failure mode.

The applicability of data generated from a small-scale case program and related to larger specimens was developed by Cross[3] at HI/ABL. His work indicated a high level of confidence in predicting full-scale case damage responses based upon sub-scale test data.

The final literature reviewed included structural evaluation of damaged filament-wound pressure vessels by Lunde[4] of Aeroject-General Corporation. This work coupled theoretical and empirical techniques to quantitatively establish strength loss attributable to surface damages. Repair criteria were discussed and actual repair materials and configurations experimentally evaluated. Test data were provided to substantiate the theoretical analysis and to compare the various repair methods. However, the data were insufficient to provide a valid basis for future application.

C. SUMMARY OF PROGRAM PLAN AND SCOPE

The contract was divided into two phases: Phase I comprised (a) the receipt, inspection and storage of Government-furnished material (GFM) motors, cases, etc., provided for use on the contract and (b) the preparation of a program plan for a test and development effort using the GFM as appropriate in pursuit of the stated objectives. Phase II comprised the test and development program with such supporting activity as was found necessary. As executed, the Phase II program was confined to consideration of case damage and case/grain and grain/insulator separation to best assure achievement of definitive results. The present report covers the entire effort through June 1968.

The actual Phase II testing was broken down into the investigation of (1) fiberglass and (2) case bond defects. The fiberglass damage investigation consisted of stress analyses, damage evaluation, and damage repair. Fiberglass damages were limited to the gouge type because of problems in the reproducibility, assessment, and analysis of the bruise and abrasion type defects. A stress analysis of an undefected chamber was followed by analysis of defected and repaired chambers in order to determine the strength degradation. The evaluation of fiberglass defects is designed to establish tolerable damage limits not requiring repair and to investigate such variables as defect location, orientation, and magnitude.

Gouge-type defects that were inflicted completely through the chamber wall had to be repaired. This repair of complete fiberglass defects was designed to (1) develop repair techniques, (2) optimize patch materials and size, and (3) establish accept/reject criteria for repairs. The propellant defect investigation consisted of defect evaluation and defect repair. The evaluation of the propellant defects was designed to establish accept/reject criteria for these defects. The repair of case bond defects was designed to (1) develop repair techniques, (2) optimize repair materials, and (3) establish accept/reject criteria for repairs.

SECTION II

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. Fiberglass Defects and Repairs

The NASA Defects Program has provided a critical evaluation of the size, location, orientation, and repair of gouge-type defects in the fiberglass chamber of the X248 rocket motor. The following major conclusions and achievements were demonstrated during the program.

(a) Partial gouge-type defects can be sustained in the domes and cylindrical sections of the X248 motor without affecting motor performance. This was demonstrated in the static firing of motors numbered NPP-409, -447, -455, -257, and -454.

(b) A field repair technique has been developed for the repair of defects completely through the wall of the cylindrical section of the X248 rocket motor. This technique includes a laminated fiberglass cloth patch bonded to the chamber by an elastomeric bonding system which can cure at room temperature. The technique has been used to successfully repair defects without regard to size or orientation of the defect. Repair by this system requires no major tooling or equipment.

(c) Although the stress analyses were vital to the interpretation of empirical results, the analytical methods used are inadequate to evaluate chamber damage and repairs. This is due largely to the geometrical limitations of the method. This method cannot account for the finite lengths of defects and thus it tended to produce highly conservative solutions when used to evaluate defects and repairs.

(d) The feasibility of repairing fiberglass defects in a rocket motor dome was demonstrated in a 6-in.-diameter bottle program.

(e) Although defects and repairs can be evaluated on an engineering basis, further effort remains to be completed before valid accept/reject criteria can be established for defects and repairs in general.

Other conclusions are as follows:

(a) Ignition transient loading is not as critical to a repair patch as sustained pressure loading of equal magnitude.

(b) Accuracy of depth measurements on partial defects by inspection methods employed has been found inadequate for direct use in analytical evaluation of the defect.

(c) The magnitude of the measured strains from the static firings has been consistent to within $\sim$ 0.25% strain. These variations indicate possible chamber manufacturing and gage installation variations between the tests.

(d) Field repair of defects may be somewhat restricted by processing problems that have been identified.

From static firings of defected and repaired X248 motors, it is concluded that gouge-type defects can be repaired regardless of X248 model. However, it may be necessary to optimize the patch technique for situations where patch weight and size must be restricted and where higher loads are to be transferred by the bond layer.

The basic assemptions that were used to design the patch for the X248 can be applied to other motors as well. The patch itself can be optimized somewhat on the basis of X248 test results. Use of these test results would tend to reduce the conservatism of the patch design for smaller defects. However, because of the possibility of patch irregularities, it may be best to continue using the conservative assumptions until the patch application technique has been perfected. The parameters that must be considered in designing a repair patch are (1) motor pressure, (2) motor case radius, (3) winding geometry, (4) defect size and depth, and (5) patch material properties.

2. Case Bond Separations and Repairs

The work done during the NASA program to investigate case bond separations (CBS), to evaluate the effects of CBS of various degrees and in certain motor locations, and to explore the feasibility of CBS repair was the basis for the following two conclusions.

(a) Large, unrepaired case bond separations in the forward domes of X248 motors have not affected motor performance and have not propagated under simulated flight loading conditions.

(b) The capability of analyzing the effects of small case bond defects in the aft dome on an individual basis was demonstrated by testing several unrepaired defects which had no effect on ballistics.

(c) The repair of small case bond separations in the aft dome by injecting a polyurethane material into the separation with a hypodermic syringe was shown to be feasible.

(d) The technique of repairing CBS by pumping resin through holes drilled in the fiberglass case appears feasible, but remains to be demonstrated.

(e) The radiographic inspection technique has certain limitations in the ability to detect and evaluate case bond separations and to verify their satisfactory repair.

B. RECOMMENDATIONS

1. Fiberglass Defects and Repairs

The results obtained in this program have clearly demonstrated that certain defects will not affect motor performance and also that extensive fiberglass defects can be successfully repaired. However, these results have been obtained from one specific type of rocket motor. The question remains as to whether or not results obtained from the X248 chamber are applicable to fiberglass structures in general. This indicates that a more general approach to the problem of fiberglass defects and repairs should be undertaken. The importance of this more generalized approach lies in the ability to take data from the limited number of selected tests and mathematically apply the results to fiberglass structures of any configuration.

The future work should be directed primarily toward extending this informational background to an analytical generalization, the objective being to make the results general enough to afford an insight into defect behavior in other fiberglass applications regardless of configuration. As in this program, attention should necessarily be addressed to gouge-type defects, because these defects are the most critical and their effects can be assessed.

The future fiberglass program should be carried out in three phases: (1) analysis, (2) patch optimization and fabrication, and (3) experimental verification. It should be conducted at three basic levels: (a) on "simple representative elements" such as flat plates with defects, (b) on sub-scale pressure tubes, and (c) on full-scale configurations other than the X248 rocket motor. These three phases would result in a more unified approach to the evaluation and repair of fiberglass defects. This would also permit the development of an accept/reject criterion for application to fiberglass defects and repairs in general.

The following recommendations are suggested for the immediate future as being consistent with the overall proposed recommendations:

(a) Development of a three-dimensional computer program to achieve more exact analyses of defects and repairs.

(b) Further investigation of both dome defects and circumferential cylindrical defects.

(c) Determination of shear strength of the patching system.

(d) Repair of cylindrical defects on X259 chambers.

(e) Further optimization of patch size, orientation, and materials.

2. Case Bond Separation and Repair

The case bond separation study has yielded information and conclusions of considerable portent in future production and use of case bonded rocket motors. The following work is recommended as the most potentially fruitful extension of this investigation.

(a) The repair and testing of NPP-424 should be completed to verify that the separation can be completely filled with repair adhesive and an adequate bond effected.

(b) Evaluation of propellant and case bond defects and development of repair procedures, using the available X248 and X259 motors, should be continued.

(c) To overcome radiographic inspection limitations, other NDT methods should be evaluated for such applications.

SECTION III

DISCUSSION OF RESULTS

A. INTRODUCTION

The NASA Defects Program consisted of two phases. Phase I consisted of receipt, inspection and storage of the rocket motors and empty chambers provided for use in this program. Inspection of the rocket motors consisted of visual, dimensional and radiographic inspections. Inspection of the empty chambers was limited to visual examination. The inspection results are summarized in Table 1, and detailed radiographic maps for each motor are given in Appendix A. The radiographic maps also contain the results of subsequent inspections conducted during the Phase II testing. These maps are presented in Mercator projection of the entire case. Location of certain features of the motors is indicated and the separations found are shown by individual bars in the index positions where observed.

Phase II consisted primarily of the static firing of X248 rocket motors. These firings were used to investigate fiberglass case defects and repairs and case bond separations in the motors. Descriptions of these defects and firing results are summarized in Table 2. Three types of fiberglass defects were investigated: (1) partial penetration, (2) complete penetration, and (3) combinations of different orientations of complete penetration. The investigation of these defects included the development of a repair technique for cylindrical section defects which would cause motor failure. The case bond separation investigation consisted of the static firing of motors with large separations in the forward dome portion of the motor. Some of these motors also contained minor unrepaired and repaired CBS in the aft end. The case bond study, however, was considered of secondary importance to the fiberglass defect and repair investigation, and case bond separation repairs were made only as needed to make the test motors suitable for use as test vehicles in the fiberglass repair program.

In addition to the X248 static firing, a small bottle program and laboratory investigations were performed. These portions of the program served mainly to evaluate repair materials, procedures and techniques.

B. FIBERGLASS DEFECTS AND REPAIRS

1. Technical Approach

Fiberglass chambers are subject to surface damages. These damages may be classified according to three basic categories: (1) bruises, (2) abrasions, and (3) gouges. A bruise is the damage which occurs when impact loading causes resin crazing in the impact area but no fibers are cut. An abrasion is defined as damage in which the surface is cut but no fibers are severed. A gouge is damage involving severed fibers and results in local destruction of the load-carrying capabilities of the fibers.

This investigation of fiberglass chamber damages was limited to machined gouge-type defects. The gouge-type was chosen for the following reasons:

(a) The loss of load-carrying capability resulting from the complete severance of fibers can be critical to the structural integrity of the motor case.

(b) Only gouges can be reliably and accurately measured by the presently available inspection techniques.

(c) The gouge is more easily reproduced and controlled because its dimensions can be assessed.

(d) The presently available analytical techniques are more adaptable to the analysis of gouge-type defects.

The three basis types of gouges investigated in the program were partial, complete, and combination. The partial type gouges do not completely penetrate the chamber wall. The complete type gouges have completely penetrated the chamber wall. The combination type gouges have completely penetrated the chamber wall, and are combinations of two or more defects.

The motors used for the fiberglass defect and repair study were selected from GFM and were thoroughly inspected before their use in this program. Because the available number of any one model of the X248 was limited, X248 motors of the A5, A6 and A10 models were used. These models differ mainly in the winding patterns as described in the mathematical analyses section of this report. All the motors selected had been previously rejected for use as flight vehicles because of case bond separations in the forward dome area and minor fiberglass damage on some motors.

The motor program was based on the conservative approach that a single failure was fully indicative, but that a single success required confirmation. Tests on fiberglass damage and repair were made at chamber pressures well above normal operating pressures of approximately 250 psia for the motors used, thus avoiding favorable interpretation of marginal results. Chamber pressures for these tests were increased by the use of undersized nozzle throats. Figure 1 shows the X248 motor configuration and Figure 2 shows normal and typical over-pressure pressure traces characteristic of these tests. Figure 1 also orients angular positions identified elsewhere in this report. The nozzles were sized to give a maximum progressive pressure of 350 psia as compared to 250 psia for normal conditions.

2. Description of Fiberglass Repair Techniques

a. Introduction

A technique has been developed for the repair of fiberglass defects in the cylindrical section of the X248 rocket motor. The design of this repair technique will permit it to be applied to other motors with possibly only minor modifications. However, its application to other motors remains to be demonstrated.

The design of the patch for the repair of fiberglass defects required several considerations. First, the bond between the patch and the fiberglass chamber had to be capable of transferring the load between the two, transmitting pressure loading on the case into the patch and then from the patch back into the case. Secondly, the patch itself had to carry the transferred load without failure.

A literature study[2] indicated that the major problem in repairing a defect was the proper shear transmission between the case and the repair. Repair methods utilizing strong patch materials such as metals and fiberglass had failed to repair defects completely because of shear stress distribution. This distribution of shear stresses along the bond length was not uniform but displayed peaks at both ends of the patch as well as at the defect edges. These peak shear stresses must be kept at a safe level, because once failure begins, the entire bond will give way.

b. Materials

The materials that were used for the X248 repairs were Epon 946 adhesive and Owens-Corning S/81-901 finish fiberglass cloth. The Epon 946 adhesive was chosen because of its (1) high elongation, (2) low modulus, (3) room temperature cure, and (4) compatibility with BUU propellant. The fiberglass cloth was chosen for the following reasons: (1) easy to work with in a field-type repair situation, (2) ability to conform to surfaces, (3) ability to be cut to almost any size or shape, (4) low weight, (5) high strength, and (6) low modulus.

The materials were tested to determine the tensile strength of the S/81-901 glass cloth and the shear strength of Epon 946. The tensile tests of this combination of glass cloth and resin were completed for

1-, 2-, 3-, and 4-ply patches. A short Type II JANAF dogbone was used to evaluate the cloth combinations at strain rates of 3 in./min/in. and 300 in./min/in. The results of these tests are shown in Tables 3 and 4. The most critical condition occurs during the slower loading rate as indicated by these tables. The decrease in tensile modulus with increasing number of plies is due primarily to the greater resin content in samples of multiple number of plies. This additional resin enables the specimens to deflect more, thus reducing the modulus. A plot of the load-carrying capabilities versus number of plies is shown in Figure 3. The shear strength of the bond of Epon 946 to the X248 fiberglass was determined by a double-lap shear test. The shear test set-up is shown in Figure 4. These specimens were tested at strain rates of 3 in./min/in. and 300 in./min/in. The bond length of the specimens was 1.0 in. The results of these shear tests are presented in Tables 5 and 6. In all cases the failures occurred between the fiberglass and the Epon 946.

c. <u>Patch Parameters</u>

The patch design is based upon the "load to be transferred" by the patch. This load must be carried in shear through the bond layer and in tension by the fiberglass cloth. The number of plies needed to repair a defect is dependent upon the "load to be transferred." This load is equal to the load that would have normally been carried by the damaged fibers in the defect. This assumption therefore accounts for variations of loads carried by layers with different winding angles.

To determine the number of plies needed for the case of a longitudinal defect completely through the X248 chamber wall, the hoop load is maximum and is:

$$\text{Load to be transferred} = Pr$$

$$= 335 \text{ psi } (8.96 \text{ in.})$$

$$= 3090 \text{ lb/in.}$$

The number of plies needed to carry this load is four, assuming the load distribution is uniform among the plies. This was determined from the tensile strength data shown in Table 3.

The required bond length normal to the longitudinal defect, assuming uniform transfer of the load from the patch back into the case, is as follows:

$$\text{Bond length} = \frac{\text{Load to be transferred}}{\text{Bond shear strength}}$$

From Table 5 the average bond shear strength is 1632 lb/in.^{2} This shear strength is used because the 3 in./min/in. strain rate approximates the X248 loading conditions during the progressive portion of the pressure versus time curve.

$$\text{Bond length} = \frac{3090 \text{ lb/in.}}{1632 \text{ lb/in.}^2}$$

$$= 1.89 \text{ in.}$$

To reduce the possibilities of shear failure in view of a rather wide data spread in Table 5, a safety factor of 1.5 was used to multiply the calculated bond length. The bond length on either side of the defect was then 3.0 in. long. The shear bond length necessary at the ends of the longitudinal defect was arbitrarily established as 1.0 in. for a defect that was only 0.10 in. wide. For wider longitudinal defects, this shear bond length at the end must be increased. By comparing the hoop and axial strains in an A6 chamber, a maximum required bond length was determined to be 2.50 in. long at either end of the defect.

The patch design, shown in Figure 5, incorporates successively overlapping plies. This overlapping concept was intended to minimize the peak shear stresses that were prevalent in the Goodyear Repair Program.(2) Subsequent stress analyses indicated that the overlapping technique would eliminate the peak shear stresses at the outer edge of the patch.

Utilizing the previous assumptions, the sizes required for various plies for various types of defects can be determined. Figure 6 illustrates the defect and repair measurements.

Thus, for ply No. 1:

$L_{min} = 2.0 \text{ in.} + \ell \qquad (\text{if } w \leq 0.10 \text{ in.})$

$L = 2.0 \text{ in.} + \ell + 2w \qquad (\text{if } 0.10 \text{ in.} < w \leq 1.5 \text{ in.})$

$L_{max} = 2.0 \text{ in.} + \ell + 3.0 \text{ in.} = (5.0 + \ell) \text{ in.}$

$W_{min} = 2.0 \text{ in.} + w \qquad (\text{if } \ell \leq 0.10 \text{ in.})$

$W = 2.0 \text{ in.} + w + 2\ell \qquad (\text{if } 0.10 \text{ in.} < \ell \leq 2.0 \text{ in.})$

$W_{max} = 2.0 \text{ in.} + w + 4.0 \text{ in.} = (6.0 + w) \text{ in.}$

The measurements of subsequent plies are dependent upon those of ply No. 1.

$$L_n = 2.0 \text{ in. } (n-1) + L_1$$

$$W_n = 2.0 \text{ in. } (n-1) + W_1$$

where n = ply number

L_1 = length of ply 1 $\quad$ ℓ = length of defect

W_1 = width of ply 1 $\quad$ w = width of defect

The assumptions of uniform load distributions were used as an initial guide for repair development. Later analytical evaluations showed this not to be the case and future repair work will take this into consideration.

d. Repair Procedure

The procedure for the repair of fiberglass defects in the cylindrical section of the X248 motor has evolved from the laboratory small bottle and X248 tests that have been performed during the program. The repair of a defect, once the number and size of the plies have been determined, is accomplished as follows:

(1) To prevent the patch plies from unraveling when they are cut out, a resin border is placed at the boundaries. The ply is then cut to a size 1/2 in. larger than the border dimensions. Warp or woof fibers are pulled away up to the resin border, thereby controlling the amount and location of fraying.

(2) The areas to be patched is marked off and then sanded until the gloss of the chamber has been removed.

(3) The sanded area is then cleaned with methylene chloride.

(4) A coat of Epon 946 adhesive is applied to the sanded area.

(5) The first ply is placed over the defect and the resin is worked up through the ply.

(6) More resin is added; the next ply is placed ~~over the first ply covering the defect and~~

the resin is again worked up through the ply. This step is repeated for all subsequent plies.

(7) Upon completion of patching, the patched area is allowed to cure for a minimum of 7 days at room temperature (75 $\pm$ 5°F).

This procedure is included in this report as Appendix B.

e. Limitations of Repair Technique

Some difficulties have been encountered in using this repair technique, but these are primarily problems in application of the patch, and are easily remedied when the operator exercises sufficient care. For example, during repair of defects in the cylindrical section of some X248 chambers, the layer of adhesive used to bond the first ply to the chamber was too thin; that is, not enough adhesive was applied to the chamber before the first ply was placed on it. This was remedied quite easily by applying more adhesive in subsequent repairs. Another difficulty encountered was the presence of voids in the adhesive. These voids usually occurred in the upper plies of the patch. The voids are primarily the result of leaving entrapped air in the patch. Such voids can be eliminated by more careful working of the adhesive when subsequent plies are added. It should be emphasized that these two problems can be a result of inexperience or negligence on the part of the person doing the repair. Personnel must be thoroughly trained if adequate repair is to be effected.

Use of the repair technique can also be limited by location of the defect. If the defect is located in areas near the doubler, adequate area might not be available for the patch application. Thus, repair of a defect located in such an area might prove to be impracticable.

