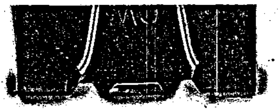

LOW-COST, LOW-WEIGHT CNG CYLINDER DEVELOPMENT

Final Report

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13. ABSTRACT *(Maximum 200 words)*

This program was established to develop and commercialize new high strength steel-lined, composite hoop-wrapped compressed natural gas (CNG) cylinders for vehicular applications. As much as 70% of the cost of natural gas vehicles can be related to on-board natural gas storage costs. The cost and weight targets for this program represent significant savings in each characteristic when compared to comparable containers available at the initiation of the program.

The program objectives were to optimize specific weight and cost goals, yielding CNG cylinders with dimensions that should, allowing for minor modifications, satisfy several vehicle market segments. The optimization process encompassed material, design, and process improvements. In optimizing the CNG cylinder design, due consideration was given to safety aspects relative to national, international, and vehicle manufacturer cylinder standards and requirements.

The report details the design and development effort, encompassing plant modifications, material selection, design issues, tooling development, prototype development, and prototype testing. Extenuating circumstances prevented the immediate commercialization of the cylinder designs, though significant progress was made towards improving the cost and performance of CNG cylinders. A new low-cost fiber was successfully employed while the weight target was met and the cost target was missed by less than seven percent.

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RESEARCH SUMMARY

Title	Low-Cost, Low-Weight CNG Cylinder Development
Contractor	Institute of Gas Technology 1700 South Mount Prospect Road Des Plaines, Illinois 60018-1804
Principal Investigators	M. E. Richards, K. Melford, J. Wong, L. Gambone
Report Period	December 1996 – November 1998
Objective	This program was established to develop and commercialize new high strength steel-lined, composite hoop-wrapped compressed natural gas (CNG) cylinders for vehicular applications. The program objectives were to optimize specific weight and cost goals, yielding two CNG cylinders with dimensions that should, allowing for minor modifications, satisfy several vehicle market segments.
Technical Perspective	A major obstacle confronting the widespread acceptance of natural gas vehicles (NGV) is their substantial cost premium over conventionally fueled vehicles. As much as 70 percent of the cost premium can be related to on-board fuel storage costs. Market growth is dependent on making NGVs more affordable and storage costs are the primary element. In 1996, the Gas Research Institute published a report co-authored by the Institute of Gas Technology and Powertech Labs concerning the market for and economics of fuel storage containers for natural gas vehicles. The report identified and assessed the market potential of compressed natural gas storage technologies and presented a number of cylinder optimization options with the greatest potential to reduce cylinder cost and weight while maintaining a high level of safety. This program was initiated as an outgrowth of the recommendations of the 1996 GRI report.
Results	Several production cylinders were fabricated and tested though extenuating circumstances prevented the immediate commercialization of the designs. Significant progress was made towards improving the cost and performance of CNG cylinders. A new low-cost fiber was successfully employed while the weight target was met and the cost target was missed by less than seven percent.
Technical Approach	The design optimization process encompassed material (higher strength steel and chemically resistant composite reinforcing fibers), design (wall thickness optimization and fabrication process selection), and process improvements (heat treatment and filament winding operations). In optimizing the CNG cylinder design, due consideration was given to safety aspects relative to national, international, and vehicle manufacturer cylinder standards and requirements.
Project Implications	Although the project did not immediately lead to a commercial product, important progress was made towards improving the cost and performance of NGV cylinders. The testing of chemically-resistant glass fibers will be of benefit to the industry in general and the frequent discussions with OEMs will likely lead to their acceptance of cylinders made with these fibers once they become widely available.

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INTRODUCTION

A major obstacle confronting the widespread acceptance of natural gas vehicles (NGV) is their substantial cost premium over conventionally fueled vehicles. As much as 70 percent of the cost premium can be related to on-board fuel storage costs. Market growth is dependent on making NGVs more affordable and storage costs are the primary element. In 1996, the Gas Research Institute (GRI) published a report co-authored by the Institute of Gas Technology (IGT) and Powertech Labs concerning the market for and economics of fuel storage containers for natural gas vehicles.[1] The report identified and assessed the market potential of compressed natural gas storage technologies that would significantly reduce the cost of on-board storage while also reducing weight. Based on weight, cost, and safety evaluations, the report presented a number of cylinder optimization options with the greatest potential to reduce cylinder cost and weight while maintaining a high level of safety. This report details a program involving Lucas Aerospace, IGT, and Powertech Labs initiated as an outgrowth of the recommendations of the 1996 GRI report.

OBJECTIVE

This project's objective was to develop two new Type 2 cylinders made from high-strength steel liners, hoop-wrapped with a composite fiber and resin matrix. Two sizes were to be developed: a 16-inch-diameter, 61-inch-long cylinder and a 16-inch-diameter, 34-inch-long cylinder. The longer cylinder was suitable for undercarriage mounting in a truck or van and in-bed mounting in pickup trucks, while the shorter cylinder was better suited for mounting in the trunk area of a passenger car. Both cylinders were intended for 3,600 psig service.

Figure 1 shows how typical cylinders in the market at the initiation of the project performed relative to weight and cost. Also shown are the request for proposal (RFP) target weight and cost for Type 1 and Type 2 cylinder designs under which this project was operating. Cylinder weight and cost (when expressed per standard cubic foot (scf) of gas storage volume) are very dependent on the dimensions of the cylinder. Smaller cylinders are naturally penalized because there is always some "fixed cost" in any cylinder design, and this fixed cost is more noticeable with small storage volumes. As the near-term expected market for NGV trucks and vans is much larger than that for passenger cars, the longer cylinder was the primary focus of this project. It is also generally much easier to make a shorter cylinder from an existing long cylinder design than to do the reverse. Qualification (to NGV2 standards[2]) of the shorter cylinder is also simpler once the longer cylinder is qualified.

Lucas recently manufactured steel-lined E-glass hoop-wrapped cylinders for the Ford Motor Company (Ford). The weight and cost performance of these cylinders appear in Figure 1 as *Current Designs*. Because some of these cylinders are somewhat small, they appear outside the area representing typical Type 2 designs. Two boxes also appear in Figure 1, each representing the proposed possible ranges of cost and weight that each of the cylinder designs undertaken in this project could achieve. The boxes should be interpreted as follows: it was predicted that the upper right corner of each box could be achieved with some certainty. As one moves towards the lower left corner (lower weight and cost), there was more uncertainty involved. The lower-left corner of each box represented approximately a 50 percent probability of success. Table 1 lists the bounding values of the two boxes described above.

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[1] Richards, M. E., et al., *Compressed Natural Gas Storage Optimization for Natural Gas Vehicles*, Final Report to the Gas Research Institute (GRI-96/0364), December 1996.

[2] *Basic Requirements for Compressed Natural Gas Vehicle (NGV) Fuel Containers*, American National Standards Institute (ANSI/AGA NGV2-98), 1998.