The shear strength capability of the adhesive system is limited to an average of 1632 psi. The patch configuration causes the shear stresses on either side of the defect to be a maximum at the defect edge. Depending upon the load to be transferred from the case to the patch, this shear strength could be exceeded. The X248 work has indicated that the load carried by the bond system was somewhat less than 3090 lb/in. that was calculated. This is apparent when comparisons of actual and theoretical strains are made as in Figures 62 and 63. It appears that the end effects (i.e., transfer of load around the defect) are quite pronounced in the X248 chamber even with defects up to 15.0 inches long. This is probably due to both the high helical winding angles (i.e., 60°, 45°) in the cylindrical section and the stiffening added to the chamber by the patch in the defected area. The high winding angle layers would tend to transfer the hoop load around the defect because of their hoop loading capabilities. The stiffening of the entire defected area would also facilitate a transfer of load around the defect. Therefore, if the theoretical calculations from the patch model and the test results are compared, it appears that the bonding system may not be capable of carrying the ultimate load of 3049 lb/in. This would also lead to the conclusion that for chambers with different winding geometries or for chambers where higher loads are to be transferred, either a new adhesive system or a new method of shear transfer would be required, even if the end effects were still considered.

During the static testing of repaired defects, strain gage data have indicated a slight tendency toward creep loading conditions in the patch. This condition occurred during the latter portion of the pressure versus time trace. However, the magnitude of the changes in strains for similar pressures was not significant. This situation therefore does not appear to be a problem in the X248 motor but could possibly cause problems in motors with much longer burning times.

f. Definition of Acceptable Repair

An acceptable X248 chamber repair depends upon use of the prescribed materials, upon the use of the proper number and size of plies as determined by the formulae given, and upon careful adherence to the procedure described.

An acceptable repair for an X248 defect is further characterized by a minimum of voids in the patch and an adequate bond layer thickness. At the present time, only the voids in the repair patch can be assessed. The available test results indicate that if voids are kept to a minimum, the motor can be safely fired at normal operating pressures. The minimum bond layer thickness should be at least 0.010 in. thick. This value was derived from the theoretical results because it cannot be assessed in the present bonding technique. If the patching procedure is followed precisely and if care is taken to eliminate voids and to ensure adequate bond layer thickness, all repairs would be considered acceptable for normal operating pressures.

3. Unrepaired Defects

Unrepaired partial defects were investigated in the aft dome, forward dome and cylindrical section of the X248 rocket motor. The primary objective of inflicting these partial defects was to establish motor failure during the progressive portion of the pressure-time trace. When failure-causing defects were defined, identical or more severe defects could be inflicted on other motors and then used to evaluate the repair technique.for fiberglass defects.

Only limited work was done on fiberglass defects in the dome areas of the X248 case. This consisted of one aft dome and two forward dome tests.

The aft dome test motor (NPP-447) had two defects 1.0 in. long x 0.10 in. wide, Defect No. 1 being 0.052 in. deep and Defect No. 2 being 0.045 in. deep. These specified defects were based upon data found in References 3 and 4. Burst was expected to occur at approximately 300 psia. The aft dome was approximately 0.065 in. thick in the defected areas. The motor was statically fired and attained a maximum progressive pressure of 290 psia without failure occurring in the areas of the defects. A visual inspection of both defects indicated slight crazing around the edges. Defect No. 1 had its remaining fibers severed on one side of the defect. A review of the strain gage data indicated no unusually high strains in the defect area. Apparently, the internal rubber insulator acted much like an internal patch and helped to redistribute the stresses in the area of the defects. Figures 7 and 8 are pictures of the two defected areas. Because of the contribution of the insulator, future aft dome tests on X248 motors were cancelled.

The first forward dome test motor (NPP-455) had defects 2.50 in. long x 0.25 in. wide, Defect No. 1 being 0.050 in. deep and Defect No. 2 being 0.040 in. deep. The approximate dome thickness in this area was 0.070 in. The motor was statically fired and successfully withstood a progressive maximum pressure of 393 psia without failure resulting at either defect. Pictures of the two defects are shown in Figure 9. It is apparent from this figure that a large amount of crazing did occur in the defected areas. The magnitude of these two defects indicated overdesign of the forward dome.

The second forward dome test motor (NPP-454) had a defect 3.0 in. long x 0.50 in. wide x 0.050 in. deep. The progressive maximum pressure during static firing was 376 psia. No failure occurred in the area of the defect. A high strain reading was obtained from one of the strain gages placed inside Defect No. 1. At a pressure of 376 psia, the hoop strain was 1.49%. No other abnormal or high strains were recorded in the defected areas. Figure 10 is a post-firing picture of the defect. There was a large amount of crazing in the defect area, but no sign of fiber failure was present.

With the completion of this test, the originally planned forward dome defecting program was suspended because of the complexities of the X248 dome. The winding geometry, the spherical shape, the overdesign of the dome, and the surface irregularities tended to prevent the establishment of accept/reject criteria for dome defects. However, the dome tests did indicate that very substantial defects could be tolerated in the domes without affecting the motor performance.

Two motor tests were used to investigate partial defects in the cylindrical section of the X248 case. Both tests employed motors containing defects 2.5 in. long x 0.10 in. wide but with varying depths.

The first test motor, NPP-409, contained Defect No. 1, 0.018 in. deep, and Defect No. 2, 0.027 in. deep, in the 0.055-in.-thick cylindrical section. The motor failed at a pressure of 281 psia at Defect No. 2. Peel-back of the severed fibers occurred at both defects. This peel-back was not limited to the outer 90° winding, but included all the cut fibers. This occurrence is contrary to the peel-backs reported in the literature that was surveyed. This peel-back of the helicals was probably due to the high winding angles that were involved, i.e., 60° and 45°.

A review of the strain gage data showed the highest strains in the area immediately aft of Defect No. 2. The maximum recorded strain at this point was 1.95% at the burst pressure of 281 psia. The strain gages located at distances of 10°, 30° and 60° away from Defect No. 2 indicated increasing peel-back as the pressure increased. The gage at 10° indicated peel-back was occurring before the ignition maximum pressure was attained. After about 10.2 seconds of firing, the gage at 30° indicated that peel-back was starting to occur. At the time of burst, the gage had indicated that peel-back had gone beyond 30°. The gage at 60° started to give a small indication of peel-back starting in the immediate area. A plot of the pressure versus strain for these three gages is shown in Figure 11. A plot of the hoop strain versus pressure along the cylindrical section at 0° is shown in Figure 12. A rapid change in strain for the gage just aft of Defect No. 2 is apparent between 251 psia and 281 psia pressures. This test resulted in the determination of the magnitude of a defect that would cause failure during the progressive portion of the pressure-time trace.

The second test in the study of partial defects in the cylindrical section employed motor NPP-257 which contained a defect 2.50 in. long x 0.10 in. wide x 0.015 in. deep. This defect was not expected to cause a motor failure. During static firing, the motor obtained a maximum progressive pressure of 380 psia. The unrepaired fiberglass defect resulted in the delamination of a 2.5-in.-wide band of fiberglass in both directions, circumferentially, from the defect. This delamination was approximately 12 inches long on one side of the defect and 6 inches on the other. Nevertheless, the case retained its integrity as a pressure vessel. A close-up of this defect is shown in Figure 13. This test demonstrated that the X248 motor case could sustain substantial defects without failing at 50% higher than normal operating pressures.

4. Repaired Defects

Repaired defects were primarily investigated in the cylindrical section of the X248 motor. However, a brief preliminary subscale bottle program was conducted to demonstrate the feasibility of repair and aid in material and technique selection. A 6-in. bottle program was used to investigate the repair of dome defects because the X248 proved to be unsuitable for dome defect repair evaluation. The primary objective of these investigations was to develop a reliable repair technique for fiberglass defects.

a. Preliminary Studies

The initial investigation of the repair of defects was performed in a preliminary bottle study. This investigation used five 6-in.-diameter Polaris bottles and eight 3-in.-diameter Picatinny bottles.

The Polaris bottle study included one control bottle, two defected bottles, and two repaired bottles. The testing of these bottles proved to be quite inconclusive. The results indicated that a fiberglass cloth repair could be performed but its capabilities would require further evaluation.

The eight Picatinny bottles were divided into two groups because of physical appearances. Each group contained one control, two defected, and one defected and repaired. These tests resulted in the first indication that fiberglass cloth patches could reinstate the strength lost due to inflicted defects. However, the optimization of patch materials and orientation remained to be evaluated in future tests.

b. Repair of Dome Defects

Dome defects were primarily investigated in a subscale 6-in.-diameter Polaris bottle program. For this program, twenty-four 1/8-scale Polaris A3 second-stage chambers were employed. These bottles were divided into three groups. Group I, the control group, contained six bottles. Group II, the defect group, contained six bottles. Group III, the defect and repair group, contained twelve bottles.

The bottles in the control group were hydroburst. The average burst pressure for the bottles was established at 2205 psig. The results of the tests are shown in Table 7.

The six bottles of Group II were defected and hydroburst to test the reproducibility of inflicted defects. The defect was 0.75-in.-long x 0.100-in. wide x 0.015 in. deep and was located 2.00 in. from the edge of the pole piece. The depth of the defect was such that not more than three of the six helical plies would be severed. The results of the tests are shown in Table 8. Typical failures were due to peel-back of the deliberately severed filaments, followed by a tension failure in the remaining filaments. Figure 14 is a picture of a typical failure. The average burst pressure was 1715 psig.

In the six bottles that were defected and repaired in Group III, the defect was 0.75 in. long x 0.10 in. wide x 0.015 in. deep and located 2.00 in. from the edge of the pole piece. The repair materials consisted of Owens-Corning S-81 fiberglass cloth with a 901 finish and an Epon 946 resin system. These same materials have been used to repair defects in the cylindrical section.

The six bottles of Group III were divided into two sub-groups. Sub-group 1 bottles were repaired with a two-ply glass cloth patch. Each ply was 3 in. long x 2-1/4 in. wide. The sub-group 2 bottles were repaired in the same manner as the sub-group 1 bottles except that a third ply was added. (See Figure 106 for patch orientation.) The test results of sub-groups 1 and 2 are shown in Tables 9 and 10.

Post-hydroburst inspection of sub-group 1 bottles indicated a patch failure for only one bottle. This failure occurred in Bottle No. 11 at a pressure of 2415 psig.

Post-hydroburst inspection of sub-group 2 bottles indicated no patch failures. However, the burst pressures of two bottles were higher than average. Dome thickness measurements indicate that the dome walls of bottles Nos. 25 and 26 were thicker than the nominal 0.032 in. These thicker domes were due to a higher number of filaments in the dome as was indicated by the weight of helicals used in the winding of the bottles. Underside views of successfully repaired defects are shown in Figures 15 and 16. Figure 15 shows a two-ply repair, and Figure 16 a three-ply repair. The larger amount of crazing is visible in the glass under the two-ply repair.

The results of these tests indicated that a two-ply patch is capable of restoring the defected bottles back to their original burst pressures. The remaining six bottles were therefore defected completely through the domes. Three of these bottles were repaired with a two-ply patch, and the remaining three with a three-ply patch. These bottles were hydroburst and the results are shown in Tables 11 and 12.

Failures of the two-ply patches occurred in shear between the patch and the dome. The average burst pressure for the two-ply patch was 1385 psig. For the three-ply patches, failure occurred in shear for bottles S/N's 6 and 19 and a tension failure occurred in the patch on bottle S/N 22. The average burst pressure for the three-ply patch was 1965 psig. Pictures of the shear failure in bottle S/N 19 and the tension failure in bottle S/N 22 are shown in Figures 17 and 18, respectively.

The three-ply repair returned the bottles to 89% of their original average burst pressure. The tension failure of the three-ply patch at 2205 psig in bottle S/N 22 indicates that it may be possible to return the Group III bottles back to their original burst pressure with a three-ply patch if the shear failure problem can be overcome.

The only dome defect repairs evaluated on X248 motors involved the repair of holes. Two 3/8-in.-diameter holes were drilled completely through the forward dome of the X248 motors NPP-454 and NPP-242. These holes were repaired with a three-ply S/81-901 fiberglass cloth, Epon 946 patch. These tests were part of an evaluation of other chamber defects. The progressive maximum pressures during static firing were 376 psia and 390 psia. No failure occurred because of these defects. Post-firing pictures of NPP-454 are shown in Figure 10. These tests demonstrated that holes in the forward dome could be drilled and repaired successfully.

c. Cylindrical Defects

Nine X248 rocket motors were used to investigate the repair of defects in the cylindrical section of the motor. These nine tests included variations of defect depth, orientation, size and the number of plies of fiberglass cloth in the repair patches. The first test was used to investigate the repair of a partial penetration longitudinal defect. The next five tests were used to investigate completely penetrating longitudinal defects with variations in length, width, and the number of plies in the fiberglass cloth repair patches. The seventh test was used to evaluate circumferential defects with a variation in the number of plies in the repair patches. The final two tests were used to evaluate combinations of longitudinal and circumferential defects.

The first test (NPP-257) was of a motor containing a 2.50 in. long x 0.10 in. wide x 0.034 in. deep longitudinal defect repaired with a three-ply S/81-901 fiberglass cloth patch. This defect was approximately 60% through the chamber wall. The motor was statically fired successfully. The maximum progressive pressure was 380 psia. This repaired defect was removed from the chamber and then sectioned. Figures 19, 20 and 21 are photomicrographs of a cross section of the defect. A large amount of resin crazing in the remaining uncut filaments is apparent on the actual cross-section but does not show up in the pictures. This crazing indicates that the fibers were loaded beyond their capabilities. Because the remaining uncut fibers were 29° helicals, most of the hoop load was carried by the patch itself. A plot of the hoop strains along the case for various pressures is shown in Figure 22. The maximum strain of 2.02% at 380 psia was found at the center of the repaired defect. This value is much lower than the allowable strain determined from the tensile testing of three layers of fiberglass cloth.

For the first test of a motor containing a repaired completely penetrating longitudinal defect (NPP-261), it was decided to repair two 2.50 in. long x 0.10 in. wide defects. These two defects were repaired with four-ply fiberglass cloth patches. This motor was statically fired to a maximum progressive pressure of 356 psia. A post-firing examination of the defected areas indicated a successful repair of the two defects. A plot of the strain versus pressure at 0° along the cylindrical section is shown in Figure 23. An extrapolated curve of expected normal strains along an A5 case for 355 psia is also included in the figure. The maximum strains in the center of the patches were 1.02% at 355 psia. This value is quite low because of the four-ply patch used in the repair. Figures 24, 25, and 26 are photomicrographs of the defect area. These pictures indicate no resin crazing of the case or any bond failure. This test gave the first indication of the capabilities of the patch. The test demonstrated that very serious defects could be repaired without compromising motor performance.

The success of this test indicated that longer defects could possibly be repaired with a four-ply patch. Increasing the defect length and successfully repairing it would also give an idea of the effects of defect changes on the patch strain distribution.

An axial defect 7.50 in. long x 0.10 in. wide was machined completely through the case of the third motor (NPP-242) and repaired. In the static firing of the motor, performance was satisfactory for 13.5 seconds, at which time the case ruptured in the aft dome at a pressure of 390 psia. The test was considered a success since one of the prime objectives of this program was to develop a repair technique that will withstand 350 psia. Examination of the motor after firing indicated that the rupture was not associated with the defect or its repair. A plot of the hoop strain versus pressure along the cylindrical section is shown in Figure 27. The maximum patch strain at 390 psia was 1.83% and was located at the midpoint of the defect. Figure 28 is a post-firing picture of the aft end failure.

Comparisons of the strain data for 2.5-in.- and 7.5-in.-long defects with four-ply repairs are illustrated in Figures 29 and 30. The maximum strain values are approximately 0.25% higher for the 7.5-in.-long defect. The plots also indicate that as the defect lengthens, the patches tend to be more highly strained. This means that they are carrying a greater load and are less affected by the end constraints. The difference in the strain values for the two 2.50-in.-long defects in Figure 29 is due to the propellant in the forward portion and its effect on the case strains during firing.

The successful repair of a 7.5-in.-long defect indicated that the optimum number of plies required for the repair of such a defect might be no more than three. Therefore, a similar defect was inflicted in the cylindrical section of motor NPP-475 and then repaired with a three-ply fiberglass cloth patch. The motor, when statically fired, failed after 26.5 seconds of burning at a pressure of 340 psia. The maximum progressive pressure was 351 psia. The maximum hoop strain on the patch occurred at the center of the defect and was equal to 2.68% at the progressive maximum pressure. A plot of the hoop strain versus pressure for the strain gages over the defect is shown in Figure 31.

This motor failed in shear between the patch and the parent case because the bond layer between the first cloth ply and the motor case wall was too thin. This thin bond layer was attributed to the method employed in applying the cloth plies in a deliberate effort to minimize patch thickness. These results indicated that the amount of resin originally placed on the chamber was insufficient to compensate for the amount absorbed into the first ply of the repair patch. This depletion reduced the amount of resin in the bond layer. Top and underside views of the defect are shown in Figures 32A and 32B. The area of lower bond layer thickness is indicated by this figure. A comparison of this patch to the previous successful ones indicated that there was not as much resin in the patch that failed in shear.

Figure 33 is a sequence of six motion picture frames of the repaired defect. The frames are at intervals of 1/1000 sec. These pictures clearly demonstrate the failure and support the shear failure theory. Frame 2 shows the first signs of failure with the tearing of the patch at the end of the second ply. This failure at the end of the second ply indicated that a shear failure had occurred. Because the load could not be carried by the last ply, it tore at its weakest point.

Comparisons of the strain data for three- and four-ply repairs of 7.5-in.-long defects are shown in Figures 34 and 35. These two figures clearly demonstrate that the load carried in the outermost ply of the three-ply patch is much greater than the load carried in the outermost ply of a four-ply patch. This difference is attributed to the fact that in the three-ply patch, one less ply is available to carry the load.

The results obtained from the 2.50 in. long and 7.5 in. long defects in the preceding motors indicated that the load carried by the patch was at a maximum at the center. It is believed that a defect of a certain length will carry the load more evenly along the patch. The test of NPP-425 was thus an attempt to simulate this situation which is referred to as an infinite length defect. The motor had a defect 15.0 in. long x 0.10 in. wide. The defect was repaired with a four-ply patch.

The motor, when statically fired, resulted in a failure after 12.5 seconds of burning at a progressive pressure of 351 psia. The patch failure was a shear failure between the first ply and the fiberglass chamber rather than a tensile failure of the patch. This failure once again indicated that there was not enough resin in the bond layer. A comparison of this patch to previous successful patches showed the failed patch to contain less resin. Review of the motion picture frames before the failure indicates that the patch failure occurred much the same as the failure of the previous test. Figures 36A and 36B are pictures of the patch. The tear of the patch is not located directly over the defect. The lack of resin is apparent in the underside view of the patch.

Most of the strain gages malfunctioned during motor ignition. The fragmentary strain data obtained indicate that the maximum strain at the center of the defect was 1.86% at 351 psia. This strain was much lower than the strain measured in the previous test at burst. However, the same load had to be transferred from the chamber to the patch and then back to the chamber. Motors NPP-425 and NPP-475 had been repaired concurrently using the same technique directed toward minimizing patch thickness. Both failed at the bond in shear. The technique was modified to assure greater bond thickness on all subsequent repairs and no further shear failures occurred.

The final longitudinal defect test was an investigation of an increase in defect width rather than length. Four defects were machined into the cylindrical section of an X248 motor, Y-195. Two defects were 2.50 in. long and two were 7.50 in. long. The 2.50-in.-long defects were 0.4 in. and 0.8 in. wide. The 7.50-in.-long defects were 0.4 in. and 0.2 in. wide. All the defects were repaired with four-ply patches. X-ray inspection of these patches indicated small voids in the 2.50 in. long x 0.8 in. wide and in the 7.5 in. long x 0.2 in. wide defects.

The static firing resulted in a failure of the patch at the 7.5 in. long x 0.2 in. wide defect. Due to a malfunction in the recording system at ignition, all tape data and approximately the first ten seconds of visicorder records were lost. The approximate pressure at burst (taken from the visicorder traces) was between 385 to 390 psia.

An examination of the available visicorder data indicated that the failure began in an area forward of the defect center. The strain values were abruptly changing before the failure, indicating possible failure of fibers in lower plies.

Figures 37 through 40 are pictures of the defect repair and motor failure. A post-firing inspection of the repair showed that the patch failed directly over the defect. As Figure 40 emphasizes, the outer 90° layer of chamber glass was still bonded to the chamber, indicating that the patch adhered to the chamber. The initial failure was thus in the patch itself.