Figure 1. CNG Cylinder Weight vs. Cost

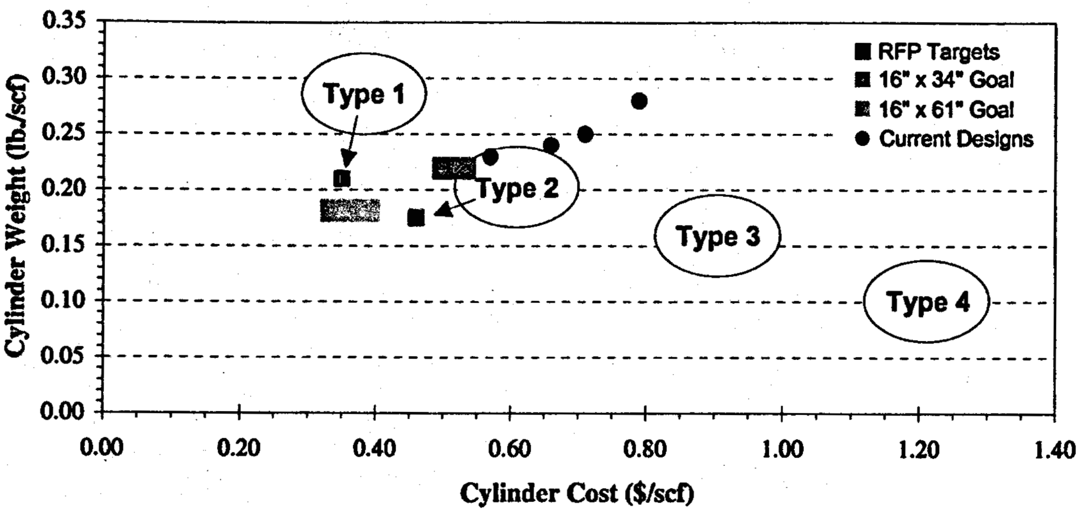


Table 1. Cost & Weight Goals

Design	100% Probability Weight (lb./scf)	 Cost ($/scf)	50% Probability Weight (lb./scf)	 Cost ($/scf)
16 x 61	0.19	0.40	0.17	0.32
16 x 34	0.23	0.54	0.21	0.48

The new cylinder designs continue to use (American Iron and Steel Institute) AISI 4130x steel as it is widely available in commercial quantities from a number of suppliers. Lucas has a great deal of experience using 4130x steels in deep draw processes for the manufacture of pressure vessels. Other alloys, such as chrome-vanadium and others, would require an exorbitant amount of testing and in-vehicle service experience to derive the same level of confidence in the final product as is exhibited by 4130x steels.

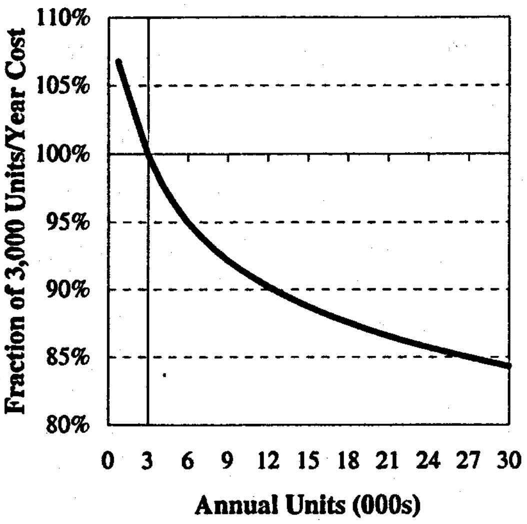
The cost goals detailed in Table 1 were based on an initial estimated production volume of 3,000 units per year. Figure 2 shows the expected effects of changes in production volume on product cost, expressed relative to base costs at 3,000 units per year. Full capacity for Lucas's facility, depending on the sizes of cylinders produced, was approximately 30,000 units per year. At an annual production volume of 30,000 units per year, costs could decrease by about 15 percent, yielding a cost between $0.27 to $0.34 per scf for the larger cylinder. At half capacity, cost for the larger cylinder falls between $0.28 to $0.36 per scf.

The program plan called for Lucas to manufacture 17 new cylinders for testing and evaluation during the course of the project. The plan also included over 60 pieces of material released into production, with the process development components being used for various trials and laboratory tests. Up to 10 additional cylinders would be made available to original equipment manufacturers (OEM) for evaluation. The following discussions are grouped by topic rather than chronologically.

PLANT MODIFICATIONS

During the project, Lucas made extensive modifications to their heat treatment facility to accommodate larger diameter cylinders of up to 16 inches in diameter and 72 inches in length. These modifications included widening of the heat-treating furnace doors, relining of the chambers with thinner insulation, and alterations to the process control logic.

Figure 2. Cost vs. Production Volume



Lucas worked with Pultrex (their winding machine supplier) to modify the fiber feed system to allow the use of internal pull spools. This change was made to accommodate the use of Advantex® glass fibers manufactured by Owens Corning. Several material handling issues were addressed, including the design of the disc transportation pallet and the establishment of a handling requirement checklist.

MATERIAL SELECTION AND ISSUES

Steel Liner

United States NGV container standards have, until recently, placed limits on the strength of steel one could use in a container. The intention of these limitations was to avoid possible sulfide stress cracking (SSC) problems in service. Changes to the standards replaced the specific strength limits with SSC test requirements. The strength level of the steel for the Lucas cylinders was determined by the steel's ability to pass the SSC test requirements of the NGV2 standard.

Lucas fabricated six 4130X steel test specimens in two compositions (melts) and three heat treatment temperatures. One sample was maintained within NGV2-92 requirements (strength less than 140 ksi). The three heat treatment levels corresponded to nominal strengths of 140 ksi, 150 ksi, and 170 ksi. These specimens were evaluated in regards to their fracture toughness and resistance to sulfide stress corrosion. Initial results indicated that strength in the neighborhood of 150 ksi, allowing for process variation (at most ± 10 ksi), would pass the sulfide stress corrosion test. Further testing refined the target strength to a value of 148 ksi. Several steel samples heat-treated to this strength successfully completed SSC testing as well as tensile and Charpy impact testing. Also, fracture performance tests were performed on steel samples to meet the requirements of the NGV2-98, clauses 18.13 & 18.4.

Lucas examined various changes to their requirements for steel composition and determined that in the areas where improvements could be achieved, these improvements would not significantly affect either the steel's quality or its SSC resistance. A new Lucas specification (402-3084) was issued for the single-source supply of plate and disc from British Steel.

Composite Reinforcement

The original intent of this project was to use carbon fiber as the basis of the new cylinder design's composite reinforcement. Carbon fiber has been shown to be more resistant than fiberglass to chemical attack, although some concerns have been expressed about the impact resistance of carbon fiber-based composites. Additionally, some OEMs favored carbon fiber-based cylinders. At the time the project was proposed, it was believed future prices for recently introduced types of carbon fiber would allow for a cost effective design. Later discussions between the project team and OEMs revealed that the OEMs—General Motors (GM) in particular—might be willing to use lower-cost acid-resistant glass fibers instead of carbon fibers. Fiber selection and liner development were highly interdependent as carbon and glass fibers yield appreciably different composite thickness for the same load-carrying ability. As the maximum outer diameter of cylinder was limited, fiber selection would determine the outer diameter of the liner and tooling parameters.