Comparisons between the strains for 2.50-in.-long defects with varying width are shown in Figure 41. Data for the 0.8-in.-wide defect indicates that strain increases with increasing width. However, the 0.4-in.-wide defect does not support this. This may be due to a lower stress level in A10 chamber than in the A5. Also, the defects in the Y-195 chamber are 1.5-in. closer to the doubler.

Figures 42 through 45 are plots of the strain vs. pressure for the four defects in the chamber. The rapid changes in the strain are evident on the 7.50-in.-long x 0.20-in.-wide defect, indicating a failure was occurring somewhere within the patch. No comparison was made between the 7.50-in.-long defects due to the lack of data points and the failure of the one defect.

This series of five tests to investigate repair of longitudinal defects has resulted in the development of a repair technique which can be successfully used to repair severe defects. All motors tested, even those resulting in failures, were operating at pressures well above the normal operating pressure of the X248 rocket motor. Therefore, the patching technique can be used, even when shear problems are encountered, to repair defects that will undergo only normal operating pressures.

In the cylindrical section of the X248 chamber, the hoop loading is twice as high as the axial loading. Therefore, longitudinal defects are more critical to the structural integrity of the motor case. A test was designed to demonstrate the feasibility of repairing circumferential defects in the X248 cylindrical section. Two circumferential defects 7.5 in. long x 0.1 in. wide and completely through the chamber were machined into the cylindrical section of motor NPP-445. One defect was repaired with a four-ply patch and the other with a three-ply patch. The motor was successfully statically fired to a maximum progressive pressure of 369 psia. Figure 46 is a comparison of the axial strains in the two defects at maximum pressure. As expected, the strains on the three-ply repair are higher than on the four-ply repair, but the three-ply patch provides an adequate repair for a 7.5-in.-long circumferential defect. However, the validity of the reading of gage S-10 is questioned. A higher reading on gage S-10 would produce a pattern similar to that of Defect No. 2. It therefore appears that gage S-10 was registering an abnormal condition which cannot be identified at this time. This successful firing demonstrated the capability of repairing a 7.5-in.-long, circumferentially oriented gouge, as described above, to withstand the patch design criteria of 350 psia firing pressure.

The successful demonstration of repairs for both longitudinal and circumferential defects indicated that eventually a square section of a motor chamber might be removed and repaired since this configuration would represent combined longitudinal and circumferential defects which completely penetrated the chamber. In the first of the two tests in this investigation, two right angles were machined into the chamber of motor NPP-453. Defect No. 1 had circumferential and longitudinal legs 7.5 in. long x 0.1 in. wide, and Defect No. 2 had legs 5.3 in. long x 0.1 in. wide. Both defects were repaired with four-ply patches. The static firing of the motor resulted in failure at Defect No. 2 after 16.5 seconds of firing. The pressure at failure was 348 psia. The failure of the patch was in tension directly over the defect. Plots of strain versus pressure are shown in Figures 47 and 48 for the two defects. The circumferential defects are at the right hand edges of the defects that are depicted in the figures. The strain pattern in Figure 48 demonstrates the effects of the voids in the patch on the strain readings. The strain values for the 5.3 in. defect are much higher than the strain for the 7.5 in. defect. The strain pattern also shows signs of fiber failures in the lower plies. These failures are evident when the difference in strain is compared to the difference in pressure. The strain pattern in Figure 47 shows the maximum strain to be approximately 1.3%. In the area of the circumferential defect, the strains are reduced by the cloth reinforcement to the right of the defect. The magnitude of the axial strains on these circumferential legs is quite small. These strains are plotted in Figures 49 and 50. A picture of the failure is shown in Figure 51.

X-rays of the repairs of these two defects indicated numerous voids in both of the patches, but the Defect No. 2 repair patch has many more than Defect No. 1. The voids, located mainly between the various fiberglass cloth plies, resulted when the patching procedure was changed in an attempt to eliminate the shear failures between the patch and the chamber wall experienced on NPP-475 and NPP-425. The change (applying resin to the glass cloth plies before putting them on the chamber rather than applying the cloth patches dry and bleeding the resin through) was intended to increase the resin thickness between the chamber and the first ply of the patch. The resin thickness was increased, but voids occurred between plies of the patch, so that the load was not carried by all of the plies in the patch.

In the second test of combination defects, two squares were machined into the cylindrical section of the X248 motor NPP-463. One square had 7.5-in. sides and the other had 5.3-in. sides. Both defects were repaired with five-ply glass cloth patches. The five plies were used to ensure the success of the firing because no information was available on such large area defects. The square pieces of fiberglass were not removed from the case since this removal might have caused a case bond separation. The X-ray inspection indicated a small number of voids in both patches. The voids were all less than 1.0 in.-long and were located mainly in the plies above the defected square areas. The motor was successfully fired at a maximum progressive pressure of 388 psia.

Figures 52 and 53 present the strains registered by the gages at the maximum pressure of 388 psia for the two square defects. The strains do not appear to be high in any area. The lower strains at the center are due to the added stiffness of the fiberglass plate beneath the patch. As was expected, axial strains were quite low.

Tables 13 and 14 show comparisons of strains on Defect Nos. 1 and 2 for similar pressures during the firing. The tables demonstrate that the strains are higher in most cases during the regressive portion of the pressure vs. time curve. In Table 13, the hoop gages at the centers of the longitudinal defects show the most increase in strain. This increase may be partially due to viscoelastic effects within the patch and to the change in grain configuration as the firing progresses.

The success of this test has indicated that the patching technique can be used to successfully repair almost any defect that might occur in the cylindrical section of the X248 rocket motor.

5. Analytical Study

An analytical study was performed to investigate the effects of variations in parameters on the stress distributions within the repair patch. The Hercules Finite Element Computer Program was used to perform a stress analysis of an idealized model of the actual longitudinal defects and repairs that were present in the X248 motor tests. The model, shown in Figure 54, is a cross-section of a longitudinal (i.e., axial) defect and the repair patch. The model comprises the individual plies of fiberglass cloth, the bond layer between plies, a defect which is completely through the X248 chamber wall, the individual layers of fiberglass in the chamber wall, and measurements to indicate the size of the elements. Because a repaired defect is symmetrical, only one-half of the defect and repair had to be modeled.

The analytical model was used to analyze eight different patch conditions. These conditions accounted for variations in bond layer thickness, type chamber, number of plies in the repair and defect width. The eight conditions that were analyzed are summarized in Table 15. The results of this analysis can be used to help evaluate and to better understand the results obtained from the static firing of repaired X248 motors. Comparisons between the eight conditions lead to the following conclusions:

(a) The stresses are not uniformly distributed among the various plies in the repair patch. The first ply carries the highest load (see Figure 55).

(b) The load is transferred from the patch back into the fiberglass chamber within a short distance (see Figure 55).

(c) The bond layer stresses are highest at the edge of the defect and then drop off very sharply (see Figure 56).

(d) As the defects become wider, the tensile load tends to become more evenly distributed among the plies (see Figure 57).

(e) The stresses in the outer ply of a patch used on the A6 motor case are about 10% less than those for an A5 motor case (see Figure 58).

(f) The bond layer shear stresses are dependent upon the thickness of the layer. By increasing the layer thickness from 0.007 in. to 0.0105 in., the shear stress is decreased by 16% (see Figure 59).

(g) The addition of a plane strain constant will increase the stresses in the first ply by about 9% (see Figure 60).

(h) A 1.0-in.-wide void between the first and second plies of the patch will increase the stresses by approximately 35% in the first ply (see Figure 61).

These results are not directly applicable to the angular or square defects. These defects cannot be analyzed because of the geometrical limitations of the computer program. The tendencies described in these conclusions are applicable to circumferential defects.

However, the magnitudes would be much lower because of the difference in loading conditions. This type defect was not analyzed because extensive modification of the analytical model would have been required and because this type of defect was not considered to be critical.

Strain gage data have been obtained from all the X248 motor tests. These measured strain values can be compared to the strains that were predicted by the analytical model.

For a 0.10-in.-wide defect in an A5 chamber repaired with a three-ply patch, the predicted strain is approximately 4.9% at 350 psia on the outermost ply. Data from the static firing of NPP-257-A5 and NPP-475-A6 indicate strains of approximately 1.7% and 2.70% for 350 psia. Figure 62 presents these comparisons in light of the 10% correction between the A5 and A6 chambers. This figure demonstrates that there are end effects in the actual tests which are not considered in the analytical model. However, the increase in strain with increasing defect length does indicate lessening of the end effects in the mid length region of the defect. The slope of the extrapolated lines seems to indicate that the predicted strain should be reached at an actual defect length of approximately 15.0 inches.

For a 0.10-in.-wide defect in an A6 chamber, repaired with a four-ply patch, the predicted strain is approximately 3.6% at 350 psia on the outermost ply. Data from the static firing of NPP-261-A5, NPP-242-A5, and NPP-425-A6 indicate strains of approximately 1.0%, 1.4%, and 1.8% for 350 psia. Figure 63 presents these comparisons in light of a 10% correction factor between the A5 and A6 chambers. This figure shows even more pronounced end effects than appeared in Figure 64. This is probably due to the stiffening of the whole area by the added fourth ply. Once again there is an increase in strain for an increase in defect length. However, the slope of the extrapolated lines indicates that the actual defect would have to be 30 inches long before the theoretical and actual strains would be equal.

The static firing of Motor Y-195-A10 produced a limited amount of data on the effects of defect width on patch strains. These data are shown in Figure 64 with the predicted strains for 0.2-in. and 0.5-in.-wide defects. The data indicate more pronounced changes in strains for the 2.5-in.-long defects than for the 7.5-in.-long defects. Comparison of Figures 63 and 64 shows little change for 7.5-in.-long defects but does show change for the 2.5-in.-long defects at widths of 0.4 in. to 0.8 in. Thus the length-to-width ratio of a defect apparently has some effect on strain. It is noted that strains are observed on gages over the defect centerline on the outermost ply. Strain in the first ply at the defect center is believed to be the maximum. Although observed strain appears to relate higher strain to wider defects, this may be due largely to improvement in load distribution among the plies. The first ply strain and shear stress in the bond may actually be less with a wider defect than a narrow one.

In conclusion, the analytical model is conservative in its estimate of the strains on the outermost ply of the patch. This conservatism is due mainly to the limitations of the computer program. The effects of the severed filaments which are an integral part of the chamber, the added stiffening of the chamber due to the patch, and the finite defect length cannot be accounted for in the analysis. The precision of the strain measurements and the reproducibility of a repair patch can also reduce the possibilities of accurate comparisons. The patch analysis can therefore be used only as a conservative estimate of the magnitudes of strain distributions within a patch for the various conditions that were analyzed.

6. Evaluation of Experimental Data

Strain gage data were obtained from all of the X248 static firings and appear to be quite consistent. The data points to the existence of possible test variables. Figures 65 and 66 are plots of hoop and axial strains versus pressure for the A5 and A6 chambers. These plots show variability within chambers of similar design for both the hoop and axial strains. However, when the age of the motors, primitive winding technology, and possible manufacturing variables are considered, the data spread does not seem to be very substantial. The only problem arises in making absolute comparisons between chambers of different models. The comparison between data for motors of similar design must always consider the above variables before making generalizations concerning the data.

C. CASE BOND SEPARATION

1. Technical Approach

The X248 rocket motor utilized in this program is a case-bonded unit containing BUU double-base propellant. The fiberglass case is protected by a rubber insulator in the aft section which is exposed to burning propellant and hot moving gases during firing. The case bond is obtained by bonding cellulose acetate (CA) cloth to the interior case surface with epoxy adhesives. The CA cloth is then coated with a layer of case bonding lacquer CBL-4 to ensure that the adhesives bonding the CA cloth into the case do not completely penetrate the cloth, thereby precluding a bond between the CA and propellant. Casting powder is loaded into the case, and casting solvent is added. The interaction of solvent and powder to form propellant also creates a bond between the CA cloth and/or CBL-4 and the propellant. The different materials present in a cross-section of the forward and aft ends of the motor are illustrated in Figure 67.

In some X248 motors, however, areas of case bond separation have been found. The location of such case bond failure in X248 motors is usually between the propellant and CBL-4, within the CBL-4 adhesive, or between the CBL-4 and the CA cloth. Case bond separation could also occur between the CA cloth and A2 adhesive or winding resin, or between the A2 adhesive and rubber insulator. Since the radiographic technique used does not identify the failure mode or combination of failure modes, the case bond separation detected by X-ray could be any one or a combination of these modes. Therefore, any repair material utilized in X248 motors for purposes other than space filling must be compatible with and bond to the materials shown on Figure 67.

Case bond separation can be categorized according to repair requirements. In the first category the CBS areas are accessible through a port opening. This type of separation either opens into a port area or can be reached with a hypodermic syringe from a port area. The second type of CBS is called inaccessible because repairing this type of CBS would require access through the case wall. Attempts to repair a defect of this type were dependent upon successful demonstration in the fiberglass repair program of a technique to repair holes in the fiberglass cases of sufficient size to permit case bond repairs. The concept envisioned was to inject adhesive or resin into the separation through a hole drilled in the fiberglass case, utilizing a hypodermic syringe or other means of injection.

The supporting laboratory testing to qualify a CBS repair adhesive was initially oriented towards developing a repair technique for X259 motors. This direction was based on the inspection results of the original group of 15 X248 and 3 X259 motors available for testing. The X248 motors contained no detected inaccessible CBS which required repair, and the small areas of accessible CBS were of such a nature and location that repair with Multron potting material was feasible. Use of Multron for CBS repairs had been demonstrated on other Hercules programs where little adhesive or tensile strength was required. The X259 motors, however, did contain large inaccessible areas of CBS which required an adhesive repair and access through the case wall.

The design of the X259 motor is somewhat different than the X248. Figure 68 shows the basic X259 motor which is a powder-embedded case-bonded unit containing CYI propellant. The fiberglass case (ECG-140-801 glass and Epon 826/Cl resin) is protected by an SBR rubber insulator in both the forward and aft ends which are exposed to burning propellant and hot moving gases during firing. The case bond is formed as follows:

(1) The inside of the insulated case is coated with a barrier layer of Epirez 504/Epicure 855 epoxy resin which is then cured. (2) A second layer of resin is applied, and before this resin completely cures, casting powder granules are partially embedded, thereby providing a mechanical bond between resin and embedment granules. (3) The powder-embedded case is then filled with casting powder, and casting solvent is added. The solvent combines with both the casting powder and embedded powder, forming the propellant and creating a bond between the embedded powder and the propellant grain.

The evaluation and laboratory testing of case-bond repair materials resulted in the selection of a resin mixture consisting of Epon epoxies 871/815/946B in the ratio 90:10:13 parts by weight.

During this material evaluation, the X259 case-bond repair effort was redirected toward X248 application for two reasons: (1) It was decided to emphasize X248 fiberglass repair work so all X259 motors were deleted from the program. (2) After X248 motor NPP-424 had fiberglass defects inflicted and repaired, X-rays of the repairs disclosed a large separation in the cylindrical section, which would definitely result in failure if the motor were fired. These events resulted in the case bond repair efforts of this program being directed towards developing a repair for X248 motors, specifically for motor NPP-424. The work done for this motor is discussed separately in a later section (IV.C.3.b.).

2. Acceptable Case Bond Separation

Case bond separations require rather complex analysis to determine what effect, if any, they will have on the performance of the rocket motor. Each defect must be analyzed individually, considering such factors as size, location and type of separation; type and magnitude of loads to be borne by the defect; and the time and manner of its exposure to the burning flame front.

Radiographic inspection results, tabulated in Table 1 and shown graphically for each motor in Appendix A, showed that all available X248 motors had case bond separation (CBS) in the forward dome area to various degrees. Five had CBS in the cylindrical section and six had small areas of CBS and/or porous propellant near the case-bond line in the aft dome. Assuming the motors burned as designed, i.e., that bonds in other areas did not fail, separations located forward of the insulator would not be exposed to the advancing flame front until motor tail-off. Therefore, it was believed that motors containing CBS defects in the forward end of the repair motor would perform satisfactorily during static firing without repair.

Two X248 motors, S/N NPP-400 and NPP-446, were used to determine if CBS in the forward end propagates under simulated flight loading. These two motors were subjected to radial spin and axial acceleration loads to simulate flight loads during firing of lower stage motors. Results showed that the CBS areas did not propagate. The results from statically firing these two motors at normal pressure showed that forward dome CBS, regardless of size, is of no ballistic significance if it is located so that it will not be exposed to the advancing flame front until the tailoff period. This was confirmed by the successful firing at higher than normal pressure of other motors in the program. The results of the simulated (centrifuge and spin) flight load testing on two additional motors, S/N NPP-409 and NPP-447, confirmed that existing CBS in the forward domes of X248 motors does not propagate under simulated flight loading.. Thus, it was concluded that the remaining X248 motors could be used as fiberglass defect and repair vehicles without repairing CBS in the forward dome areas.

The aft ends of two motors, S/N NPP-454 and NPP-453, contained (near the case bond line) minor surface propellant cracks and voids of such size and location that analysis indicated they would not compromise fiberglass repair test objectives. The largest crack was approximately 2 in. long x 0.04 in. deep and hairline in width; the largest void was 1-1/4 in. by 1/32 in. Firing results demonstrated that these defects had no detectable effect on ballistics.

A fiberglass repair in motor NPP-425 failed before a case bond separation in the cylindrical section was exposed to the flame front, precluding evaluation of this defect.

3. Demonstration of Repaired Case Bond Separation

Successful repair of minor CBS accessible to the aft port was demonstrated by four motor firings. The materials and techniques required to effect a repair of CBS requiring access through the fiberglass chamber wall were studied in attempting repair of motor NPP-424.

a. Motor Static Firings

The technique of filling separations with an obturating material (polyurethane) by means of a hypodermic syringe inserted from a port area was utilized to repair four motors having minor aft dome CBS. Analysis had indicated that these defects, if not repaired, would affect the ballistic performance of the motors. Static firing results demonstrated that these repaired defects had no detectable effect on ballistic performance.

b. Repair of Rocket Motor NPP-424

This motor was utilized to study the repair of case bond separations known to be critical, but inaccessible to repair by conventional means (hypodermic syringe) from a port area.

Supporting laboratory testing resulted in the selection and qualification for use on X248 motors of a repair adhesive consisting of Epon 871/815/946B in the ratio 90:10:13 parts by weight. The repair technique is to pump the selected resin mixture through holes drilled in the fiberglass case into the separation. Proper orientation of the motor and location of the holes would permit resin to flow into the bottom of the separation, then upward and outward, expelling air from bleed holes at the edges and top of the separation. Following cure of the CBS repair adhesive, the holes in the fiberglass chamber would be repaired using a glass cloth patch and the technique demonstrated in the fiberglass repair program.

The CBS repair technique was demonstrated only to the point of drilling holes through the fiberglass chamber into the separation. The resin did not flow into the separation because the separation tended to close after the holes were drilled through the chamber. It was demonstrated that conditioning the motor to 40°F opened the separation. Repair of the separation at 40°F is believed feasible. Because of program funding and time limitations, work on this motor was stopped before it could be demonstrated that the separation could be completely filled with repair adhesive and an adequate bond effected.

The radiographic inspection results on this motor confirmed known inadequacies of this inspection technique. The cylindrical section defect was not detected in the original inspection because 100% coverage is not practical, and no X-rays were taken in the area of the defect. X-rays taken after the separation closed did not identify the condition where two surfaces were in contact but not bonded. The limitations of the radiographic inspection technique do present some problems in detecting, evaluating and verifying satisfactory repair in defects of this type.

SECTION IV

EXPERIMENTAL

A. X248 DESCRIPTION AND ANALYSIS

1. Description

The X248 rocket motor and its propellant configuration used for the static tests of this program are depicted in Figure 1. The fiberglass chamber is fabricated with Owens Corning ECG 140 glass rovings (12 ends/strand, 801 finish) and Shell 828 resin with Shell D catalyst. Both domes of the motor are spherical. Typical pressure-time traces for the X248 are shown in Figure 2.

The static test portion of the program utilized three models of the X248 chamber. The basic difference between the models is in the winding geometry and winding fabricators.