The project team decided to examine several types of fibers because potential customers were willing to consider fiber systems other than carbon and there was some uncertainty concerning future carbon fiber pricing. The availability and pricing for the six fiber types in Table 2 were investigated. Pricing information was obtained for production levels of 3, 10, and 30 thousand cylinders per year. Vetrotex was used in Lucas's existing designs. Tow refers to the number of individual fiber strands that make up the fiber roving (e.g., 12k tow consists of 12,000 individual fibers).

Table 2. Fibers Considered

Type	Supplier
Advantex glass (ECR)	Owens Coming
Zentron glass (ECR)	Owens-Coming
Vetrotex glass	Vetrotex
12k-tow carbon	Toray
Low-cost 48k-tow carbon	Zoltek
Low-cost 50k-tow carbon	Akzo Nobel

Two fiber application methods were also considered: wet winding, in which the fiber is passed through an epoxy bath prior to application onto the metal liner; and pre-impregnated (prepreg) winding, in which the epoxy and fibers are applied as a single entity as received from the manufacturer. Although prepreg material is more costly than the combined material costs of fiber and resin in a wet winding system, processing simplifications and improved yields using a prepreg system could yield net savings.

Cost Studies

The team evaluated the "as wrapped" costs to determine which fibers could meet the cost and performance goals of the project. As mentioned above, the original thrust of the project was towards carbon fiber. Team members met with representatives from Thiokol (now Cordant Technologies) to discuss the possibility of using Thiokol's prepreg carbon fiber technology. Thiokol quoted a range of prices (Table 3) dependent on purchased quantity. The quotes were developed using Fortafil 50k-tow carbon fiber from Akzo Nobel.

Table 3. Price/Quantity for Thiokol/Fortafil Prepreg
(Quoted March 1997)

Quantity (lb)	Price ($/lb)
< 1,000	14.50
1,000 to 10,000	14.00
10,000 to 25,000	13.50
> 25,000	13.00

Thiokol also provided estimated costs and composite weights for a variety of prepreg systems based on a 12-inch cylinder (Table 4). The costs were per cylinder and did not account for increases or decreases in other processing costs or required plant modifications. There was little benefit to using large-tow fiber compared to some traditional grades of carbon fiber. This was due to differences in physical properties of the fibers and in lower realizable strengths of large-tow grades once applied to a liner (i.e., translation strength).

Table 4. Carbon Prepreg Cost Comparisons

Composite Type	Designation	Composite Weight per Cylinder (lb.)	Composite Cost Relative to Large-Tow Prepreg
Large Tow Carbon	3C-50k	16.5	—
Traditional Carbon	T700-24k	10.7	$7.76
Traditional Carbon	T700-12k	10.3	$14.09
Traditional Carbon	G30-700	8.3	($45.99)
Traditional Carbon	M30S-18k	7.6	$56.37
Aramid	Twaron 2200	13.2	($51.67)

Traditional glass fibers were not considered from the outset due to their vulnerability to environmental attack. ECR glass, a more chemically resistant form of commonly used E-glass, had been available on a limited basis for some time, but its cost per pound was typically twice that of E-glass. During the project, Owens Corning announced that a new form of ECR glass (dubbed Advantex) would soon be available. Owens Corning's plans included initial production at three facilities in Canada, Belgium, and France. The new boron-free formulation came about in part because it minimizes air pollutants during the manufacturing process, helping Owens Corning meet environmental regulations. It was claimed Advantex would have strength and modulus properties on par with E-glass and would be priced similarly.

Advantex had certain advantages in that it cost much less per pound than carbon fiber and it could be used in Lucas's existing production processes. Wet winding carbon fiber posed potential production problems related to wet-out speed and carbon dust contamination of electrical equipment. Advantex's cost advantage was only slightly offset by its lower modulus (which requires a thicker wrap and reduces cylinder capacity for a given envelope) and greater density (which increases weight). The cost advantage in terms of dollars per scf was much more significant than the weight disadvantage in pounds per scf. Some modifications to Lucas's winding equipment were required as Advantex was packaged as an internal pull spool compared to Lucas's external pull setup.

Preliminary comparative cost figures showed the use of prepreg carbon fiber resulted in an increase in cost of about $200 per cylinder compared to wet-wound carbon fiber. The latter was about $200 more per cylinder than wet-wound Advantex glass fiber cylinder. These figures were for the 61-inch long cylinder and did not include some plant and process modification costs. The use of prepreg Advantex was not economically viable due to the relatively large amount glass needed and low cost of the Advantex fiber.

The cost analyses yielded two directions in which the project could go:

1. An Advantex-based composite using Lucas's existing or slightly modified manufacturing processes (wet winding).
2. A prepreg carbon fiber-based composite using a modified manufacturing process.

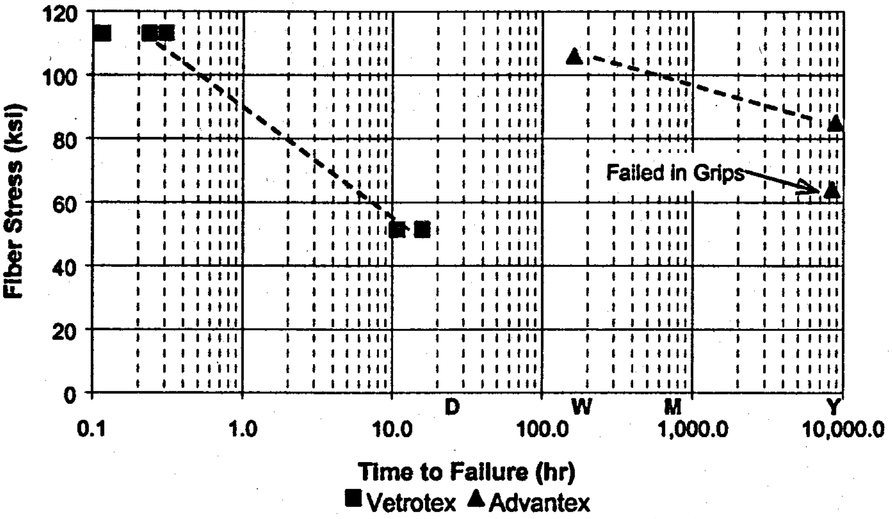
OEMs were willing to consider Advantex as an alternative to carbon fiber (assuming all qualification tests could be passed) and that the cost analyses favored Advantex. Thus, it was decided that further discussions with Thiokol regarding the prepreg carbon fiber approach would be suspended until the environmental performance of Advantex could be gauged.

Some consideration was also given to Twaron, an aramid fiber produced by Akzo Nobel. Twaron is similar to Kevlar, a DuPont product. Twaron was priced more competitively in Europe than in the United States due to U.S. import tariffs. Initial estimates of system cost showed that a Twaron-based system would be markedly less expensive than a carbon fiber-based system, though still more expensive than an Advantex-based system.

Environmental Performance

Initial environmental evaluations of Advantex fibers placed fabricated tensile samples under constant load exposed to a room temperature acidic environment. These tests showed that Advantex glass fibers were appreciably more resistant to acid attack than conventional glass fibers. Figure 3 shows the time to failure for Advantex and Lucas's existing glass fiber (Vetrotex) under different loading conditions. One Advantex specimen failed in the grip area, which is not considered a valid test. The letters D, W, M, and Y in Figure 3 indicate day, week, month, and year lengths of time.

Figure 3. Glass Fiber Acid Test Results



Based on the improved acid resistance at room temperature of Advantex in comparison to conventional E-glass, the team decided to forgo high-temperature acid resistance testing in favor of sub-scale prototype environmental testing. Lucas fabricated three cylinders (12-inch diameter by 60-inch length) using existing liners, epoxy, and processes—the only differences were the substitution of Advantex for Vetrotex fibers and the omission of coatings. All the cylinders went through environmental testing: two through a hybrid of the NGV2-98 and GM's Draft 6 environmental tests and one through the Canadian Standards Association (CSA) B51-97 environmental test.[3]

The CSA B51-97 environmental test was performed at Powertech. The cylinder was pressurized to 1.25 times service pressure and held for 100 hours while subjected to battery acid. The residual burst pressure was 10,600 psig, far in excess of the 7,650 psig required by the test and typical of the burst pressures observed on virgin cylinders. There was no evidence of damage to the Advantex fibers after the 100-hour acid exposure.

IGT discussed the future direction of Draft 6 with GM and received material from GM that indicated the likely revisions to Draft 6. As portions of Draft 6 are likely to be changed to be more similar to NGV2, those elements expected to change were performed to NGV2-98 rather than Draft 6. The test performed was a hybrid of NGV2-98 and GM Draft 6 and the specifics appear in Table 5.

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[3] *High Pressure Cylinders for the On-Board Storage of Natural Gas as a Fuel for Automotive Vehicles*, Canadian Standards Association (CSA B51-97 Part 2), 1997.

Table 5. NGV2/GM Draft 6 Hybrid Environmental Test

Test Step	Procedure	Comments
Preconditioning	Hybrid of NGV2 and GM Draft 6	Gravel impacts in the five "other fluid" (OF) areas and three on bottom. Pendulum impacts in the five OF areas, three on bottom in cylindrical section. (Dome impacts were omitted as the cylinders are Type 2). All preconditioning was performed at room temperature rather than –40°F prescribed in Draft 6. Two flaws were cut in the bottom area of the composite, one 0.030 inches deep by 8 inches long and the other 0.050 inches deep by one inch long.
Fluid Application (three times)	NGV2	GM Draft 6 will likely use NGV2 fluid specifications but its future application method is not clear.
Ambient Cycling	NGV2	The cycle sequence of NGV2 will be used (7,500 cycles at ambient, 3,750 each at high and low temperatures) though the high portion will be performed before the cold portion as it is believed that the high temperature cycling is the most injurious. GM Draft 6 pressure limits will be used (100 psi lower level rather than 10% of service pressure). GM Draft 6 will likely change its cycle sequence to match that of NGV2.
High Temperature Cycling	GM Draft 6	Temperature will be measured on the cylinder skin (composite) and controlled to GM Draft 6 specifications: 190°F. 3,750 cycles will be performed in one step as per the discussion above.
Low Temperature Cycling	GM Draft 6	Temperature will be measured on the cylinder skin (composite) and controlled to GM Draft 6 specifications: -60°F. 3,750 cycles will be performed in one step as per the discussion above. The upper pressure limit will be 80% of service pressure as GM Draft 6 will likely adopt this specification (rather than 125% of service pressure).
Burst	GM Draft 6	No leak test will be performed (a GM Draft 6 requirement) as this is directed at Type 4 cylinders, Type 2 cylinders that survive cycling should not leak.

Both cylinders were labeled according to Section 18.4.1 of NGV2-98. Figure 4 shows how the cylinders were marked. The thick line indicates the mid-line of the cylinder while the dashed line indicates the fill line when the cylinder is immersed in the saltwater solution. The dashed circles do not need to be drawn on the cylinders.

Preconditioning

Gravel impacts were performed on the five "other fluid" (OF) areas and three on the bottom. Pendulum impacts were performed on the five OF areas and on five areas on the bottom of the section. All preconditioning was performed at room temperature rather than -40°F prescribed in Draft 6. Two flaws were cut in the bottom area of the composite, one 0.030 inches deep by 8 inches long and the other 0.050 inches deep by one inch long. The drops specified by Draft 6 were also omitted as they are primarily directed at Type 4 containers.

Upon completion of the gravelometer impact tests, each impact area was evaluated and assigned an ASTM chip rating.[4] Table 6 lists the impact areas for each cylinder and their corresponding chip ratings. Figure 5 shows sample ASTM chip ratings.

Figure 4. Representation of Cylinder Markings and Preconditioning Locations

(P = Pendulum, G = Gravelometer)

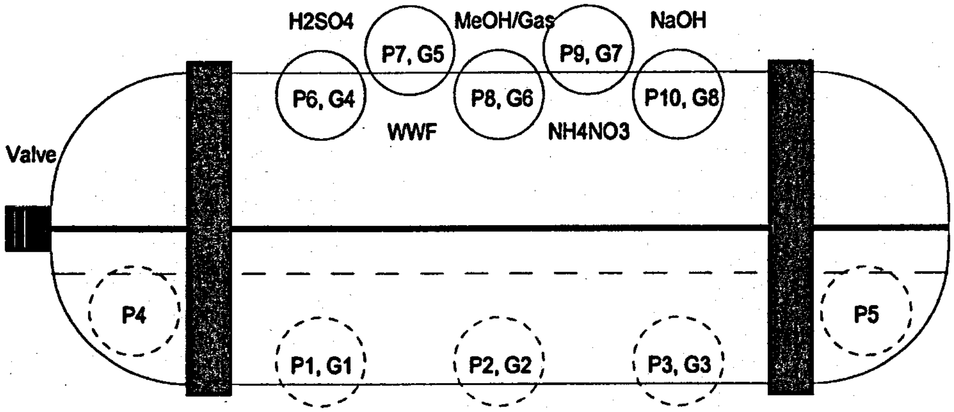

Table 6. Gravelometer Impact Results

Area	Cylinder A	Cylinder B
P1G1	4B	4C
P2G2	4B	4C
P3G3	4B	3C
P6G4	5B	3C
P7G5	4B	3C
P8G6	4B	5C
P9G7	4C	3C
P10G8	4B	3C

Fluid Application

It was expected that Draft 6 would use NGV2 fluid specifications, though the exact application method was still unknown. Therefore the application method and fluid compositions specified in NGV2 were used.