The A5 model is wound with eight strands; the winding direction is changed after each layer according to the following winding sequence:

29° helical
29° helical
90°
45° helical which ends at the mid-domes
60° helical which ends in the doublers
90°

The A6 and A10 models are wound with ten strands; the winding direction is changed after each layer according to the following winding sequence:

29° helical
29° helical
90°
45° helical ending at the mid-domes
90°
60° helical ending at the mid-domes
90°

The major difference between the A6 and A10 models is that the A6 chambers were wound by Black, Sivalls, and Bryson and the A10 was wound by Hercules at Rocky Hill, New Jersey.

The calculation of the thickness of the cylindrical section of the A5, A6 and A10 models is as follows:

Using the parameters

A_{end} = 2.31416×10^{-5} in.^{2}

A_{strand} = 27.76992×10^{-5} in.^{2}

A5 = 115 ends/inch/band

A6 and A10 = 144 ends/inch/band

The thickness of the cylindrical wall is based on 0.012 in./layer of helicals and 0.010 in./layer of 90°.

A5

$$2\left(\frac{115}{144}\right) @ 29° = 1.6 \text{ layers}$$

$$2\left(\frac{115}{144}\right) @ 90° = 1.6 \text{ layers}$$

$$1\left(\frac{115}{144}\right) @ 45° = 0.8 \text{ layers}$$

$$1\left(\frac{115}{144}\right) @ 60° = 0.8 \text{ layers}$$

1.6 (0.012) = 0.0192 in.

1.6 (0.010) = 0.0160 in.

0.8 (0.012) = 0.0095 in.

0.8 (0.012) = 0.0095 in.

0.0544 in.

t_{A5} = 0.054 in.

A6 and A10

$$2\left(\frac{144}{144}\right) @ 29° = 2.0 \text{ layers}$$

$$3\left(\frac{144}{144}\right) @ 90° = 3.0 \text{ layers}$$

$$1\left(\frac{144}{144}\right) @ 45° = 1.0 \text{ layers}$$

$$1\left(\frac{144}{144}\right) @ 60° = 1.0 \text{ layers}$$

2.0 (0.012) = 0.024 in.

3.0 (0.010) = 0.030 in.

1.0 (0.012) = 0.012 in.

1.0 (0.012) = 0.012 in.

0.078 in.

t_{A6} = 0.078 in.

2. Finite Element Analysis of A5 Chamber

A preliminary, finite element analysis of the X248 A5 chamber was performed to determine the stress-strain distribution within the fiberglass chamber. The purpose of this analysis was to locate the areas of highest stress. These areas would then be considered the most critical locations for defects.

The analysis indicated that the A5 dome stresses were the highest in the areas just off the doublers. The stresses in the aft dome area were approximately 50% higher than in the forward dome. In the cylindrical section, the highest axial and lowest hoop stresses were located in the areas of the doublers. This is due to the buildup of predominantly 90° layers of glass and the ending of the 60° helical layer which results in higher axial loads carried by the hoop layers. The A5 cylindrical section had fairly uniform stresses along its length with the hoop stresses being approximately two times greater than the axial stresses. This analysis did not consider the propellant because it has a minimal effect on the chamber stiffness.

3. Comparison of Strains

In the cylindrical section of the X248 A5 chamber, the calculated strains are in agreement with actual measurements. The following is a comparison of the two for a progressive pressure of 350 psia:

		Actual	Calculated
Hoop Strain	NPP-261	1.68%	
	NPP-242	1.52%	1.56%
	NPP-257	1.50%	
Axial Strain	NPP-261	0.84%	
	NPP-242	0.74%	0.70%
	NPP-257	0.75%	

Based on a maximum allowable strain of 2.0% for the fiberglass chamber, the predicted burst pressure for an A5 chamber in the cylindrical section would be approximately 465 psia. The actual measurements of strain for an A6 chamber at 350 psia are:

		Actual
Hoop Strain	NPP-475	1.13%
	NPP-454	1.05%
	NPP-425	0.92%
Axial Strain	NPP-475	0.75%
	NPP-454	0.79%
	NPP-425	0.77%

Based on a maximum allowable strain of 2.0% for the fiberglass chamber, the predicted burst pressure for an A6 or an A10 chamber would be approximately 665 psia in the cylindrical section. The hoop stresses in the cylindrical section are thus approximately one-third higher than the axial stresses.

The following membrane analysis of the three X248 models further substantiates these predicted burst pressures.

4. Membrane Analyses of X248 Chamber Cylindrical Section

a. Analysis of A5 Model

Allowable Filament (f) Stresses

$f_\varphi = 202{,}500$ psi $\qquad \varphi$ = axial

$f_\theta = 242{,}000$ psi $\qquad \theta$ = hoop

$$p\frac{R}{2} = N\,T_\varphi \sum n \cos^2 \alpha$$

where:

N = end/inch/band $\qquad P$ = pressure, psi

n = number of layers $\qquad R$ = radius, in.

$T_\varphi = f_\varphi$ x area of an end $\qquad \alpha$ = winding angle

$P = 450$ psi $\qquad R = 8.953$

$$\frac{450\ (8.953)}{2} = 230\ (2.31416 \times 10^{-5})\ f_\varphi\ [2(.8746)^2 + (.7071)^2 + (.5)^2]$$

$$f_\varphi = \frac{450\ (8.953)}{2\ (230)\ (2.31416 \times 10^{-5})\ (2.2798)}$$

$f_\varphi = 166{,}000$ psi

$$\text{Margin of Safety} = \frac{202{,}500}{166{,}000} - 1 = \boxed{+0.28} \quad \text{In Axial}$$

$$pR = N\,T_\theta \sum n \sin^2 \alpha$$

$$450\ (8.953) = 230\ (2.31416 \times 10^{-5})\ [2\ f_\theta + \{\ 2\ (.4848)^2 + (.7071)^2 + (.866)^2\}\ f_\varphi]$$

$$4025 = 5.3226 \times 10^{-3}\ [2\ f_\theta + 1.7201\ f_\varphi]$$

$$f_\theta = \frac{\dfrac{4025}{5.3226 \times 10^{-3}} - 1.7201\ (166{,}000)}{2}$$

$$f_\theta = \frac{756{,}000 - 285{,}500}{2}$$

$$f_\theta = 235{,}250 \text{ psi}$$

$$\text{Margin of Safety} = \frac{242{,}000}{235{,}250} - 1 = \boxed{+\ 0.03} \quad \text{In Hoop}$$

b. Analysis of A6 and A10 Models

$$P\frac{R}{2} = N\ T\varphi \sum n \cos^2 \alpha$$

$$P = 650 \text{ psi}, \ R = 8.971$$

$$\frac{650\ (8.971)}{2} = 288\ (2.31416 \times 10^{-5})\ f_\varphi\ [2(.8746)^2 + (.7071)^2 + (.5)^2]$$

$$f_\varphi = \frac{650\ (8.971)}{2(288)\ (2.31416 \times 10^{-5})\ (2.2798)}$$

$$f_\varphi = 191{,}500 \text{ psi}$$

$$\text{Margin of Safety} = \frac{202{,}500}{191{,}500} - 1 = \boxed{+\ 0.06} \quad \text{In Axial}$$

$$PR = N\ T\theta \sum n \sin^2 \alpha$$

$$650\ (8.971) = 288\ (2.31416 \times 10^{-5})\ [3\ f_\theta + \{2(.4848)^2 + (.7071)^2 + (.866)^2\} f_\varphi]$$

$$f_\theta = \frac{\dfrac{650\ (8.971)}{288\ (2.31416 \times 10^{-5})} - 1.7201\ f_\varphi}{3}$$

$$f_\theta = \frac{875{,}000 - 329{,}500}{3}$$

$$f_\theta = 181{,}500 \text{ psi}$$

$$\text{Margin of Safety} = \frac{242{,}000}{181{,}500} - 1 = \boxed{+\ 0.33} \quad \text{In Hoop}$$

B. FIBERGLASS DEFECTS

1. Material Evaluation

The development of a repair technique requires the evaluation of candidate materials. Besides propellant compatibility, a limitation placed on the repair materials was that they must be applicable to field type repairs. This limitation indicated that such factors as room temperature cure and ease of application were of prime importance. Other factors to consider were weight, size, tensile strength and shear strength of the patch.

The initial repair of an X248 chamber (NPP-401) was attempted with Owens Corning S/81-901 glass cloth and an Epirez/Epicure resin system. With the motor in a horizontal position, the resin flowed down and around the Spiralloy case. To control the resin flow, a thixotropic additive was needed. Simple laboratory tests showed that 3% Cab-O-Sil was more effective in preventing run-off than Bentone 27. However, samples of glass cloth impregnated with Epirez/Epicure containing Cab-O-Sil did not cure properly at 70°F/50 ± 5% relative humidity. They remain tacky for a month. Under arid conditions (in a desiccator) the resin cure was normal. It was concluded that moisture has an adverse effect on the cure of the Epirez/ Epicure system. Therefore, other resin systems were considered.

Shear tests were made on Epon 946, Epon 826/Shell Curing Agent D, and Epirez/Epicure/Cab-O-Sil, using one-inch strips of flat Spiralloy mat. Two such strips of mat were overlapped one inch at the ends and bonded with a resin. After cure, they were pulled in tension at a strain rate of 0.05 inch per minute. Tensile shear values are reported in Table 16. Although the tensile data for Epon 946 was 8.5% lower than that for Epirez/ Epicure/Cab-O-Sil, the average value of about 1000 psi for Epon 946 was considered adequate shear strength for the bond between case and patch.

Besides possessing adequate shear strength, Epon 946 was an ambient cure system unaffected by humidity, with excellent thixotropic and elongation (62%) properties, and known compatibility with propellant and casting solvent. Therefore, Epon 946 was chosen for patching defects in fiberglass.

The shear strength of the bond of Epon 946 to the X248 fiberglass was determined by utilizing a double-lap shear test. The shear test setup is shown in Figure 4. These specimens were tested at strain rates of 3 in./min/in. and 300 in./min/in. These rates approximate the ignition and progressive loading rates that the motor encounters during static testing. The results of these shear tests are presented in Tables 5 and 6.

The average shear stresses for the two rates were 1632 and 1595 psi, respectively.

Owens-Corning S/81-901 finish fiberglass cloth was the other material chosen for the patch. The cloth and Epon 946 resin were tested in a series of tensile tests for 1-, 2-, 3-, and 4-ply patches. A short Type II JANAF dogbone was used to evaluate the cloth combinations at strain rates of 3 in./min/in. and 300 in./min/in. The results of these tests are shown in Tables 3 and 4. The decrease in tensile modulus with increasing number of plies is due primarily to the greater resin content in samples of multiple number of plies. This higher resin content permits the specimens to deflect more and thus reduce the modulus. The most critical condition occurs during the lower loading rate as indicated by these tables. A plot of the load-carrying capabilities versus number of plies is shown in Figure 3. These tests indicated that the combination of S/81-901 glass cloth and Epon 946 could be used to repair defects.

The development of a field-type repair technique would require ambient storage conditions for the repair materials. However, S/81-901 glass cloth requires refrigeration. During the program, S/81-904 glass cloth became available from Owens-Corning. The 904 epoxy compatible finish does not require refrigeration. Laboratory tests were conducted to compare the relative shear values of the two glass cloths.

Tensile-shear specimens, known as three plate shear, were made by bonding two plies of cloth to Spiralloy mat (lightly sanded), cured for seven days at ambient conditions, and pulled in tension at a crosshead speed of 0.2 in. per minute. The three plate shear specimens were made as follows.

One-inch squares of Spiralloy mat were bonded to both faces of an aluminum bar (1 in. wide x 7.5 in. long) with Armstrong C7/Activator W adhesive. After an oven cure at 200°F for four hours, double plies of glass cloth were bonded to the Spiralloy and to outside aluminum bars with fresh Epon 946 (Figure 69). The two plies of glass cloth were previously bonded together with Epon 946 and B-staged for 24 hours at ambient conditions before cutting to size and assembling. The total assembly with three aluminum bars was allowed to cure at ambient conditions for seven days before testing. Five such specimens were made for each type of glass cloth.

The results of these tests are listed in Table 17. All specimens failed at the Spiralloy/resin interface. Reproducibility was poor in the S/81-904 samples, as indicated by the wide range between minimum and maximum shear values. However, because the averages were very nearly the same for both cloths, it was concluded that the S/81-904 cloth could be substituted safely for the S/81-901, but no motor firings on cases repaired with S/81-904 have been made.

At this point, there appeared to be a contradictory situation regarding the use of nonrefrigerated cloth with a refrigerated, B-staged resin border. It was believed that if the border resin were allowed to B-stage too far or become cured, it would not bond well to fresh resin during the patching operation. Accordingly, a laboratory test was performed to clarify this supposition.

Three-plate lap shear specimens (Figure 69) were made in triplicate for three varieties of resin-to-resin bonding. In one set, Epon 946 was coated on the faces of the two outer aluminum bars, allowed to B-stage at ambient temperature for 16 hours, and then baked at 300°F for three hours. Fresh Epon 946 was then applied to the cured surfaces and pressed against the center aluminum bar. Fine wires were laid side by side in the fresh resin to guarantee constant resin thickness at the bond line. A second set was treated the same way, except that the glossy surface of the cured resin was sanded before application of the fresh resin. In a third set, the Epon 946 was not oven cured. Fresh resin was applied directly to the 16-hour staged resin and the assembly completed. All assembled specimens were allowed a 7-day ambient cure before testing. Specimens were pulled at a crosshead speed of 0.2 in. per minute at 77°F.

The results (Table 18) indicate a slightly better average shear strength for the cured than for the B-staged Epon 946, and a significant increase in shear for the sanded samples. The latter showed a 35% increase in adhesion over the unsanded, cured samples and a 45% increase over the B-staged samples. It was concluded that the resin border on glass patches need not be protected from curing and, consequently, refrigeration was unnecessary. However, this result had been obtained late in the program, and all X248 repairs utilized cloth with refrigerated B-staged resin borders.

2. Preliminary Fiberglass Repair Study

This section covers work done at the start of Phase II to determine whether the laminated patch concept had a significant potential as a repair system for damaged motor cases. Two types of bottles were used for this work.

a. 6-Inch Bottles

Six 6-in.-diameter bottles remaining from another program were used to determine the feasibility of candidate repair materials and a repair technique. These bottles were wound with single-end S-994 glass with an Epirez 504, Epicure 855 resin system. The winding geometry consisted of 3 layers of 11° helical windings and 8 layers of 90° hoop windings wound sequentially on a Styrofoam mandrel. The average burst pressure for these bottles, determined in the other program, was 2711 psi. One bottle was burst as a control for this program to see if aging had affected the strength. It burst at 2300 psi, 15% lower than the previously determined average.

The other five 6-in.-diameter bottles were defected 1.75 in. from the tangent line created by the level windings at the domes. The cuts were carved in a plane normal to the bottle axis with an Exacto knife. Each cut was 0.75 in. long x 0.50 in. wide x 0.017 in. deep. The depth was calculated to yield about 70% strength retention of the burst pressure. The defects were placed in the domes because the bottles had been designed to fail in the domes.

Two of the grooved bottles were burst with no attempt at repair, in order to assess the strength loss due to the defect. One burst at 1350 psi, a loss of 41% based on the control, and the other burst at 840 psi, a loss of 62%.

Repairs were made to the remaining two bottles with one layer of #181 glass cloth (Volan A finish), size 2.25 x 1.50 inches. First, the Spiralloy was sanded in a restricted area around the grooves and then the grooves were filled with a putty made by mixing 1.5 wt. % of S994 chopped glass fibers (1/8 in. segments) with Armstrong C7 adhesive. Next, the sanded areas were coated with Armstrong C7/Activator W (60-40 pbw) without chopped fibers, and the glass cloth patches applied to the resin. The patches were pressed firmly in position and manipulated with the fingers to expel entrapped air. Finally, the entire cloth patch was given a top coating of resin which was allowed to cure at ambient conditions for 48 hours.

The burst pressure of one of the repaired bottles (Table 19) was 31% lower than the control, suggesting a reinstatement of at least 10% of the burst strength. The other repaired bottle burst at the same level as one of the unrepaired, defected bottles, at 1350 psi. The patches in both instances failed in tension. Since the bottle burst capabilities were improved only slightly by the repair, it was obvious that more than one ply was required to repair such defects. The addition of the chopped glass fibers was considered to be of no help in restoring the bottle strength. Therefore, it was not used in future investigations.

b. Picatinny Bottles

Eight bottles, 3 in. in diameter x 18 in. long, were filament wound with E-801 glass roving and Epon 828/Shell curing Agent D (18 phr) matrix resin. The geometry consisted of 2 layers of 54° helical windings and 3 layers of level (90°) windings to make the bottles sensitive to failure in the domes. They were B-staged at 150-200°F with infrared lamps until no longer tacky and cured at 250°F for 2 hours in an oven. The bottles were wound in groups of four, and each group developed different appearances. The Group A bottles were light amber with dark brown streaks running through them. The Group B bottles were dark green. It was believed that Group B had fewer voids than Group A, but void content was not determined. Each group would be represented by one control bottle and three for defecting and/or defecting and repair.

In Group A, one bottle was to be hydroburst as a control and three bottles were to be defected with 0.25 in. long x 0.05 in. wide x 0.01 in. deep defects. Then one bottle would be repaired. In Group B, one bottle was to be hydroburst as a control and three bottles were to be defected with 0.25 in. long x 0.05 in. wide x 0.01 in. deep defects. Then all three bottles would be repaired.

Based on the observation from the 6-inch bottles that a single ply patch failed in tension, this group of bottles was patched with three plies. The first two pieces of glass cloth were aligned such that they paralleled the helical windings. The third ply was placed perpendicular to the level winds. Again the grooves were filled with Armstrong C7 adhesive containing chopped glass fibers, and the patches were coated with the same resin. All patches were allowed a 48-hour ambient cure before testing. The special repair of #1-6 consisted of two plies of #181 cloth and a third ply of very heavy glass cloth. This was due to a weak site in the knuckle region of the bottle.

The bottles were tested at a pressurization rate of 50 psi/sec and the results are in Table 20.

The average of the two controls was 3900 psi. Similar bottles made with S994 glass had an average burst value of 4200 psi. The one unrepaired bottle (#1-4) burst at a very low pressure (540 psi), but all the patched bottles burst at values above 3000 psi, except the special case. It was inferred, therefore, that bottle strength was reinstated to a considerable degree by repairs with glass patches.

Bottle #1-4, which burst at 540 psi at the defect site, was otherwise intact. It was repaired with 3 plies of glass cloth, oriented as described for the others. The adhesive was changed to Epirez 504/Epicure 855 (10:7) because it wets glass cloth much better than Armstrong C7. The patch was B-staged at room temperature for 24 hours and oven cured at 210°F for 2 hours. The burst pressure of this bottle was 2125 psi, an increase of 300% over the unrepaired bottle. This was the first occasion to truly evaluate the effect of repairing a defect, because burst values were obtained before and after the repair on the same bottle.

3. Motor Tests

Fiberglass defects and repairs were investigated by statically firing sixteen X248 rocket motors. These firings provided the basis for an evaluation of fiberglass defects and repairs under actual static firing conditions on a full-scale rocket motor. Two of the motors were used to provide information concerning the strain distribution within an X248 chamber. Two motors were used to evaluate partial defects in the cylindrical section. Three motors were used to evaluate defects in the motor domes, and the final nine motors were fired with defects that completely penetrated the cylindrical section wall. The defects in these nine motors were repaired with fiberglass cloth patches.

The X248 chamber, propellant configurations and angular reference system are shown in Figure 1. Typical pressure versus time curves are shown in Figure 2. The descriptions of the sixteen X248 static firings will be presented in the order of their occurrence. All recorded data from the tests can be found in Appendix D. All the patches used to repair the chambers were X-rayed before the static firings to determine whether voids were present and if the patches were satisfactorily bonded to the fiberglass chamber.

The X-ray examination of the chambers consisted of tangential exposures of repair zones utilizing low-energy (75 KV 4 MA) beryllium window exposures in conjunction with fine grain film. Subject exposures readily resolved the individual 0.014-in.-thick plies of cloth and separation between layers. In addition, in the view projecting through the patch thickness (on the tangent) the individual cords within the 0.014-in.-thick cloth plies could be discerned.

a. X248 A5S S/N NPP-400

The main objective for this static firing was to investigate the effects of a case bond separation in the forward dome on motor performance. More specific details on the separation can be found in the propellant defects section. A secondary objective was to determine the strains in the cylindrical section of the A5 chamber. The locations of the hoop and axial strain gages on the chamber can be found in Table 21.