Cycle Testing

The cycle sequence of NGV2 was used: 7,500 cycles at ambient, 3,750 each at low and high temperatures. Draft 6 was expected to change to match the cycle sequence of NGV2. Because it was believed that the high temperature cycling is the most injurious the high portion was performed before the low portion. Draft 6 pressure limits were used (100 psig at the low lower level rather than 10% of service pressure). Draft 6 also specified an exact cycle profile of 15 seconds to pressurize, 60 seconds held at pressure, and 15 seconds to depressurize. This pressure profile was not strictly adhered to because it was believed that the NGV2 requirements were sufficient and the Draft 6 requirements were neither more nor less severe. To expedite testing, both cylinders were cycle tested simultaneously.

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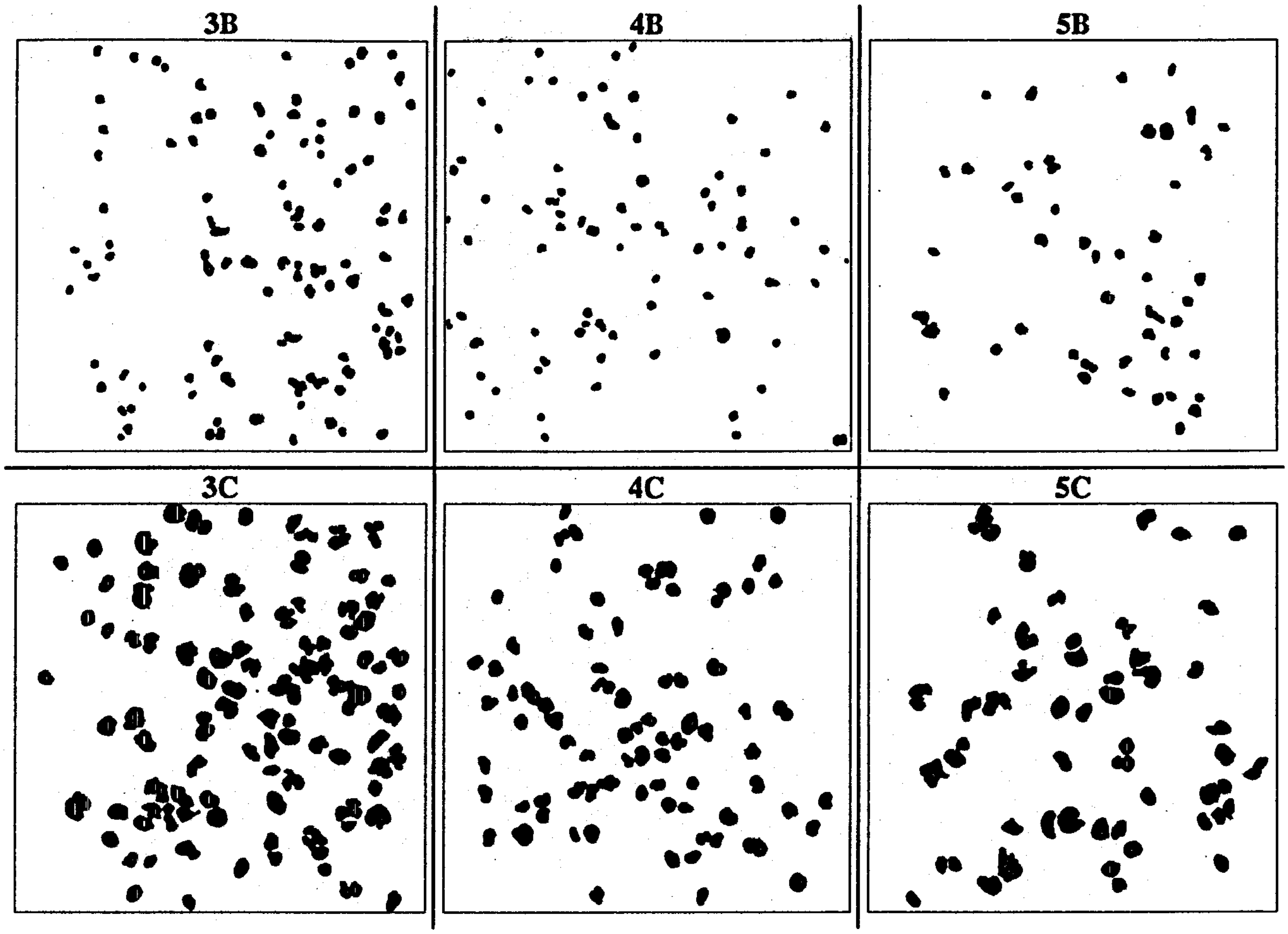
[4] *Standard Test Method for Chipping Resistance of Coatings*, American Society for Testing and Materials (D3170-87(1996)e1), 1997.

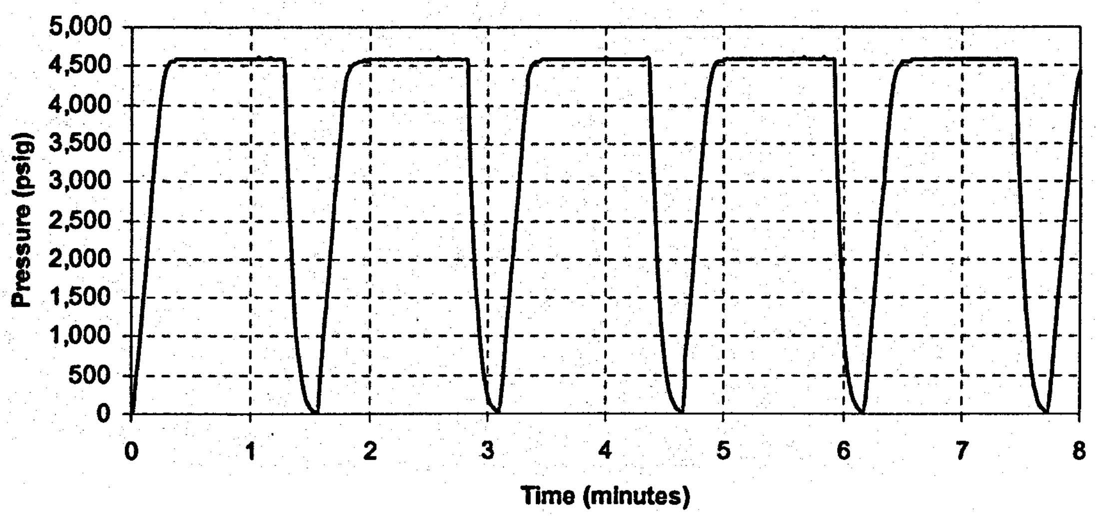
Figure 5. Sample ASTM Chip Ratings



Ambient Cycling

Figure 6 shows the typical pressure profile versus time during the ambient cycle test segment.

Figure 6. Ambient Cycling Pressure Profile



Inspection of the cylinders after the ambient cycling portion of the test did not reveal any signs of stress corrosion cracking, composite discoloration, delamination, loose fibers, or cylinder bulging.