On July 17, 1967, the motor was statically fired after being conditioned to a temperature of 75 $\pm$ 5°F for a minimum of 120 hours. The performance was normal, and there was no evidence of abnormal propellant burning in the unrepaired separation. This motor, 58 months old at the time of firing, was the oldest X248 motor ever fired. The ignition maximum pressure was 276 psia, and the progressive maximum pressure was 255 psia. Hoop and axial strain gages were located along the cylindrical section of the motor case. Table 21 shows the locations of these gages and compares strain measurements for ignition and progressive maximum pressures. These data indicate that the propellant in the forward cylindrical section of the chamber helps to reduce the case strains during the ignition pressure rise. Plots of hoop and axial strains along the case for the progressive maximum pressure are shown in Figures 70 and 71. Because strains are lower at ignition in the forward portion of the cylindrical section, the unrepaired partial defects withstand failure during the early phase of firing. Failure of defects in the forward section should be limited to the progressive pressurization portion of motor operation. Table 22 compares strains at various locations for the same pressures at two different times. This table demonstrates the effect of propellant configuration on strain measurements during the firing.

b. X248 A6 S/N NPP-446

The main objective of this static firing was to investigate the effects of a case bond separation in the forward dome on motor performance. More specific details on the separation can be found in the propellant defects section. The secondary objective was to determine the strains in the cylindrical section of an A6 chamber. The locations of the hoop and axial strain gages on the chamber can be found in Table 23.

On July 20, 1967, the motor was statically fired after being conditioned at a temperature of 75 $\pm$ 5°F. for a minimum of 120 hours. The performance of the motor was considered to be normal. The ignition maximum pressure was 276 psia and the progressive maximum pressure was 258 psia. Table 23 not only contains the locations of the hoop and axial gages but also compares the strain measurements for the ignition and progressive maximum pressures. The data in this table indicate that the propellant in the forward cylindrical section of the chamber helps to reduce the case strains during the ignition pressure rise. Plots of the hoop and axial strains along the case for the progressive maximum pressure are shown in Figures 72 and 73.

c. X248 A5S S/N NPP-409

This motor was the first to be used to investigate the effects of defects in the cylindrical section of the chamber on the structural integrity of the motor. At this time, it was decided that only gouge-type defects should be investigated. The gouge-type defect was choosen over the bruise and abrasions type defects for the following reasons: (1) the gouge can be assessed, (2) the gouge is more easily reproduced and controlled, (3) available analytical techniques were more adaptable to analyze the gouge-type defect, and (4) the gouge would be much more critical to the structural integrity of the motor case because fibers have been completely severed and have thus lost their load-carrying capabilities.

~~Based on the data reviewed in References 1, 2, 3, and 4, the~~ following partial longitudinal defects were specified for NPP-409:

Defect No. 1 - 250 in. long x 0.10 in. wide x 0.018 in. deep, located at 0° and between 8.0 in. and 10.5 in. aft of the forward doubler.

Defect No. 2 - 250 in. long x 0.10 in. wide x 0.027 in. deep, located at 0° and between 14.5 in. and 17.0 in. aft of the forward doubler.

These defects were placed in the forward portion of the cylindrical section because of the strain data obtained from the firing of NPP-400 and NPP-446. These data indicated that the strains in the forward portion of the motor remained low during the ignition pressure rise. Thus, to avoid the expected failure at Defect No. 2 during the ignition pressure rise, the defects were placed in the forward portion of the cylindrical section.

The machining of the defects to match the specified depths was hampered by the roughness of the case surface. It was therefore necessary to run the cutting tools along the case surface until approximately one-half of the specified defect area was scratched. This then served as the initial surface of the infliction of the specified defects. For actual machining of the defects, the motor was placed on a lathe. A bar with a cutting tool was then moved back and forth over the defect area until the specified depth was reached.

After the defects had been machined in the chamber, they were evaluated. Measurements of the inflicted defects consisted of (1) X-ray, (2) depth gage, (3) photomicrographic, and (4) rubber cast and shadowgraph. A comparison of the measurement techniques indicated that the X-ray measurements tended to be inconsistent with results of the other techniques. This is because of the lack of accuracy in the X-ray measuring technique. The depth gage measurements for the two defects are shown in Table 24. This table illustrates the inability of getting a precise depth machined into the rough surface of the X248 chamber when it is compared to the specified defect depth.

Based on the data reviewed in References 1, 2, 3, and 4, the expected strength retentions for these two cylindrical defects were as follows:

Defect No. 1 - 76% of the 465 psia allowable for the X248 chamber.

Defect No. 2 - 68% of the 465 psia allowable for the X248 chamber.

Therefore, the predicted burst at Defect No. 2 should occur at approximately 316 psia. Both the Finite Element and Netting Analyses indicated that Defect No. 2 would fail at approximately 200 psia. These analyses were both conservative because they both had to assume that severed fibers were removed completely around the cylindrical section. Thus the failure estimates were conservative because of the geometrical limitations.

~~After the defecting of the motor, fifteen strain gages were~~ placed on the motor. These gage locations with respect to the chamber are shown in Figure 74.

On August 18, 1967, the motor was statically fired after being conditioned at a temperature of 75 $\pm$ 5°F for a minimum of 120 hours. The motor case failed after 12.26 seconds of burning at a pressure of 281 psia. The ignition maximum pressure was 341 psia. A visual inspection of the motor case indicated that the failure occurred at Defect No. 2. Peel-back of the severed fiberglass occurred in the immediate area of the defect. This peel-back was not limited to the outer 90° winding, but included all the cut fibers.

Strain gage data showed strains to be highest in the area immediately aft of Defect No. 2. The maximum recorded strain at this point was 1.95% at the burst pressure of 281 psia. A plot of the hoop strain versus pressure along the cylindrical section at 0° is shown in Figure 12. The gage just aft of Defect No. 2 recorded a rapid change in strain between 251 psia and 281 psia pressures, indicating the beginning of chamber failure. The strain gages located 10°, 30° and 60° away from Defect No. 2 indicated an increasing peel-back as the pressure increased. The gage at 10° indicated peel-back was occurring before the ignition maximum pressure was attained. The gage at 30° indicated that peel-back was starting to occur after 10.2 seconds of firing. At the time of burst the peel-back had gone beyond 30° and the gage at 60° had begun to indicate peel-back starting in that area. A plot of pressure versus strain for these three gages is shown in Figure 11.

d. X248 A6 S/N NPP-447

This motor was used to investigate the effects of fiberglass damage on the X248 aft dome. Two gouge-type defects were machined into the aft dome of this motor. These defects were located in the area of the highest dome stresses as indicated by the preliminary Finite Element Analysis of the rocket motor case. The defects were machined by placing the motor on a lathe and turning the motor back and forth as a cutting tool advanced. The dome surface was rough and thus required the tool to scratch one-half of the defect surface areas before the actual depth was machined. Based on References 3 and 4, the defects were specified as follows:

Defect No. 1 - 1.00 in. long x 0.10 in. wide x 0.052 in. deep, located at 0° and 2.0 in. horizontally from the aft doubler face.

Defect No. 2 - 1.00 in. long x 0.10 in. wide x 0.045 in. deep, located at 270° and 2.0 in. horizontally from the aft doubler face.

Defect No. 1 was expected to cause failure of the motor. Table 25 presents the depth gage measurements of these two defects. The X-ray measurements indicated that Defect No. 1 was 0.054 in. deep and No. 2 was 0.038 in. deep. The X-rays also indicated that approximately 0.009 in. of glass remained under Defect No. 1 and approximately 0.014 in. to 0.023 in. under Defect No. 2. The strain gage locations with respect to the motor are shown in Figure 75.

On August 18, 1967, this motor was statically fired after having been conditioned at a temperature of 75 ± 5°F for a minimum of 120 hours. The performance was considered normal. The maximum ignition pressure was 337 psia and the progressive maximum pressure was 290 psia.

A visual inspection of both defects indicated slight crazing around the edges. Defect No. 1 had its remaining fibers severed on one side of the defect. A review of the strain gage data indicated no unusually high strains in the defect area. It appears as though the rubber insulator acted much like an internal patch and helped to redistribute the stresses in the area of the defects. Figure 7 and 8 are pictures of the top and underside view of the two defects. The underside view pictures demonstrate the lack of remaining fibers in Defect No. 1 and the resin crazing in the area of the defects.

e. X248 A5S S/N NPP-401

The results of the static firing of NPP-409 indicated that a defect 2.50 in. long x 0.10 in. wide x 0.027 in. deep would cause a failure at approximately 281 psia. The test of NPP-401 was therefore designed to determine (1) if a defect that would definitely fail could be successfully repaired and (2) if a chamber could sustain a defect without causing it to fail. The following two defects were specified for this test:

Defect No. 1 - 2.50 in. long x 0.10 in. wide x 0.015 in. deep, located at 0° between 8.0 in. and 10.5 in. aft of the forward doubler.

Defect No. 2 - 2.50 in. long x 0.10 in. wide x 0.034 in. deep, located at 0° between 14.5 in. and 17.0 in. aft of the forward doubler

These defects were once again placed in the forward portion of the cylinderical section so that the possible failure would occur during the progressive portion of the pressure versus time curve. Defect No. 1 was not expected to fail at the maximum expected operating pressure of 350 psia. Defect No. 2 was expected to fail at approximately 250 psia and would, therefore, have to be repaired.

Once again the machining of the defects was hampered by the roughness of the case surfaces. It was, therefore, necessary to run the cutting tool along the case until one-half of the specified defect area was scratched. This then served as the initial surface for the specified defects. The defects were measured with (1) depth gages, (2) photomicrographs, (3) X-rays and (4) rubber casts and shadowgraphs. Data obtained by these methods proved to be inconsistent, especially the X-ray measurements. Table 26 gives the depth gage measurements of the two defects.

The expected failure of Defect No. 2 indicated that a repair would be necessary. Therefore, a three-ply, overlapping S/81-901 fiberglass cloth patch was bonded in place with an Epirez 504/Epicure 855 resin system. However, because of its low viscosity, the resin tended to flow down the sides of the motor, reducing the amount of resin remaining in the patch. After room temperature cure of 7 days, the strain gages were placed on the motor. The locations of the 23 gages with respect to the motor case are shown in Figure 76.

On September 26, 1967, the motor was statically fired after being conditioned at a temperature of 75 $\pm$ 5°F for a minimum of 120 hours. The firing resulted in a chamber rupture at 0.049 second after first indication of pressure at a point remote from the defects and repair. Chamber pressure at the time of rupture was 322 psia. Postfiring analysis involving review of field history revealed that the motor had been dropped at NOS/Indian Head. Chamber rupture, just forward of the aft doubler, probably resulted from a combination of structural damage and case bond failure in the aft end which was not disclosed during X-ray examination. It was also concluded that the malfunction was not associated with either of the inflicted defects or the forward dome separation. The firing was, therefore, declared a "no-test" and was repeated.

Strain gage data from this firing were quite limited due to the short burning time. However, nothing unusual appeared in the strain readings near the defects. Figure 77 is a picture of the failure area.

f. X248 A6 S/N NPP-455

The results of the static firing of NPP-447 indicated that all future X248 dome work should be done on the forward dome to avoid the internal insulator. The defects for NPP-455 were located in the area of highest stress as was indicated by the preliminary Finite Element Analysis. The defects were specified as follows:

Defect No. 1 - 2.50 in. long x 0.25 in. wide x 0.050 in. deep, located at 0°, 2.125 in. horizontally forward from the forward doubler face.

Defect No. 2 - 2.50 in. long x 0.25 in. wide x 0.040 in. deep, located at 240°, 2.125 in. horizontally forward from the forward doubler face.

Figure 78 shows the locations of these defects. The dome thickness in this location is approximately 0.070 in. This test was designed to obtain a dome failure and the defects were therefore unrepaired. The locations of the 16 strain gages with respect to the motor are shown in Figure 78.

On September 27, 1967, the motor was statically fired after being conditioned at a temperature of 75 ± 5°F for a minimum of 120 hours. The expected failure of Defect No. 1 did not occur. The ignition maximum pressure was 427 psia and the progressive maximum pressure was 393 psia.

A visual inspection of the defects indicated resin crazing in the area of Defect No. 1. Pictures of these two defects are shown in Figure 9. The underside view of Defect No. 1 clearly shows the resin crazing around the defect.

A review of the strain gages in the area of the defect indicated no unusually high strains. However, since the strain gages could not be placed close to the edges of the defects, they would not detect any increase in strain at the edges of the defect.

g. X248 A5D S/N NPP-257

This motor was a repeat of the test of NPP-401. The defects were of the same size and depths. The only difference between the two was the use of Epon 946 as the bonding agent in the patch of NPP-257 because Epon 946 had a higher viscosity than Epirez/Epicure. This helped to reduce the amount of resin that drained out of the repair patch and down the sides of the motor case.

The defects were machined, and the depth gage measurements are shown in Table 27. Defect No. 2 was repaired and allowed to cure for 7 days. The 23 strain gages were mounted as shown in Figure 76.

Static testing was performed on October 26, 1967, after the motor had been conditioned a minimum of 120 hours at 75 ± 5°F. The motor functioned properly, and postfiring inspection revealed that the patch remained intact. The unrepaired fiberglass defect resulted in the delamination of a 2.5-in.-wide band of fiberglass in both directions, circumferentially, from the defect. This delamination was approximately 12 in. long on one side of the defect and 6 in. on the other. Nevertheless, the chamber retained its integrity as a pressure vessel. The ignition maximum pressure was 421 psia and the progressive maximum pressure was 380 psia.

~~Figure 79 is a postfiring picture of the two defects.~~ ~~Figure~~ 13 is a close-up view of Defect No. 1 to demonstrate the peel-back of the severed fibers. Defect No. 2 was removed from the chamber and then sectioned. Figures 19, 20, and 21 are photomicrographs of a cross-section of Defect No. 2. A large amount of resin crazing in the remaining uncut filaments is apparent on the actual cross-section but does not show up in the pictures. This crazing indicates that the remaining chamber wall was loaded beyond its capabilities, causing the resin to craze. Because the remaining uncut fibers were 29° helicals, most of the hoop load was carried by the patch itself. The actual patch thickness was measured to be 0.071 in.

A plot of the hoop strains along the case for various pressures is shown in Figure 22. The maximum strain of 2.02% at 380 psia was found at the center of the repaired defect.

h. X248 A6 S/N NPP-454

The lack of a failure at Defect No. 1 in the forward dome of NPP-455 necessitated another partial defect test on the forward dome. This test was designed to determine (1) if a forward dome failure could be obtained, and (2) if holes could be drilled completely through the forward dome and then repaired successfully. Also, more information was needed concerning the strain distribution in the cylindrical section of an A6 chamber. The following defects were machined into the forward dome:

Defect No. 1 - 3.0 in. long x 0.50 in. wide x 0.050 in. deep, located at 0°, 2.125 in. horizontally forward from the doubler face.

Defect Nos. 2 and 3 - 0.375 in. diameter holes completely through the domes located at 90° and 270°, 2.125 in. horizontally forward from the doubler face.

Defects Nos. 2 and 3 were repaired with three-ply S/81-901 fiberglass cloth patches and using an Epon 946 resin system. The repair of these holes was of interest since such holes would be necessary for execution of any CBS repairs in the forward domes. The locations of 39 strain gages with respect to the motor case are shown in Figures 80 and 81.

On November 3, 1967, the motor was statically fired after being conditioned at 75 ± 5°F for a minimum of 120 hours. The motor performed normally and there was no evidence of failure at the defects. The ignition maximum pressure was 433 psia and the progressive maximum was 376 psia.

A review of the strain gage data indicated a high strain reading inside Defect No. 1. At a pressure of 376 psia, the hoop strain was

1.49%, indicating that the desired failure had almost been attained. About 6 seconds later in the firing the maximum strain of 1.57% was attained even though the pressure had decreased slightly. This would tend to indicate some failure occurring in the remaining unsevered fibers. Other gages on the forward dome indicated that the two holes were repaired successfully. Figure 10 is a postfiring picture of two of the defects. Figures 82 and 83 are pictures of Defect No. 1. A large amount of resin crazing is visible in the remaining undefected material on the underside view. A comparison of the cylindrical section strains at similar pressures during the static firing is shown in Table 28. The table demonstrates that in all cases the strains are higher for pressures during the regressive portion of the pressure versus time curve. However, the magnitude of these differences is in most cases not very significant. These differences, especially in the forward portion of the motor, are probably due to the loss of support from the burned propellant.

i. X248 A5S S/N NPP-261

After the firing of NPP-257, it was decided that future cylindrical section defects would completely penetrate the chamber. The reasons for this decision are as follows: (1) the partial gouges cannot be accurately assessed as to either their depth or the condition of remaining uncut fibers, (2) reproducibility of defects is limited by surface variations, (3) any machining problems would be eliminated, (4) a defect completely through the case would be easier to analyze, and (5) if a defect which is completely through a chamber can be repaired, then it can be conservatively assumed that the same size partial defect can be repaired with the same repair patch.

The defects inflicted in the cylindrical section of the case were as follows:

Defect No. 1 - 2.50 in. long x 0.10 in. wide x 100% deep, located at 0°, 8.0 in. and 10.5 in. aft of the forward doubler.

Defect No. 2 - 2.50 in. long x 0.10 in. wide x 100% deep, located at 0°, 16.5 in. and 19.0 in. aft of the forward doublers.

The two defects were repaired with a four-ply S/81-901 finish glass cloth patch and Epon 946 resin system. The locations of the 20 strain gages with respect to the chamber are shown in Figure 84.

On January 2, 1968, the motor was statically fired after having been conditioned at 75 ± 5°F. for a minimum of 120 hours. The motor was successfully fired. The ignition maximum pressure was 402 psia and the maximum progressive pressure was 356 psia. A visual inspection of the defected areas indicated a successful repair of the defects.

~~A plot of the strain versus pressure at 0° along the cylindrical~~ section is shown in Figure 23. An extrapolated curve of expected normal strains along the case for 355 psia is also included in the figure. The maximum strain in the center of the patches was 1.02% at this pressure. The strains over the first repaired defect, which was located nearer the forward end, lag the strains over the second repaired defect because of the support provided by the propellant in the forward section of the motor. As the propellant was consumed, the difference between the strains at the two locations decreased.

Figures 24, 25, and 26 are photomicrographs of the defect area. These pictures indicate no resin crazing of the chamber nor any bond failure. A postfiring measurement of the repair patch indicates that it was 0.126-in. thick.

j. X248 A5S S/N NPP-242

The successful firing of NPP-261 indicated that longer defects could possibly be repaired with a four-ply patch. Increasing the defect length and successfully repairing it would also give an idea of the effects of defect changes on the patch strain distribution.

The following defects were machined into the motor case:

Defect No. 1 - 7.50 in. long x 0.10 in. wide x 100% deep, located at 0°, 14.5 in. and 22.0 in. aft of the forward doubler.

Defect Nos. 2 and 3 - 0.375-in.-diameter holes completely through the dome located at 90° and 270° and 2.125 in. forward horizontally from the doubler face.

Defect Nos. 2 and 3 are additional validation of the repair of holes in the forward dome. Defect No. 1 was repaired with a four-ply glass cloth patch and Defect Nos. 2 and 3 were repaired with three-ply glass cloth patches. The locations of the 25 strain gages on the motor are shown in Figure 85. In addition to the three deliberately inflicted defects mentioned above, this motor also possessed one "natural" defect, a radially oriented gouge, 3.25 in. long x 0.05 in. wide x 0.02 in. deep (estimated), in the forward dome. This defect was not repaired.

The motor was statically fired on January 31, 1968, after being conditioned to 75 ± 5°F for a minimum of 120 hours. Performance was satisfactory for 13.5 seconds, at which time the chamber ruptured in the aft dome at a pressure of 390 psia. The test was considered a success since one of the prime objectives of this program was to develop a repair technique that would withstand 350 psia. Hydrotest pressure for empty X248 chambers is 380 psig (395 psia). Furthermore, this chamber was produced early in the X248 program at a time when Black, Sivalls and Bryson (chamber fabricators) were having a high rate of chamber failures during hydrotesting. Examination of the motor after firing led to the conclusion that the rupture was not associated with the defects or their repairs.