High Temperature Cycling

Temperature was measured on the cylinder skin (composite) and controlled to GM Draft 6 specifications of 190°F. A buffer volume of hydraulic fluid was used to help maintain cylinder surface temperature. Figure 7 shows the typical pressure profile versus time graph during the high-temperature cycle test segment.

Figure 7. High-Temperature Cycling Pressure Profile

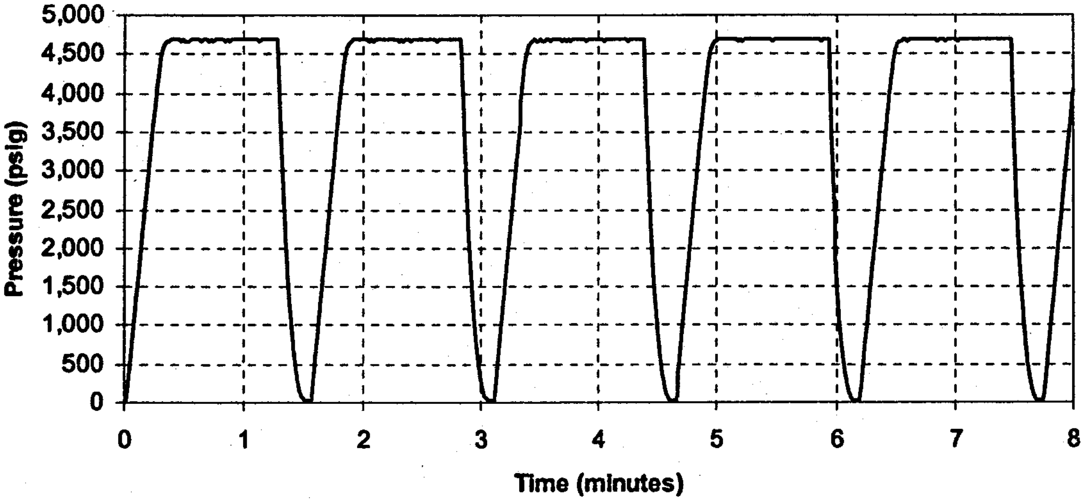
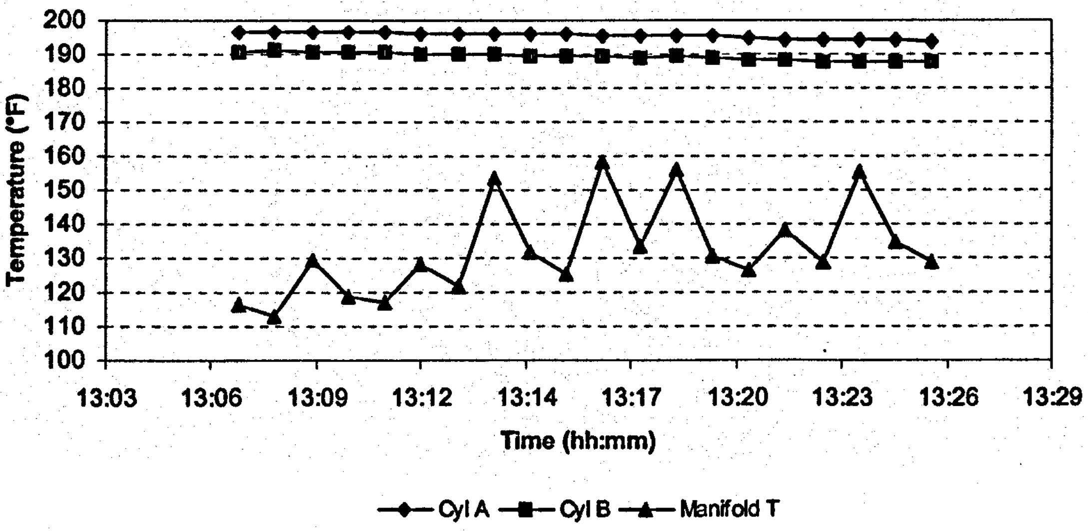


Figure 8 shows a sample of the temperature traces during the high-temperature cycling segment. The time axis is time of day, not test duration. The trace of hydraulic fluid manifold temperature was measured before the fluid buffer, which exhibited a much lower temperature than the cylinder surfaces. The variation in this trace was due to flowing "cold" fluid from the pump on pressurization and "hot" fluid from the downstream system on depressurization. The temperature of the surrounding environment was only slightly higher than the cylinder surfaces.

Figure 8. High-Temperature Cycling Temperature Profiles



Upon completion of the high-temperature cycles, inspection of the cylinders did not reveal any signs of stress corrosion cracking, delamination, loose fibers, or cylinder bulging.

Low-Temperature Cycling

Temperature was measured on the cylinder skin (composite) and controlled to GM Draft 6 specifications of -60°F. A buffer volume of hydraulic fluid was used to help maintain cylinder surface temperature. The upper pressure limit was 80% of service pressure as it was expected that Draft 6 would likely adopt this specification (rather than 125% of service pressure). No leak-related interruptions were experienced.

Cycling at -60°F presented a particular challenge as that temperature was very close to the pour point of the hydraulic fluid used. Even with the buffer volume and the surrounding environment in the neighborhood of -100°F, it was not possible to cycle indefinitely. Hydraulic fluid heating due to flow friction and heat of compression would gradually raise the temperature of the cylinder surfaces. Cycling was halted until such time that the cylinder surfaces were sufficiently below -60°F to continue.

Figure 9 shows the typical pressure profile versus time graph during the low-temperature cycle test segment.

Figure 9. Low-Temperature Cycling Pressure Profile

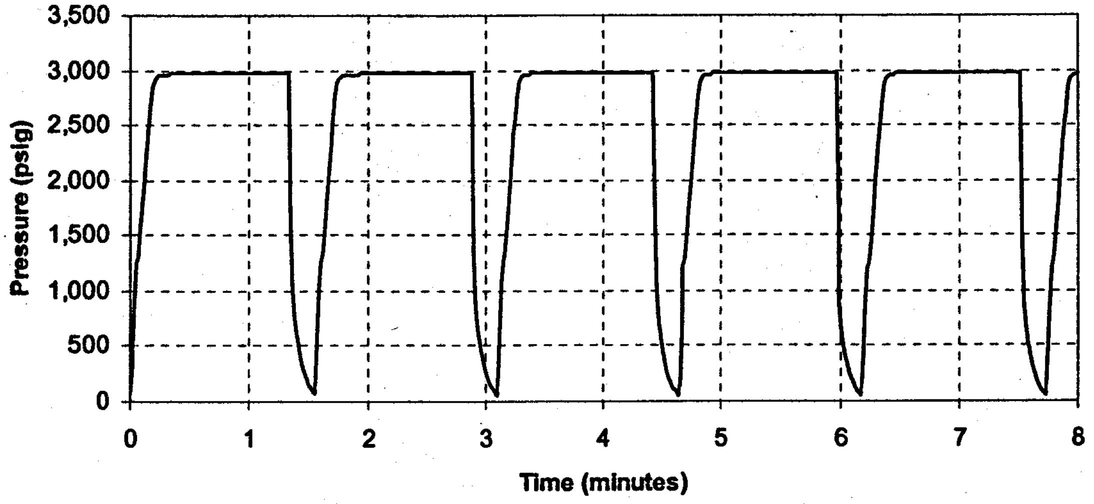


Figure 10 shows a sample of the temperature traces during the low-temperature cycling segment. The three *Cham Tx* traces are of thermocouples within the chamber. These temperatures typically varied between -70°F and -100 °F. The uppermost trace (*Man T1*) is the hydraulic fluid temperature before the fluid buffer. The oscillation in temperature was due to a combination of warm fluid coming in from the pump, fluid heating due to friction and compression, and subsequent cooling during the one-minute holds and depressurization. *Man T2* is the hydraulic fluid temperature after, or on the cylinder side of, the fluid buffer. Note the gradual rise in *Man T2* over time. The non-steady-state characteristics shown here are typical of cold-temperature cycling.

At the completion of the low temperature cycling phase, inspection of the cylinders did not reveal any signs of stress corrosion cracking, delamination, loose fibers, or cylinder bulging. Figure 11 and Figure 12 show the acid application areas of each cylinder at the completion of the cycle segments. Some hairline cracking and minor discoloration were evident, but these conditions are typically benign.

Figure 10. Low-Temperature Cycling Temperature Profiles

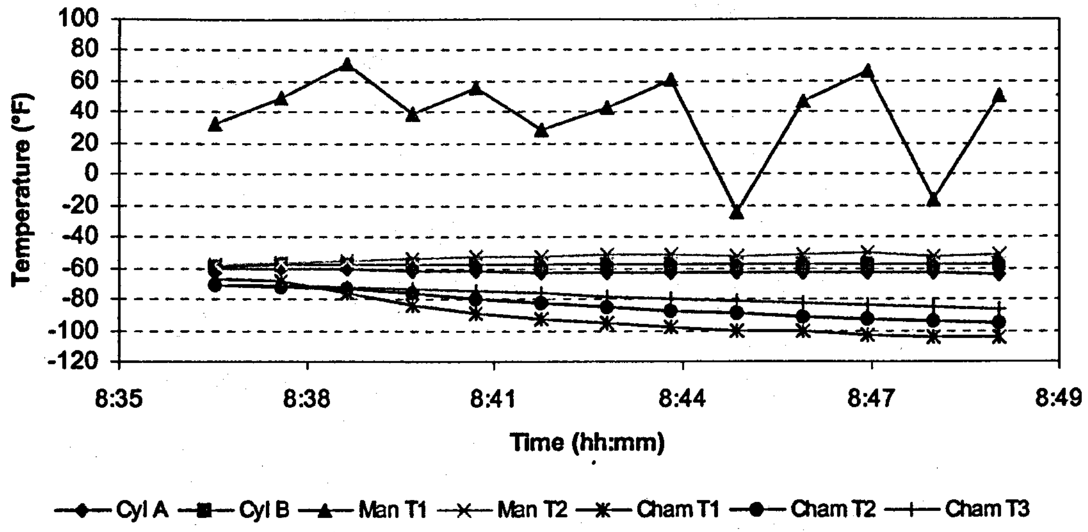


Figure 11. Acid Application Area, Cylinder A

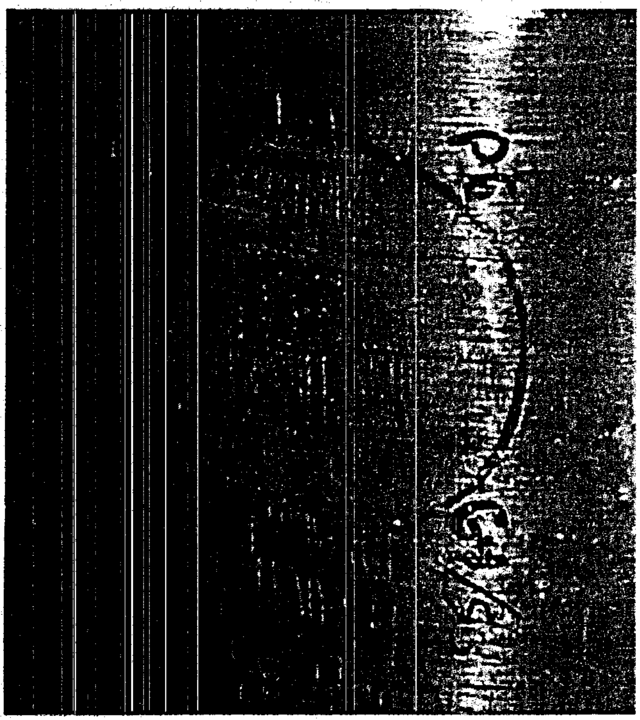
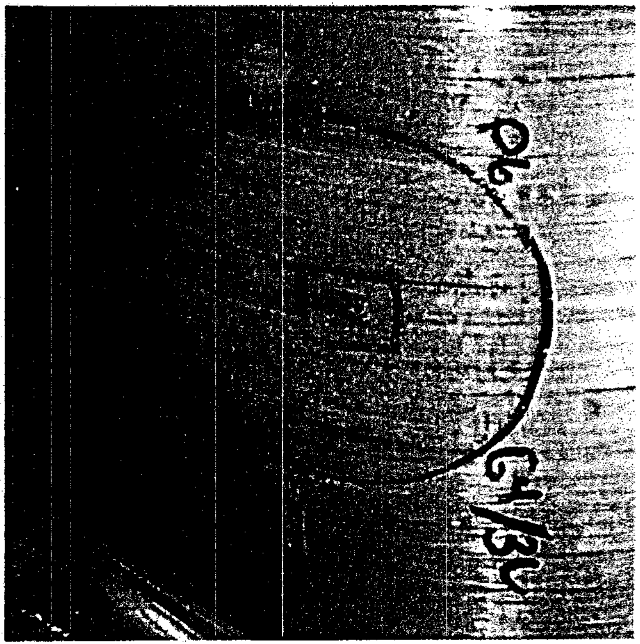


Figure 12. Acid Application Area, Cylinder B



Burst Testing

No leak test was performed (Draft 6 requirement) as this is aimed at Type 4 cylinders. Type 2 cylinders that survive cycling should not leak. Draft 6 required that cylinders hold two times service pressure rather than the 1.8 times service pressure required by NGV2. Cylinder A was pressurized to slightly over two times service pressure and held there for approximately 20 seconds. The cylinder did not fail at two times service pressure and remains available for inspection. Figure 13 shows the pressure profile for Cylinder A. Cylinder B was pressurized to failure. Figure 14 shows the burst pressure profile for Cylinder B. The maximum recorded pressure in the test of Cylinder B was 9,865 psig, well in excess of the 7,200 psig requirement.