A plot of the hoop strain versus pressure along the cylindrical section is shown in Figure 27. The maximum patch strain at 390 psia was 1.83% and was located at the midpoint of the defect. Figure 28 is a postfiring picture of the aft end failure.

k. X248 A6 S/N NPP-475

The successful repair of the 7.5-in.-long defect in motor NPP-242 indicated the optimum number of plies required for a repair might be three. Therefore, the following defect was inflicted in the cylindrical section and was repaired with a three-ply fiberglass cloth patch.

Defect No. 1 - 7.50 in. long x 0.10 in. wide x 100% deep located at 0°, 14.5 in. and 22.0 in. aft of the forward doubler.

The results of this firing were to be compared to the results of S/N NPP-242 to determine the optimum number of plies required for a defect that completely penetrates the cylindrical section of a motor case. The location of the 31 strain gages with respect to the motor are shown in Figure 86.

The motor was statically fired on February 23, 1968, after being conditioned at 75°F ± 5°F for a minimum of 120 hours. The motor performance was normal until the time of failure. The motor failed after 26.5 seconds of burning at a pressure of 340 psia. The ignition maximum pressure was 412 psia, and the progressive maximum pressure was 351 psia. The maximum hoop strain on the patch occurred at the center of the defect and was equal to 2.68% at the progressive maximum pressure. A plot of the hoop strain versus pressure for the strain gages over the defect is shown in Figure 31.

The failure of this motor was due to a thin bond layer between the first cloth ply and the chamber wall. This thin bond layer was attributed to the method employed in applying the cloth plies. A measurement of the patch indicated a thickness of 0.063 in. This is about 0.008 in. thinner than the three-ply patch on NPP-257. This finding, plus the fact that a ply of cloth is approximately 0.010 in. thick, indicates that NPP-475 had approximately 17.5% less resin in the patch.

Figure 33 is a sequence of six motion picture frames of the repaired defect. These frames are at intervals of 1/1000 sec. These pictures clearly demonstrate the failure and support the shear failure theory. Frame 2 shows the first signs of failure with the tearing of the patch at the end of the second ply. This failure at the end of the second ply indicated that a shear failure had occurred. Because the load could not be carried by the last ply, it tore at its weakest point. Figure 32A and B are top and underside postfiring pictures of the repair patch. In the underside view, the areas of the thin bond layer are shown. As shown by Figure 87, the patch was still partially bonded to the case on the one side of the defect.

1. X248 A6 S/N NPP-425

The results obtained from the 250 in. long and 7.5 in. long defects in the preceding motors indicated that the load carried by the patch was a maximum at the center. It is believed that for a certain length of defect the load will be carried more evenly along the patch. The test of NPP-425 was thus an attempt to simulate this situation which we refer to as infinite length defect. The motor had the following defect machined into the cylindrical section and was located directly over the radial slot.

Defect No. 1 - 15.0 in. long x 0.10 in. wide x 100% deep, located at 52½°, 9.5 in. to 24.5 in. aft of the forward doubler.

This defect would also help to determine both the maximum length defect that is repairable and the strain distribution along the length of the longer defect. The defect was repaired with a four-ply glass cloth patch and Epon 946 resin system. The locations of the 33 strain gages with respect to the chamber are shown in Figure 88.

The motor was statically fired March 22, 1968, after being exposed to 75 $\pm$ 5°F for a minimum of 120 hours. The motor failed at the patch after 12.5 seconds of burning. The pressure at failure was 351 psia. The maximum ignition pressure was 435 psia. The patch failure was a shear failure between the first ply and the fiberglass chamber rather than a tensile failure of the patch. The pressure-time curve exhibited no anomalies up to the time of patch failure. The water quench system was unable to extinguish the propellant completely until it had burned in the top part of the unit.

A measurement of the patch indicated a thickness of 0.088 in. This is about 0.038 in. thinner than the four-ply repair on NPP-261, indicating a lack of resin in the repair patch. Review of the motion picture frames before the failure indicates that the patch failure occurred much the same as the failure of NPP-475. Figures 36A and 36B are pictures of the patch. The tear of the patch is not located directly over the defect. The lack of resin is apparent in the underside view of the patch. Figures 89 and 90 are postfiring pictures of the motor.

~~Most of the strain gages malfunctioned during motor ignition.~~ The fragmentary strain data obtained indicate that the maximum strain at the defect center was 1.86% at 351 psia. This strain was much lower than the strain on NPP-475 at burst. A plot of the strains vs pressure along the defect is shown in Figure 91. This figure demonstrates the possibility of shear failure initiating under the forward end of the patch. The increase in strain on the outer ply over a similar gage located in the aft end of the patch points out this possibility.

m. X248 A6 S/N NPP-445

In the cylindrical section of the X248 chamber, the hoop loading is twice as high as the axial loading. Therefore longitudinal defects are more critical to the chamber's integrity. The test of NPP-445 served as a demonstration of the ability to repair circumferential gouges. The following two defects were inflicted in the cylindrical section of the motor:

Defect No. 1 - 7.5 in. long x 0.1 in. wide x 100% deep, located 22.0 in. aft of the doubler and centered at 90°.

Defect No. 2 - 7.5 in. long x 0.1 in. wide x 100% deep, located 22.0 in. aft of the doubler and centered at 270°.

Since these circumferential defects were not as critical as similar longitudinal defects, Defect No. 1 had a four-ply patch and Defect No. 2 had a three-ply patch. It was felt that the three-ply patch was adequate to repair the defect. Comparisons of strain magnitudes with 3- and 4-ply patches and comparisons of strain patterns and magnitudes with typical repaired longitudinal defects were sought in this test. The locations of the 42 strain gages with respect to the motor are shown in Figures 92 and 93.

The motor was statically fired April 17, 1968, after being exposed to 75 $\pm$ 5°F for a minimum of 120 hours. The firing was successful, and test objectives were met with a full-duration (34.6 seconds) motor burn time. Maximum sustained pressure was 369 psia, which is 19 psia above the test objective of 350 psia. No indication of failure of the repaired defects was evident upon visual examination after firing. The ignition maximum pressure was 418 psia.

Figure 46 is a comparison of the axial strains in the two defects at maximum pressure. As expected, the strains on the three-ply repair are higher than on the four-ply repair, but the three-ply patch provides an adequate repair for a 7.5-in.-long circumferential defect. The magnitudes of the strains are much lower than the magnitudes found on longitudinal repairs because of lower axial loads. This successful firing demonstrated the capability of repairing a 7.5-in.-long, circumferentially oriented gouge, as described above, to withstand the patch design criteria of 350 psia firing pressure.

n. ~~X248 A6 S/N NPP-453~~

The next type of defect to be inflicted in a chamber was one in which longitudinal and circumferential defects were combined. These combination defects were in the form of right angles and are described as follows:

Defect No. 1 - A longitudinal leg 7.5 in. long x 0.10 in. wide x 100% deep - located at 57½° between 14.5 in. and 22.0 in. aft of the forward doubler face. A circumferential leg 7.5 in. long x 0.10 in. wide x 100% deep - 21.95 in. aft of the forward doubler and between 57½° and 105½°.

Defect No. 2 - A longitudinal leg 5.3 in. long x 0.10 in. wide x 100% deep - located at 237½° between 16.7 in. and 22.0 in. aft of the forward doubler face. A circumferential leg 5.3 in. long x 0.10 in. wide x 100% deep - located at 21.95 in. aft of the forward doubler and between 237½° and 271½°. (This defect was sized to give a 7.5-in.-long diagonal.)

A picture of Defect No. 1 is shown in Figure 94. Figure 95 illustrates the defects and their locations with respect to the chamber. Both defects were repaired utilizing four-ply glass patches. X-rays of the repairs of these two defects indicated numerous voids in both of the patches but the Defect No. 2 repair patch has many more than Defect No. 1. The voids, located mainly between the various fiberglass cloth plies, resulted when the patching procedure was changed in an attempt to eliminate the shear failures between the patch and the chamber wall experienced on NPP-475 and NPP-425. The change (applying resin to the glass cloth plies before putting them on the chamber rather than applying the cloth patches dry and bleeding the resin through) was intended to increase the resin thickness between the chamber and the first ply of the patch. The resin thickness was increased, but voids occurred between plies of the patch, thereby decreasing the tensile strength of the patch as a result of abnormal load distribution. Figures 96 and 97 show the locations of the 44 strain gages with respect to the motor chamber.

On May 23, 1968, the motor was statically fired after being conditioned at 75 ± 5°F for a minimum of 120 hours. The static firing of the motor resulted in failure at Defect No. 2 after 16.5 seconds of firing. The pressure at failure was 348 psia. The failure of the patch was in tension directly over the defect. Plots of strain versus pressure are shown in Figures 47 and 48 for the two defects. The circumferential defects are at the right hand edges of the defects that are depicted in the figures. The strain pattern in Figure 48 demonstrates the effects of the voids in the patch on the strain readings. The strain values on the 5.3-in. defect are much higher than the strain on the 7.5-in. defect. The strain pattern also shows signs of fiber failures in the lower plies. These failures are evident when the change in strain is compared to the change in pressure. The strain pattern in Figure 47 shows the maximum strain to be approximately 1.3%. In the area of the circumferential defect, the strains are reduced by the cloth reinforcement to the right of the defect.

The magnitude of the axial strains on these circumferential legs is quite small. These strains are plotted in Figures 49 and 50. A picture of the failure is shown in Figure 51.

Even though the quality of the patches on this unit was much lower than previously obtained, the repair failed very near the design criteria of 350 psia firing pressure. This result further demonstrates that defects of this magnitude can be repaired to withstand the normal firing pressure for X248 units of 240 to 250 psia. The failure of this patch in tension indicates that the problem of shear failures between chamber and patch can be solved.

o. X248 A10 S/N Y-195

Motor Y-195 had the only Rocky Hill-fabricated chamber in the program. It has the same winding geometry as the BS&B A6 chambers.

The motor had four defects inflicted in the cylindrical section. These defects were designed to study the effects of widening defects beyond the 0.10-in. width that had been used in all previous defected motors.

The defects, illustrated in Figure 98, were as follows:

Defect No. 1 - 2.50 in. long x 0.4 in. wide x 100% deep, located at 52½° between 6.5 and 9.0 in. aft of the forward doubler face.

Defect No. 2 - 2.50 in. long x 0.8 in. wide x 100% deep, located at 232½° between 6.5 and 9.0 in. aft of the forward doubler face.

Defect No. 3 - 7.50 in. long x 0.4 in. wide x 100% deep located at 52½° between 16.5 and 24.0 in. aft of the forward doubler face.

Defect No. 4 - 7.50 in. long x 0.2 in. wide x 100% deep located at 232½° between 16.5 and 24.0 in. aft of the forward doubler face.

All the defects were repaired with four-ply patches. However, the patching technique was again modified. The coating of the plies with resin before applying them was eliminated. The resin was once again permitted to work up through the plies, but with a more liberal application of resin between the plies than had previously been used. X-ray inspection indicated some small voids in patches for defect Nos. 2 and 4. The locations of the 44 strain gages with respect to the chamber and patches are shown in Figures 99 and 100.

On June 27, 1968, this motor was statically fired after being conditioned at a temperature of 75 ± 5°F for a minimum of 120 hours. This firing resulted in a failure of the patch at Defect No. 4. Due to a malfunction in the recording system at ignition, all tape data and approximately the first ten seconds of visicorder records were lost. The approximate pressure at burst (taken from the visicorder traces) was between 385 to 390 psia.

An examination of the strain gage data indicated that the failure started in the area of strain gage No. 20 (see Figure 100). Gage Nos. 25 and 26 also had high strains during the firing. The strain gage data indicate a rapid change immediately before the failure. Since the gages were not located over the center of the defect they should not have been strained more than the middle gage. This leads to the indication that there was probably failure of fibers in the lower plies in this area.

Figures 37 through 40 are pictures of the defect repair and motor failure. A postfiring inspection of the repair indicated that the patch failed directly over the defect. As Figure 40 emphasizes, the outer 90° layer of chamber glass was still bonded to the chamber, thus indicating that the patch adhered to the chamber. The attachment of the 90° fibers to the patch also indicates that the bond between the patch and chamber was better than that between the individual chamber layers. The evidence would thus seem to indicate that the failure was in the patch and occurred much the same as the previous failure caused by voids in the patch.

Comparison between the strains for 2.50-in.-long defects with varying width is shown in Figure 41. The 0.8-in.-wide defect indicates that strain increases with increasing width. However, the 0.4-in.-wide defect does not support this. This may be due to a lower stress level in the A10 chamber than in the A5. Also, the defects in the Y-195 chamber are 1.5 in. closer to the doubler, thus possibly affecting the strain pattern on the patch.

Figures 42 through 45 are plots of the strain vs. pressure for the four defects in the chamber. The rapid changes in the strain are evident on the 7.50-in.-long x 0.20-in.-wide defect, indicating a failure was occurring somewhere within the patch. No comparison was made between the 7.50-in.-long defects due to the lack of data points and the failure of the one defect.

p. <u>X248 A6 S/N NPP-463</u>

The motor NPP-463 was the final motor to be tested in the defects program. This motor was used to investigate combinations of longitudinal and circumferential defects to form square defects. The two square defects were as follows:

Defect No. 1 - Two longitudinal sides 7.5 in. long x 0.10 in. wide x 100% deep located at 57½° and 106° between 14.55 in. aft and 21.95 in. aft. Two circumferential sides 7.5 in. long x 0.1 in. wide x 100% deep, located between 57½° and 106° at 14.55 in. and 21.95 in. aft.

Defect No. 2 - Two longitudinal sides 5.3 in. long x 0.10 in. wide x 100% deep located between 16.7 in. aft and 22.0 in. aft and at 237½° and 271½°. Two circumferential sides 5.3 in. long x 0.10 in. wide x 100% deep located between 237½° and 271½° at 16.75 in. and 21.95 in. aft.

These two defects are essentially an approach to area defects. A picture of Defect No. 2 is shown in Figure 101. Figure 102 is an illustration of the defects and their locations. Both defects were repaired with five-ply glass cloth patches. Five plies were used to ensure the success of the firing because not much information was available on such large area defects. The square pieces of fiberglass were not removed from the case since this removal might have caused a case bond separation. The X-ray inspection indicated a small number of voids in both patches. The locations of the 44 strain gages with respect to the chamber are shown in Figure 103.

The motor was statically fired on June 28, 1968, after being conditioned at a temperature of 75 ± 5°F for a minimum of 120 hours. The motor fired without mishap. The maximum ignition pressure was 412 psia and the maximum progressive pressure was 388 psia.

Figures 52 and 53 present the strains registered by the gages at the maximum pressure of 388 psia for the two square defects. The strains do not appear to be high in any area. The lower strains at the center are due to the added stiffness of the fiberglass plate beneath the patch. Axial strains were quite low as was expected.

Tables 13 and 14 show comparisons of strains on Defect Nos. 1 and 2 for similar pressures during the firing. The tables demonstrate that the strains are higher in most cases during the regressive portion of the pressure vs. time curve. In Table 13, the hoop gages at the centers of the longitudinal defects show the most increase in strain. This increase may be partially due to viscoelastic effects within the patch and to the change in grain configuration as the firing progresses.

4. Dome Repair Study

The X248 dome proved to be unsuitable for the development of a dome repair technique. Preliminary tests utilizing five 6-in.-diameter bottles and eight 3-in.-diameter Picatinny bottles had been performed to determine the feasibility of candidate repair materials and repair technique. These tests indicated that additional testing would be necessary to demonstrate the feasibility of dome repairs. Therefore, the development of a repair technique and evaluation of repair materials for elliptical dome defects were investigated with a 6-in.-diameter bottle program. The main objective of this program was to determine if the technique and materials could provide a repair which would be applicable to full-scale motors. The secondary objectives were: (1) to determine whether inflicted dome damage could be duplicated, (2) to establish additional information concerning strength degradation for a specific defect in the dome, and (3) to determine damage limits for which repair is feasible.

a. Bottle Fabrication

This phase of the chamber repair program was set up to utilize 24 bottles. These bottles were the same as the 1/8 scale Polaris A3 second stage bottles cited in Reference 3. These bottles had a winding geometry which made the bottle "dome-critical."

Figure 104 illustrates both the winding geometry and dimensions of the bottles. A total of 26 bottles were wound using single-end S-994 glass with an Epirez 504/Epicure 855 resin system. The winding geometry consisted of three layers of 11° helical windings and eight layers of 90° hoop windings wound sequentially on a Styrofoam mandrel. The bottles were numbered according to order of fabrication.

The fabrication of the bottles proceeded according to the following five steps:

(1) Styrofoam mandrels were constructed and machined.

(2) Pole pieces were inserted and the mandrel was covered with two rubber balloons.

(3) The three layers of 11° helicals and eight layers of 90° hoops were wound sequentially over the mandrel.

(4) These bottles were allowed to B-stage at room temperature for 24 hours. They were then cured in an oven at 250°F for two hours and conditioned at ambient temperature and humidity for several weeks.

(5) The Styrofoam mandrels were dissolved with acetone.

b. Bottle Testing

Of the 26 bottles that were wound, 24 were used for the testing program. Bottle Nos. 1 and 12 were eliminated because No. 1 was much heavier and No. 2 was much lighter than the other bottles, indicating a discrepancy in their fabrication.

Three groups of tests were conducted. Group I tests consisted of the hydrobursting of nondefected bottles. Group II tests consisted of the hydrobursting of defected bottles. Group III tests consisted of the hydrobursting of defected and repaired bottles.

(1) Group I: Hydroburst of Undamaged Bottles

Six nondefected bottles were randomly selected and then hydroburst to determine the average burst strength of the dome-critical bottles. The bottles were hydroburst at a pressurization rate of 50 psi/sec. All the failures occurred in the area of the pole pieces. These failures were caused by the breaking of filaments which allowed the pole piece to be ejected. A picture of a typical failure is shown in Figure 105. The results of the tests are shown in Table 7. A review of the burst pressure results indicates fairly good agreement with the exception of Bottle No. 2. The burst pressure of Bottle No. 2 appears to be much higher than that of the others in the control group. A check of the fabrication data indicates a possible error. The weights of helical glass used in Bottle No. 1 and Bottle No. 3 were 218 g and 190 g, respectively. The amount of resin by weight used in Bottle No. 2 was approximately the same as the amounts used in Bottles 1 and 3. These data would seem to indicate a possible error in the measurement of the weight of helical glass used in fabrication of Bottle No. 2. Therefore, the control burst pressure average does not include the burst pressure of Bottle No. 2. The average burst pressure based on the other five bottles is 2205 psig.

(2) Group II: Hydroburst of Defected Bottles

Six bottles were defected and hydroburst to determine the reproducibility of inflicting a specified defect. The defect was 0.75 in. long x 0.100 in. wide x 0.015 in. deep and was located 2.00 in. from the edge of the pole piece. The depth of the defect was specified such that not more than three of the six helical plies would be severed. The defects were oriented in a plane perpendicular to the bottle axis. This was done to facilitate the machining and to sever the maximum number of fibers. The bottles were placed on a lathe and the defects were machined with a U-shaped tool. After the defects had been machined, the bottles were hydroburst at a pressurization rate of 50 psi/sec. Typical failures were due to peel-back of the deliberately severed filaments, followed by a tension failure in the remaining filaments. Figure 14 is a picture of a typical failure. The results of the bottle tests are shown in Table 8.

The burst pressure of bottle No. 9 is much lower than the others. A check of the dome thickness in the area of the defect indicated a thickness of 0.029 in. Previous dome thickness measurements indicated a thickness of 0.032 in. in the defect area. This indicates that only 0.014 in. of material would be remaining at the defect. This would also mean that a small portion of the filaments in the third ply was severed, thus possibly weakening the filaments in the third ply enough to cause a premature failure. Therefore, bottle No. 9 was disregarded in average burst pressure calculation. The average burst pressure for the five bottles is 1715 psig. The predicted burst pressure was 1550 psi based upon data taken from work done by Cross(3) on similar bottles.

(3) Group III: Repair of Inflicted Defects

Six bottles were placed on a lathe and a defect 0.75 in. long x 0.10 in. wide x 0.015 in. deep and located 2.00 in. from the edge of the pole piece was machined into each dome. The six bottles were then divided into two sub-groups. Sub-group 1 bottles were repaired with a two-ply glass cloth patch and sub-group 2 with a three-ply repair. The repair consisted of Owens-Corning S-81 fiberglass cloth with a 901 finish and an Epon 946 resin system. These same materials had been used to repair defects in the cylindrical and dome sections of X248 motors.

The repair of sub-group 1 bottles consisted first of sanding the surface surrounding each defect to promote better bonding, care being taken to avoid abrasion of the glass filaments. Epon 946 (15 pts B to 100 pts A) was allowed to stand for 20 minutes at ambient conditions, then brushed on each sanded surface and on the surface of each glass ply as it was laid in position. Each ply was 3 in. long and $2\frac{1}{4}$ in. wide. The first ply was oriented in the direction of the outermost ply of filaments on the dome. The second ply was oriented in the direction of the second fiberglass ply from outermost surface of the dome (i.e., at $+\alpha$ and $-\alpha$, where α is the winding angle). The warp direction of the fiberglass cloth is oriented in the direction of the winding angle on the dome. For a sketch of the patch layup, see Figure 106. Each ply was finger-pressed to remove entrapped air, and resin was applied freely to the total patch. After a 16-hour ambient B-stage, the patches were cured in an oven at 200°F for four hours. The results of the sub-group 1 tests are shown in Table 9.

The sub-group 2 bottles were repaired in a manner similar to that used for sub-group 1 bottles except that a third ply was added. The third ply was oriented with its longest axis perpendicular to the defect. The results of the sub-group 2 tests are shown in Table 10.

Post-hydroburst inspection of sub-group 1 bottles indicated a patch failure for only one bottle. This failure occurred in bottle No. 11 at a pressure of 2415 psig. The failure was in shear between the patch and the dome.

Post-hydroburst inspection of sub-group 2 bottles indicated no patch failures. However, two bottles had higher than the average burst pressure of the undefected bottles. Dome thickness measurements indicate that bottles Nos. 25 and 26 were thicker than the nominal 0.032 in. These

~~thicker domes are due to a higher number of filaments in the dome as was~~ indicated by the weight of helicals used in the winding of the bottles.

Underside views of successfully repaired defects are shown in Figures 15 and 16. Figure 15 shows a two-ply repair and Figure 16 shows a three-ply repair. The larger amount of crazing that is visible in the glass under the two-ply repair indicates more interlaminar shear is occurring.

The results of these tests indicate that a two-ply patch is capable of restoring the defected bottles back to their original burst pressures. The remaining six bottles were therefore defected completely through the domes. Three of these bottles were repaired with a two-ply patch and the remaining three with a three-ply patch. These bottles were hydroburst and the results are shown in Tables 11 and 12.

Failures for the two-ply patches occurred in shear between the patch and the dome. The average burst pressure for the two-ply patch was 1385 psig. For the three-ply patches, failure occurred in shear for bottle Nos. 6 and 19 and a tension failure occurred in the patch on bottle No. 22. The average burst pressure for the three-ply patch was 1965 psig. Pictures of the shear failure in bottle No. 19 and the tension failure in bottle No. 22 are shown in Figures 17 and 18, respectively.

The three-ply repair returned the bottles to approximately 89% of the original average burst pressure for the undefected bottles. The tension failure of the three-ply patch at 2205 psig in bottle No. 22 indicates that it may be possible to return the Group III bottles back to their original burst pressure with a three-ply patch if the shear failure problem can be overcome.

5. Mathematical Analyses of Defect and Repair

A mathematical analysis was made to study the effects of variations of parameters on the stress distributions within the repair patch. The results of this analysis can be used to help evaluate and to better understand the results obtained from the static firing of repaired X248 motors.

The actual X248 tests were of partial, complete, and combinations of partial and complete defects. The analysis was limited to the analysis of complete longitudinal defects. The main reasons for this restriction are as follows: (a) most of the static firing data are related to complete longitudinal defects, (b) the longitudinal defects are more critical than the circumferential, and (c) the partial and combination defects cannot be properly analyzed.

a. Computer Program

The repair of a defect in the X248 fiberglass case was analyzed utilizing the Hercules Finite Element Computer Program.

This digital computer program is based upon a finite-element, direct stiffness method for obtaining elastic stress-strain solutions for bodies of revolution; the program can be used to analyze two-dimensional geometric approximations of the actual three-dimensional configuration. A major feature of the program is its capability to consider the orthotropic material properties for all elements. Temperature dependence of the orthotropic properties is also automated through the use of material property input to the computer program.

The Hercules finite element computer program comprises four functionally separate sub-programs which perform the following operations:

(1) generate nodal locations of interior grid elements,

(2) generate individual stiffness matrices and loads for the various quadrilateral elements in the grid and store them in an intermediate magnetic tape,

(3) assemble individual stiffness matrices generated by sub-program (2) and obtain the composite stiffness matrix for the total structure, then solve for the equilibrium displacement field, and

(4) solve for strains and stresses in the finite elements through elasticity relationships between the strains and displacements and stresses and strains.

In using these analytical techniques, the body under consideration is approximated by an assemblage of quadrilateral elements. The corners of each element are described as nodal points. Within each element, the displacement field is assumed to have a known linear form and is, therefore, given in terms of the unknown nodal displacements. Based upon the linear theory of elasticity, stresses are then expressed in terms of nodal displacements associated with each element under consideration together with the applied forces. The procedure is repeated for each element of the system. The solution is obtained when minimization associated with the principle of virtual work is accomplished with respect to each of the independent unknown nodal displacements. This results in a system of linear algebraic equations which describe the equilibrium state for the body. Solution of the system of linear algebraic equations yields displacements from which strains and stresses can be obtained. Use of this technique permits a detailed study of overall structural deformations as well as detailed analyses of movements of individual fibers or structural elements within quadrilateral elements.

b. Analytical Model

The model used for the analysis is an idealization of the actual defects and repairs that were present in the X248 motor tests. The model is shown in Figure 54. It is a cross-section of a longitudinal (i.e., axial) defect and the repair patch. The model contains the individual plies of fiberglass cloth, the bond layer between plies, a defect which is completely through the X248 chamber wall, the individual layers of fiberglass in the chamber wall, and measurements to indicate the size of the elements. Because of the symmetrical condition on either side of a repaired defect, only one-half of the defect and repair had to be modeled.

Before the analysis could be started, the moduli of elasticity had to be determined for the materials in the model. The method of analysis to determine the modulus of elasticity parallel and normal to the filaments for the X248 fiberglass case material is based upon Reference 5. This method has been extended to calculate the orthotropic fiberglass properties. Input for these calculations include: (1) layer thickness, (2) resin content, (3) winding angle and (4) filament and resin moduli, Poisson's ratios and densities. The properties of the patch materials were obtained from tensile test data. The modulus for a single glass cloth ply was used for the various plies in the model. Calculation of the cross modulus was based on a method described in Reference 6. The properties used for the various materials in the model are listed in Table 29.

The following boundary conditions were induced on the model so that it could be analyzed:

(1) The model was assumed to be infinite in the longitudinal direction because of the geometrical limitations of the computer program,

(2) The nodal points directly above the defect were fixed both radially and circumferentially to zero deflection,

(3) The X248 chamber surface was fixed radially to zero deflection,

(4) The left side of the chamber model was displaced in the circumferential direction to simulate the deflection caused by a 350-psia chamber pressure.

The analytical model was used to analyze eight different conditions. These conditions accounted for variations in bond layer thickness, type chamber, number of plies in the repair and defect width. The eight conditions that were analyzed are summarized in Table 15.

c. Conditions Analyzed

(1) Condition 1 - Idealized Model

Condition 1 is the analysis of a four-ply patch applied to a 0.10-in.-wide defect in an A5 chamber. A plot of the circumferential isostrain pattern is shown in Figure 107. This figure clearly demonstrates the rapid changes of strains in the area of the defect, with strains of approximately 9% in the ply directly above the defect. Figure 55 shows the equivalent stress (E.S.) distribution within the repaired area. The computer program permits this calculation to be made and it is based upon the Von Mises failure criterion and defined as:

$$E.S. = \frac{1}{\sqrt{2}} \sqrt{(\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{cc})^2 + (\sigma_{cc} - \sigma_{11})^2}$$

where σ_{11} = Maximum principal stress
σ_{22} = Minimum principal stress
σ_{cc} = Hoop stress

The equivalent stress pattern within the patch model demonstrates that the stress is maximum in ply No. 1 and then decreases with each subsequent ply. Also, the load appears to be transferred from the patch back into the chamber within a half of an inch. A plot of the average equivalent stress directly above the defect in each ply is shown in Figure 108. It is evident that approximately 40% of the load is carried by the first ply. The shear stress distribution along the bond line is plotted in Figure 56. The shear stress is a maximum at the defect edge and then drops off markedly at a small distance from the defect. Thus, initiation of shear failures in the bond will be limited to the area adjacent to the defect.

(2) Condition 2 - A 0.2-In.-Wide Defect

This condition varies from Condition 1 only in defect width. It has been changed from 0.1 in. to 0.2 in. wide. Figure 109 shows the equivalent stress distribution within the repaired area. The pattern appears to be similar to that shown in Figure 55. However, the magnitudes of the stresses in the outer three plies are higher for the wider defect. This means that the load is tending to be distributed more equally among the plies. A plot of the circumferential isostrain pattern is shown in Figure 110. This figure demonstrates that the load is becoming more uniformly distributed because of the higher strains in the outer plies of the patch.

(3) Condition 3 - A 0.5-In.-Wide Defect

Again, this condition varies from Condition 1 only in defect width. It has been changed from 0.10 in. to 0.5 in. wide. A plot of the equivalent stress distribution in the defect area is shown in Figure 111. A comparison of the average equivalent stress per ply in the three elements located over the defect is shown in Figure 112. This figure demonstrates that toward the center of the defect the stresses tend to be more uniformly distributed among the plies and just the opposite at the edge of the defect. A final comparison is made in Figure 57 for the average equivalent stresses for the 0.1-in., 0.2-in., and 0.5-in.-wide defects. The elements are the ones closest to the defect center. This plot clearly shows that as a defect widens, the load becomes more uniformly distributed among the plies. A plot of the hoop isostrain pattern is shown in Figure 113. This pattern shows the widening effects on the patch strains.

(4) Condition 4 - A Three-Ply Repair

This condition varies from Condition 1 in that the number of plies used in the repair patch is three instead of the four used in Condition 1. Figure 114 shows the equivalent stress distribution within the patch model. A comparison of the average equivalent stresses per ply for three and four ply repairs is shown in Figure 115. As expected, the stresses are higher in a three-ply repair. A plot of the hoop isostrain pattern for this condition is shown in Figure 116. The comparison of the equivalent stresses and isostrain pattern indicated that the load normally carried by the fourth ply is being almost equally distributed among the remaining three plies. The shear stress in the bond layer is distributed almost exactly as shown in Figure 55 .

(5) Condition 5 - Four-Ply Repair on A6 Chamber

This condition considers a variation in the type of chamber that has been defected and repaired. Since both A5 and A6 chambers were defected, a comparison must be made between them. Figure 117 shows the equivalent stress distribution within the model. A comparison between the equivalent stresses in the plies over the defect for A5 and A6 chambers is shown in Figure 58. This comparison shows that the type of chamber does affect the stresses in the repair. The degree of variation is highest (almost 10%) on the fourth ply. A plot of the hoop isostrain pattern (Figure 118) indicates slightly lower strains in an A6 repair.

(6) Condition 6 - Variation In Bond Layer Thickness

This condition represents a variation in the bond layer thickness between both the individual plies and the first ply and the chamber wall. The bond thickness has been varied from 0.007 in. to 0.0105 in. This condition is intended to give an idea of the effects of bond thickness on shearing stresses.

Figure 119 shows the equivalent stress distribution within the model. A small decrease in stresses in each ply is apparent, as well as slightly higher stresses in elements that are over the chamber wall. This would tend to indicate that a 50% thicker bond helps to redistribute the stresses better than the 0.007 in. bond layer thickness. Figure 59 shows a comparison of the shear stresses for the two thicknesses of bond line. This comparison indicates a 16% drop in the peak shear stress at the edge of the defect, thus indicating that a bond layer thickness can greatly affect the possibilities of a shear failure. This also helps to explain why shear failures occurred in the X248 repair program.

(7) Condition 7 - Plane Strain Constant Added

On the actual chamber there is an additional stress which is imposed in the axial direction. To determine the effect of this biaxial stress situation, a plane strain constant of 0.79% was added into the plane of the model. This constant would be the approximate axial strain in an A5 chamber without a patch at 350 psia. However, the repair patch would tend to reduce the 0.79% strain because it will carry some of the axial load. This reduction was not considered because the axial load carried by each ply is unknown.

Figure 120 shows the equivalent stress distribution within the model. Figure 60 compares the average equivalent stresses in each ply over the defect for Condition 1 and Condition 2. This figure indicates that the plane strain constant mostly affects the first ply of the patch. The equivalent stress increases by approximately 9% because of the plane strain constant.

(8) <u>Condition 8 - Void Included In Patch</u>

The repair of the defects on NPP-453 was X-rayed before the motor was statically fired. These X-rays indicated numerous voids between the plies of the patch. Condition 8 is an attempt to determine the effect of a void on the stress distribution within the patch. A 1.0-in.-wide void was placed in the bond layer between the first and second plies of the patch directly over the defect. Figure 121 shows the equivalent stress distribution in the model. The stresses in the first ply are much higher than the stresses in a void-free patch model. Figure 61 compares the stresses in the void-containing and void-free models for the average equivalent stress in each ply above the defect. This figure indicates that the void between the first and second ply can increase the stresses in the first ply by approximately 35%. Thus, when voids do occur, there is a much greater possibility of failure in the first ply of the patch. Figure 122 is a plot of the hoop isostrain distribution. The highest strains occur in the first ply directly over the defect.

C. CASE BOND SEPARATION

The study of case bond separation (CBS), unrepaired in the forward end of the motor and repaired and unrepaired in the aft end, was conducted in the following manner: To investigate X248 forward dome case bond separation (CBS), four motors were subjected to simulated flight loading by spinning the motor about the longitudinal axis and centrifuging. These motors were radiographically inspected before and after testing to determine any changes. Two of these motors were statically fired at normal operating pressure to verify performance. The other two motors were used to demonstrate fiberglass defects and repair and then statically tested at 1.25 times the normal operating pressure. The firing results of these four motors with respect to forward dome CBS were further confirmed by the other 12 motors fired at higher operating pressures (described in the foregoing subsection on fiberglass defects) since all sixteen motors contained some degree of forward dome CBS.

Testing of unrepaired areas of minor CBS in the aft end of X248 motors was accomplished in the static firings of three motors S/N's, 454, 425, and 453.

Four motors S/N's NPP-257, 261, 475 and 425, had areas of aft dome CBS that had been repaired by potting with polyurethane injected with a hypodermic syringe.

The early laboratory testing was directed towards qualifying a repair adhesive for X259 motors. However, when it became necessary to repair X248 motor S/N NPP-424, the laboratory program was modified to qualify a repair adhesive for use on X248 motors.

The development of a CBS repair procedure based on gaining access via holes in the fiberglass chamber was carried out on the X248 motor S/N NPP-424. The application of this technique had originally been planned for X259 motors.

This work is described in more detail in the following.

1. Motor Tests

a. Unrepaired Forward Dome Defects

(1) Motor X248 A5S S/N NPP-400

This motor possessed the most extensive forward dome case bond separation of any motor in the program. For this reason it was selected for use in determining if forward dome CBS would propagate under simulated flight loading or if it would affect motor ballistics during static firing. The secondary objective, obtaining fiberglass strain data, is discussed in the Fiberglass Defects and Repairs section.

The motor was subjected to spin rates of 600 rpm for 45 to 60 seconds on the dynamic balancer and to axial acceleration loads of 40 g for 58 seconds on the centrifuge and then X-rayed. The results of the pre- and post-test X-rays were compared as illustrated in Figure 123. No significant change in the forward CBS was noted.

A nozzle with standard throat size was used to attain the desired normal ballistic performance. On July 17, 1967, the motor was statically fired after being conditioned to a temperature of 75 ± 5°F for a minimum of 120 hours. The performance was normal, and there was no evidence of abnormal propellant burning in the unrepaired separation. The pressure and thrust traces are shown in Figures 124 and 125. Ignition maximum pressure was 276 psia and the progressivity maximum pressure was 255 psia.

Comparison of the ballistic data of NPP-400 to the model specification (Table 30) clearly shows the performance of this 58-month-old unit to be nominal.

(2) Motor X248 A6 S/N NPP-446

This motor possessed the third most extensive case bond separation in the forward dome, plus minor separations in the cylindrical section at the forward edge of the insulator. The motor was selected to determine if a lesser degree of forward dome separation would propagate under simulated flight loading. The motor was statically fired to confirm the results obtained from NPP-400, thereby providing sufficient basis to use the remaining X248 motors with unrepaired CBS in the forward end to investigate fiberglass defects and repairs.

The motor was subjected to spin rates of 600 rpm for 45 to 60 seconds on the dynamic balancer and to axial acceleration loads of 40 g for 45 to 60 seconds on the centrifuge. The post-test X-ray results are compared with the pre-test results in Figure 126. No significant change in the CBS resulted from these tests.

The motor was fired as a standard pressure motor. After being conditioned at a temperature of 75 ± 5°F for a minimum of 120 hours, NPP-446 was statically fired on July 20, 1967. The performance was normal, and there was no evidence of abnormal burning in the unrepaired separation.

The pressure and thrust traces are shown in Figures 127 and 128. The ignition maximum pressure was 276 psia, and the progressivity maximum pressure was 258 psia.

(3) Motors X248 A5 NPP-409 and X248 A6 NPP-447

To confirm the results of NPP-400 and NPP-446, two additional motors were subjected to simulated flight loads before static firing. These motors then became fiberglass defect and repair vehicles and are discussed in that area of this report. These motors served to confirm that unrepaired forward dome CBS in X248 motors would not affect ballistic performance.

After the initial radiographic inspections had been made, these motors were spun at 600 rpm for 45 to 60 seconds on the dynamic balancer and then centrifuged to an axial acceleration load of 40 g. Following these two tests, the motors were again X-rayed. The results of the pre- and post-test X-rays were compared as illustrated in Figures 129 and 130. No significant change occurred in the areas affected by CBS.

Both motors were statically fired following infliction of fiberglass defects. Motor NPP-409, fired August 18, 1967, failed after 12.26 seconds of burning at a pressure of 281 psia. The failure is attributed to one of the inflicted fiberglass defects. This is discussed in detail in Section III.B.3.c. Motor NPP-447, fired August 18, 1967, burned for the full planned duration and reached a progressivity maximum pressure of 290 psia. The ballistic results of these motors, shown in Figures 131, 132, 133 and 134, as well as the postfiring visual inspection show no evidence of abnormal burning in the unrepaired separation.

(4) Remaining Twelve X248 Motors

The remaining twelve motors were used primarily to investigate fiberglass defects and repairs and are reported fully in that section of this report. All of these motors, however, did contain forward dome CBS of varying degrees as is depicted by the radiographic inspection results contained in the Appendix. These motors were statically fired at 1.25 times normal operating pressure to provide an overtest of the fiberglass investigations. All of these motors except one (NPP-401) burned either for the full duration or for sufficient time to verify that the forward dome CBS did not affect ballistics. Pressure and thrust curves illustrating this are contained in the data packages for each motor in Appendix D. The static firing of NPP-401 was declared a "no-test." The motor failed at 0.049 second after first indication of pressure at a chamber pressure of 322 psia. Postfiring analysis involving review of field history disclosed that the motor had been dropped at NOS/Indian Head. Chamber rupture probably resulted from a combination of structural damage and case bond failure in the aft end which was not disclosed during X-ray examination. It was concluded that the malfunction was not associated with either the inflicted defects or the forward dome CBS.

b. Unrepaired Aft Dome Defects

Three motors containing various minor defects in the aft end of the motor were fired. The existing conditions are described and test results are presented in the following.

(1) Motor X248 A6 NPP-454

This motor contained two minor propellant cracks and three voids. The largest crack was approximately 2 in. long x 0.04 in. deep x hairline in width and the largest void was 0.3 in. by 0.35 in. The size and location of these defects are shown on Figure 135.

The motor was fired November 3, 1967. It performed normally with no evidence of abnormal burning noted from the ballistic data on postfiring inspection.

(2) Motor X248 A6 NPP-425

The condition of the case bond in this unit was reported as shown in Figure 136. The CBS opening into the aft port was repaired as discussed under Section IV-C.1.c. of this report. The CBS in the cylindrical section was in the form of a definite 1½-in.-long separation at the 180° location. Also, a heavy case bond resin layer was evident around the entire circumference in the cylinder section. The anomalies between 212½° and 252½° reported on the radiographic inspection map were originally interpreted as resin buildup but, based on X-ray of the fiberglass repairs, were officially reported by Quality Assurance as CBS.

Since the defect located at 180° was exactly half way between fin slots and was on the edge of the insulator, it would not be exposed to the flame front until the very end of firing and therefore would not affect ballistics. If the anomalies between 212½° and 252½° were resin buildup, no effect on ballistics would occur. If the anomalies were separations, additional burning surface would be exposed but not until late in the firing so that the chamber would burst or burn through after a pressure of 350 psia (the fiberglass repair objective) had been reached. Based on the foregoing engineering analysis, it was decided to fire the motor.

The motor was statically fired March 22, 1968. The fiberglass repair failed after 12.5 seconds of burning at a chamber pressure of 351 psia. The pressure-time curve exhibited no anomalies up to the time of patch failure. The water quench system was unable to completely extinguish the propellant in the top part of the unit. This low-pressure burning, lasting for approximately 15 minutes, destroyed the burning surface pattern in most of the motor and charred the insulation and fiberglass chamber. Thus, it was not possible, in the postfiring visual inspection, to determine whether the burning front had advanced into this anomalous area prior to failure, nor was it possible to verify the presence or absence of separations. It was concluded that the burning front had probably not reached the CBS area and therefore had no effect on the test. This firing was a no-test as far as the cylindrical section CBS condition was concerned.

(3) Motor X248 A6 NPP-453

Several small voids were present in the aft dome near the case bond of this motor as shown on Figure 137. The largest of these voids was 1¼ in. by 1/32 in. These voids were located at or near the bottom of the fin slots and would therefore be exposed within the first second or two of firing. Because of their size and orientation (long dimension parallel to the burning front), very little additional surface would be exposed and any effect would probably last for only a few seconds.

The motor was statically fired May 23, 1968. The motor performed normally for 16.5 seconds, when a fiberglass repair failed at 348 psia as discussed in the fiberglass defect and repair section. The pressure and thrust traces (see Figures 138 and 139) appear normal until time of failure. Therefore, as expected, these small propellant defects had no detectable effect on motor performance.

c. Repaired Aft Dome Defects

Four motors, NPP-257, -261, -475 and -425, had minor CBS near the aft port opening. The case bond separations were of such a nature that they could be expected to affect ballistics if not repaired. All CBS defects were repaired by filling the separations with a polyurethane potting material injected by a hypodermic syringe inserted from the port area. This material has been used extensively by Hercules and others for various applications of potting or inhibiting propellant in many different solid propellant rocket motors.

(1) Motor X248 A5 NPP-257

This motor had minor CBS and propellant voids near the aft port opening at the bottom of the fin slots as shown on Figure 140. These defects were repaired with polyurethane in accordance with UOP 1-1738 (see Volume III, Appendix C).

The motor, when fired on October 26, 1967, functioned properly with a progressivity maximum pressure of 380 psia. The pressure and thrust traces are found in the Appendix. Postfiring inspection revealed no evidence of abnormal burning.

(2) <u>Motor X248 A5 NPP-261</u>

This motor had minor CBS opening into the aft port. The CBS extended over an area from 127½° to 307½° as indicated on Figure 141. The maximum length of the CBS was approximately 1 in. at the 307½° location. The defect was repaired with polyurethane in accordance with UOP 1-1758.

The motor was statically fired January 2, 1968 and burned full duration. The ballistic performance was normal with a maximum progressivity pressure of 356 psia. Postfiring inspection revealed no evidence of abnormal burning.

(3) <u>Motor X248 A6 NPP-475</u>

This motor contained minor CBS around the entire circumference of the aft port as shown on Figure 142. The maximum length of separation was 3/4 in. This defect was successfully repaired with polyurethane in accordance with UOP 1-1758 except that the amount of dimethyl sebacate in the polyurethane was increased from 8.4% to 15.5% to make the uncured mixture less viscous.

The motor was fired February 23, 1968 and performed normally until a fiberglass defect repair failed after 26.5 seconds of burning at a pressure of 340 psia. A progressivity maximum pressure of 351 psia was reached approximately 3 seconds before failure. The ballistic performance and postfiring inspection indicate that no abnormal burning occurred.

(4) <u>Motor X248 A6 NPP-425</u>

Motor NPP-425 contained CBS opening into the aft port area as shown on Figure 136. This CBS extended a maximum length of 2-1/8 in. The defect was successfully repaired with polyurethane in accordance with UOP 1-1758; however, two attempts were necessary. Radiographic inspection showed that after the polyurethane had been forced into the separation the first time, a small (1-in.) area was still separated at the 0° location. Additional material was injected at this location. Subsequent X-rays confirmed a satisfactory repair.

The motor, statically fired March 22, 1968, performed normally until a fiberglass defect repair failed after 12.5 seconds of burning at a chamber pressure of 351 psia. The results of this firing are also discussed under the fiberglass repair section and the section on unrepaired aft dome defects motor tests. Postfiring visual inspection revealed that in the aft dome at 330° in the area where the repaired propellant-to-separation ended, there was evidence of advanced propellant burning (case bond separation) over a very small area (approximately 1/2 in. radius). This area is too small to be reflected in the pressure trace. Had the motor burned full duration, this advanced surface would have burned itself out early. With additional insulator erosion occurring over the entire dome, it is not likely that any evidence of advanced burning would have been detected. Even though minor advanced burning occurred, it is concluded that the propellant-to-insulator repair at 0° was 100% successful and the one at 330° was 95% successful. Had these defects not been repaired, the pressure-time curve would definitely have been affected, showing over-pressurization.

2. Propellant Repair of X248 Motor S/N NPP-424

The X248 motor NPP-424 had fiberglass damage inflicted in the form of two cylindrical defects and four holes in the forward dome. The defects were as follows:

Defect No. 1 - 2.5 in. long x 0.2 in. wide x 100% deep, located at 0°, 8.0 in. to 10.5 in. aft of the forward doubler.

Defect No. 2 - 2.5 in. long x 0.2 in. wide x 100% deep, located at 0°, 18.0 in. to 20.5 in. aft of the forward doubler.

Defect Nos. 3, 4, 5, and 6 - 0.375-in.-diameter holes completely through the forward dome and located 2.125 in. horizontally forward of the doubler face and at 0°, 90°, 180°, and 270°.

Defect Nos. 1 and 2 were repaired with four-ply S/81-901 glass cloth patches with an Epon 946 resin system. Defect Nos. 3, 4, 5, and 6 had three-ply glass cloth patches. The effects of an increase in defect width were to be evaluated by this test.

However, after these defects had been inflicted in the fiberglass motor, an X-ray indicated the presence of an extensive separation between the insulator and the propellant in the cylindrical section of the chamber, at the bottom of the grain slot located at 307½°. (The X-ray map for this unit is presented in Appendix A.) It was predicted that chamber burn-through or rupture, due to high pressure resulting from additional burning surface, would result if this motor was fired without repair. Location of this separation was such that it could not be potted by normal means; that is, pumping an adhesive through a hypodermic needle into the separation from an exposed interface edge.

A study was conducted on pumping repair adhesive into holes drilled through the fiberglass chamber and insulator. The following procedure was devised for pumping the epoxy resin into the case bond separation: The motor is placed in a vertical position, aft end up. Regulated air pressure forces the mixed resin from a pressure pot through flexible tubing to a hole (1/4 in. - 3/8 in. diameter) through the side of the chamber and insulation near the base of the separation. Resin is forced upward and outward, expelling air from a hole at the top of the separation. Bleed holes at the edges of the separation area provide an indication that resin is flowing and that no air is entrapped. When resin flow is assured, the holes are plugged temporarily so that the epoxy resin will fill the separation. The operation is completed when resin flows out the hole at the top of the separation area.

Based on the laboratory testing reported in the following section, an epoxy resin system consisting of 90 parts by weight (pbw) Epon 871, 10 pbw Epon 815 and 13 pbw Epon 946 B was selected to repair NPP-424. A trial repair was performed successfully on the cut-off dome of partially burned unit X248 S/N NPP-242. No difficulties were encountered except for minor resin leakage at the chamber surface around the connection from the resin supply. The design for connecting the resin supply to the chamber was revised and functioned satisfactorily when checked with air pressure.

Attempts to pump this epoxy resin system into the case bond separation in the cylindrical section of X248 S/N 424 were not successful. The procedure (UOP 1-1741, Appendix C) used was similar to that successfully used to pump resin into the case bond separation in the dome of X248 S/N 242. In attempting to repair S/N 424, the resin supply was sealed on the outside of the chamber by a rubber O-ring held in place by a steel band around the chamber. It was possible that the band arrangement could deflect the chamber against the propellant, sealing the separation area. Therefore, a pressurized air line nozzle was placed in the various holes drilled in the chamber. Seam sealing compound (CS) around the nozzle of the air line maintained the hand-held air supply at 40 psi. No evidence of a separation was found; that is, no air came out any of the uncovered holes. Drilling two additional 3/8-in.-diameter holes near the center of the separation area gave the same results: no separation apparent.

The unit was X-rayed again to check the location of case bond separation relative to holes drilled through the chamber wall. Only a minor separation at the base of the slot was found. The unit was conditioned to 40°F to determine if the separation could be detected at the lower temperature. X-ray of the unit at 40°F showed a separation between the propellant and case, but only partially covering the areas originally reported on February 15, 1968. However, at this point, the separation was determined to be completely open since an operator could blow air through all of the holes.

After allowing the unit to return to ambient temperature, a cellulose acetate potting fixture was bonded, according to UOP 1-1741, Appendix F, over one of the 3/8-in. holes through which resin was to be pumped to repair the separation, thereby eliminating the steel band used in the first repair attempt. However, air pressure tests indicated that the separation had again closed, and it would be necessary to repair the separation while the unit was chilled (40°F). At this point, all further work on this unit was suspended because of funding and time limitations.

3. Laboratory Testing

a. X259 Case Bond Repair Adhesive Testing

The main objective of this laboratory effort was to qualify an existing adhesive system for repair of separation-type failures of the following types that may occur during manufacturing, handling and storage of X259 rocket motors:

1. Barrier resin(1) to insulator(2)
2. Barrier resin-to-fiberglass chamber(3)
3. Embedment powder(4) to-embedment resin(5)
4. Propellant-to-propellant (i.e., cohesive failure of CYI).

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(1) The powder embedment system consisted of a cured barrier coat of Epirez 504/Epicure 855 (100 phr) onto which the embedment resin, Epirez 504/Epicure 755 (70 phr), and the embedment powder are cast. Both components of the E/E resin contain 2% Bentone.

(2) The X259 insulator is asbestos-filled styrene-butadiene rubber (SBR).

(3) The X259 fiberglass chambers A-1 through A-6 were wound with ECG-140-801 glass roving and Epon 826/CL resin.

(4) Embedment powder consists of a mixture of 0.050 x 0.050 in. and 0.070 x 0.070 in. solid cylinders.

(5) The powder embedment system consisted of a cured barrier coat of Epirez 504/Epicure 855 (100 phr) onto which the embedment resin, Epirez 504/Epicure 855 (70 phr), and the embedment powder are cast. Both components of the E/E resin contain 2% Bentone.

X-ray techniques usually can confirm the presence of a separation and its location in a loaded motor case, but it cannot discriminate between the varieties of separations. To repair such a defect, a "universal adhesive" must be found. In this report, "universal adhesive" means a material which will form an effective repair bond for any of the above listed separations or combinations of them. Because of financial and time limitations, this program was restricted to tests necessary to qualify a state-of-the-art resin for repair of the major separation. The resin had to bond well to both substrates forming the gap. In addition, the resin (a) should be compatible in both cured and uncured states with CYI propellant and casting solvent, (b) should be curable at temperatures between 50 and 100°F, (c) have a low viscosity and (d) have a burning rate equal to or less than the burning rate of CYI in a motor environment.

It was arbitrarily established that the criterion for minimum bond strength would be the lowest tensile strength exhibited between any pair of components in the case: (1) fiberglass-Epirez/Epicure (E/E), (2) E/E-CYI, or (3) SBR-E/E. A comparison of tensile and shear strengths is presented in Table 31. The lowest value (77 psi) is the tensile strength between propellant and E/E embedment resin. Tensile values for fiberglass-E/E and for SBR-E/E were not available, but they were expected to be much higher than 77 psi. Therefore a minimum tensile strength of 77 psi was established for any candidate resin in a bond test with each component.

The compatibility requirement was to be met by the resin in both the cured and the uncured states since some types of repair would involve direct contact of freshly mixed resin with the propellant. Furthermore, there was always the remote possibility that casting solvent might be present on the surfaces to be repaired.

The resin must cure at ambient temperature in order to avoid exotherms in excess of 200°F, the maximum safe temperature for CYI propellant. If this propellant is exposed for a long enough time to 400°F, it may ignite. Exotherms may build up to a considerable magnitude with some epoxy resins, especially when the resin must cure in a crevice between propellant and embedment layer where there is no conductive material to dissipate heat rapidly. Therefore, exothermic properties of candidate resins were taken into consideration. It should be noted at this point that highly exothermic systems have relatively short pot lives, a fact which would eliminate them as candidates anyhow.

The low viscosity requirement was imposed so that the resin could be forced through a #13 hypodermic needle into the case bond cavity. Furthermore, the more fluid the resin is, the more likely it is to be drawn into tapered areas by capillary attraction.

Finally, in certain types of repairs where the flame front must be retarded to prevent backburning, it is important that the adhesive have a low burning or decomposition rate. Partial burner tests, with blocks of propellant joined together by the candidate adhesive to form a cube, were scheduled for future work.

Table 32 presents data for candidate resins which cure at ambient temperature. From the standpoint of propellant compatibility and low viscosity, Sprint Potting Compound (Sprint PC)[1] and Epon 953[2] appeared to be the best choices. The E/E system was eliminated because in its uncured state it is incompatible with propellant. The Multron system, known to be susceptible to degradation by zinc compounds in SBR, was also eliminated as an active candidate.

Because of its lower viscosity and successful application in Sprint, the Sprint potting compound was chosen for evaluation first. It was demonstrated that freshly mixed resin could easily be pushed through a #13 hypodermic needle, but that the resin tended to thicken rapidly after the second hour; a reduction in initial viscosity was thus desirable.

The standard Sprint PC formulation consists of 90 pbw of Epon 871 (a flexible epoxy resin), 10 pbw of Epon 815 (a low viscosity epoxy resin containing 12% butyl glycidyl ether) and 13 pbw of Epon 946 B (a eutectic aromatic amine containing 3% Bentone-27 clay). Some properties of this system have been itemized in Table 33. Its tensile strength was low (and relatively constant over a 3-month period), but more than adequate to meet the first criterion. The high elongation was necessary so that it could expand and contract with the strains imposed on the patch. Its working life was limited to two hours by its viscosity which increased rapidly after reaching 2000 cps. Because the resin in both its cured and uncured forms was compatible with casting solvent, it was concluded that the resin would also be compatible with the less potent CYI propellant.

In spite of its ability to absorb a relatively large amount (9%) of nitroglycerin in a 7-day soak in casting solvent, it passed the

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(1) Epon 871/815/946 B in the ratio 90:10:13 pbw.

(2) Epon 953A/B (100:15 pbw). The 953A is a blend of flexible Epon 871 and rigid Epon 828 in a weight ratio of 3:1. The 953 B is a eutetic aromatic amine hardener. When this amine is made thixotropic with 3% by weight of Bentone 27, an inert clay, it is known as Epon 946B.

modified Taliani test. In a 23-hour period, neither cured nor uncured resin reacted enough with casting solvent to reach the maximum allowable pressure of 200 mm.

Attempts to modify the Sprint PC formulation were based on increasing the quantity of low viscosity epoxide, Epon 815, at the expense of the flexible Epon 871. Because of differences in the epoxide equivalent of each component, the modifications were compensated approximately by the amount of Epon 946B hardener. In some cases, exact stoichiometry was followed; in other cases, a nonstoichiometric ratio of hardener was used to obtain good flexibility and retention of compatibility with casting solvent. Brookfield viscosities were determined on each modified formula for periods up to three hours. The resins were then cast in silicone dogbone molds for mechanical property tests. These data are reported in Table 34.

A stoichiometric amount of Epon 946B would have been 15.8 parts for formulation 2B and 18.6 parts for 1C, 2C and 3C. The latter three experiments were attempts at reproducibility. The 1C dogbones were cured at ambient conditions for 47 days before testing; they had the highest average tensile and modulus values of all the nonstoichiometric formulae. The 3C dogbones were cured for 25 days and the 2C dogbones for 30 days at ambient. The values for these were reasonably close. The best modification was 2B because of its fair tensile strength and modulus, its high elongation and moderately low viscosity of 1000 cps. Dogbone cures at 300°F for three hours after allowing the resins to B-stage at ambient temperature for 16 hours resulted in considerably higher tensile strengths and moduli for the modified formulae. Comparative data for the standard Sprint PC formulation (2A) appeared to be anomalous and are not reported in the table. The average tensile strength and elongation of three Sprint slivers cured at ambient conditions for three days and tested at 0.1 in./in./min were 1050 psi and over 67%, respectively. From the other data in Table 34, it may be inferred that an oven cure would have yielded a considerably higher tensile strength and lower elongation.

A Taliani test was conducted on modification 2B with casting solvent. It generated a questionable 202 mm pressure and was tested again. A higher pressure (255 mm) was obtained the second time. Since it did not pass the compatibility test, the 2B formula was rejected, leaving the standard formula (2A) as the recommended resin for X259 motors.

b. <u>X248 Case Bond Repair Adhesive Tests</u>

During the course of this program it was necessary to repair an X248 motor CBS defect which required repair adhesive properties that the previously used polyurethane material did not meet. Laboratory testing was undertaken to expand the results obtained in the X259 laboratory testing to verify that the prime candidates would be satisfactory for X248 CBS repairs.

Laboratory support was provided in the form of bond strength determinations between standard Sprint PC (Formula 2A) and the various components of the X248 motor and also between modification 2B and the X248 components.

Square tensile specimens, described in Table 35, were prepared in triplicate utilizing Formula 2A adhesive and BUU propellant (freshly machined surface), nitrile butadiene rubber (NBR) insulation, Spiralloy mat (Epon 828, Catalyst D/E glass), Armstrong A2 adhesive, and aged motor case bond interface samples. The motor case bond interface samples were obtained from the unburned remains of fired X248 motor NPP-242. The motor samples were 2 in. square by 1 in. thick and consisted of insulator (NBR), Armstrong A2 adhesive, CA cloth/CBL-4, case bond interface, and BUU propellant. The CA cloth and case bond interface was manually separated and rebonded with Formula 2A without surface praparation. The separation of the CA cloth/CBL-4 interface produced a legging condition (i.e., strings or legs of degraded adhesive formed and then broke as the two surfaces were separated). The adhesive was presumably degraded by absorption of NG or some other propellant ingredient.

Round tensile specimens, described in Table 35, were prepared in triplicate utilizing formula 2B adhesive and NBR, Spiralloy, and Armstrong A2 adhesive. Propellant and motor samples were not prepared with formula 2B adhesive because it was shown to be incompatible with these components. Results of the case bond tests are recorded in Table 35. The data indicate good bond strength with Formula 2A (standard Sprint PC) and modified formulation 2B, with one notable exception. The CA cloth/CBL-4 surface (aged case bond interface) of the cut-up motor sample bonded poorly to the Sprint PC, resulting in a tensile value lower than the minimum requirement of 77 psi. This sample is believed to be more representative of the conditions likely to exist in a motor case bond separation, and this result is therefore highly significant since it indicates that at least under some conditions bonding of motor surfaces without surface preparation may result in low bond strength. The data also indicate that the modified resin (2B) was a better adhesive than the standard (2A) but it was abandoned because it was not compatible with casting solvent.

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Technical Investigation