Figure 13. Burst Pressure Profile, Cylinder A

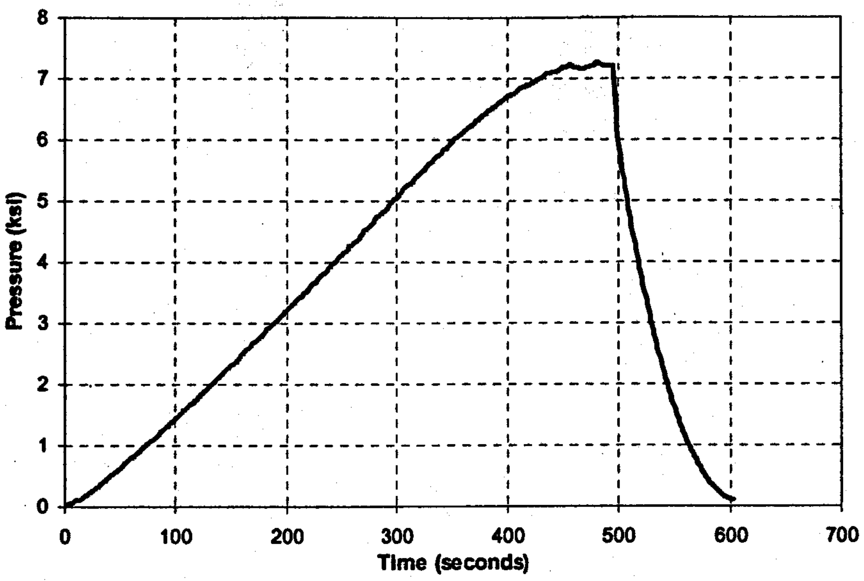


Figure 14. Burst Pressure Profile, Cylinder B

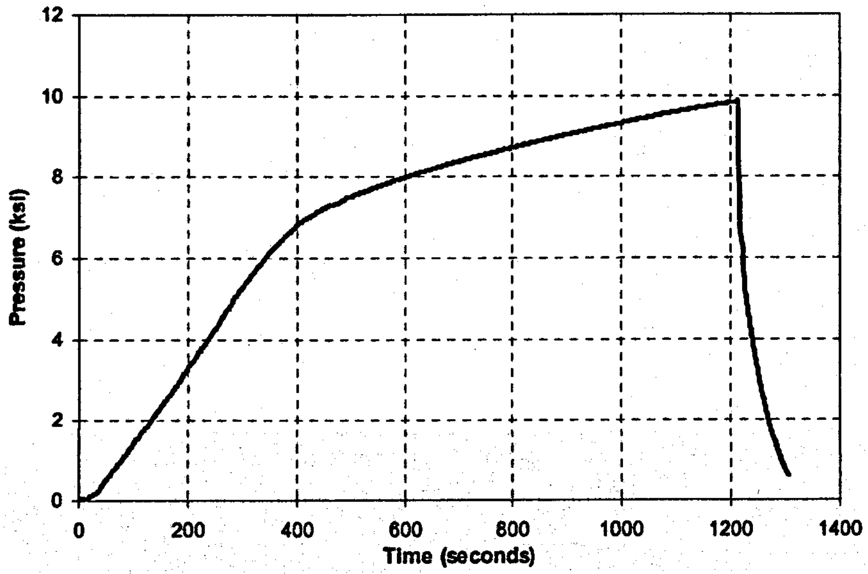


Figure 15 through Figure 17 show Cylinder B after the completion of the burst test. It appeared as though the composite failed in the area of the 8-inch by 0.030-inch induced flaw (Figure 16). There was also some composite separation at the location of the 1-inch by 0.050-inch induced flaw (Figure 17) but it was not as dramatic.

Figure 15. Cylinder B After Burst Test

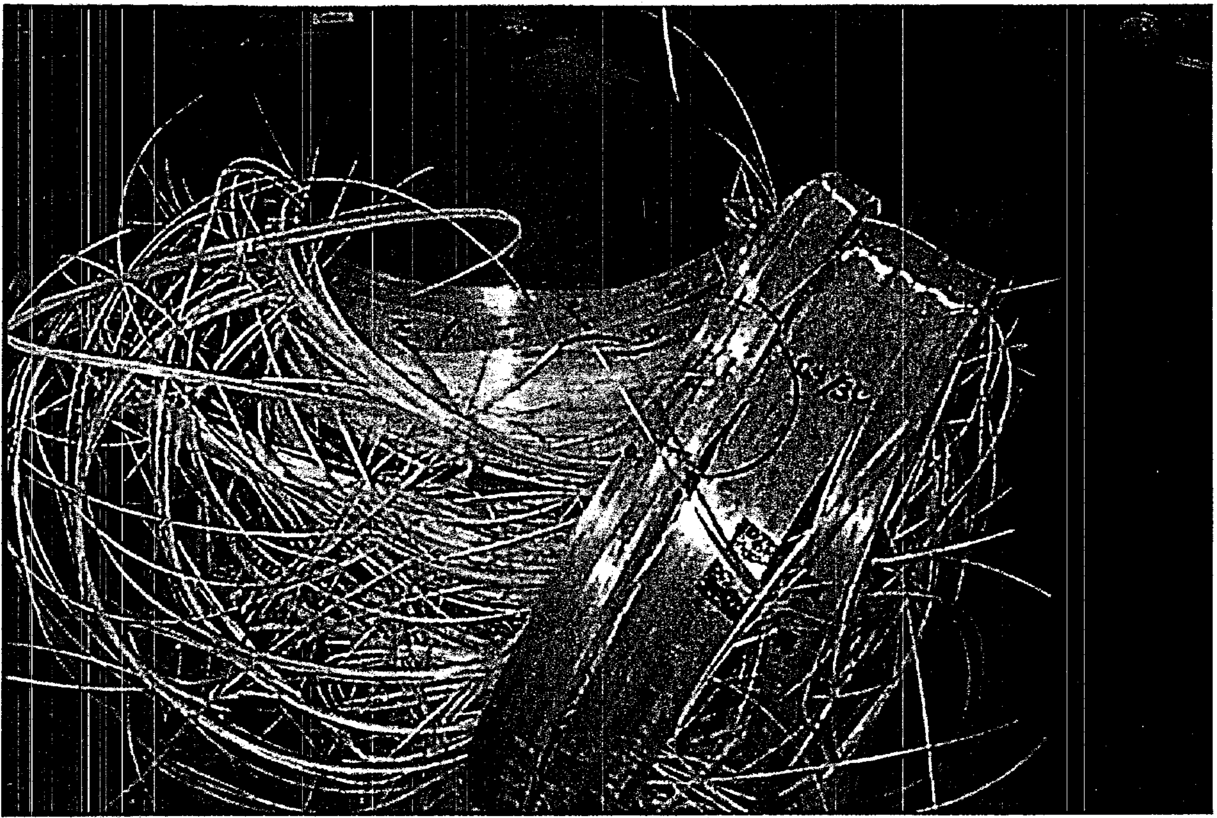


Figure 16. Cylinder B, Opposite Side

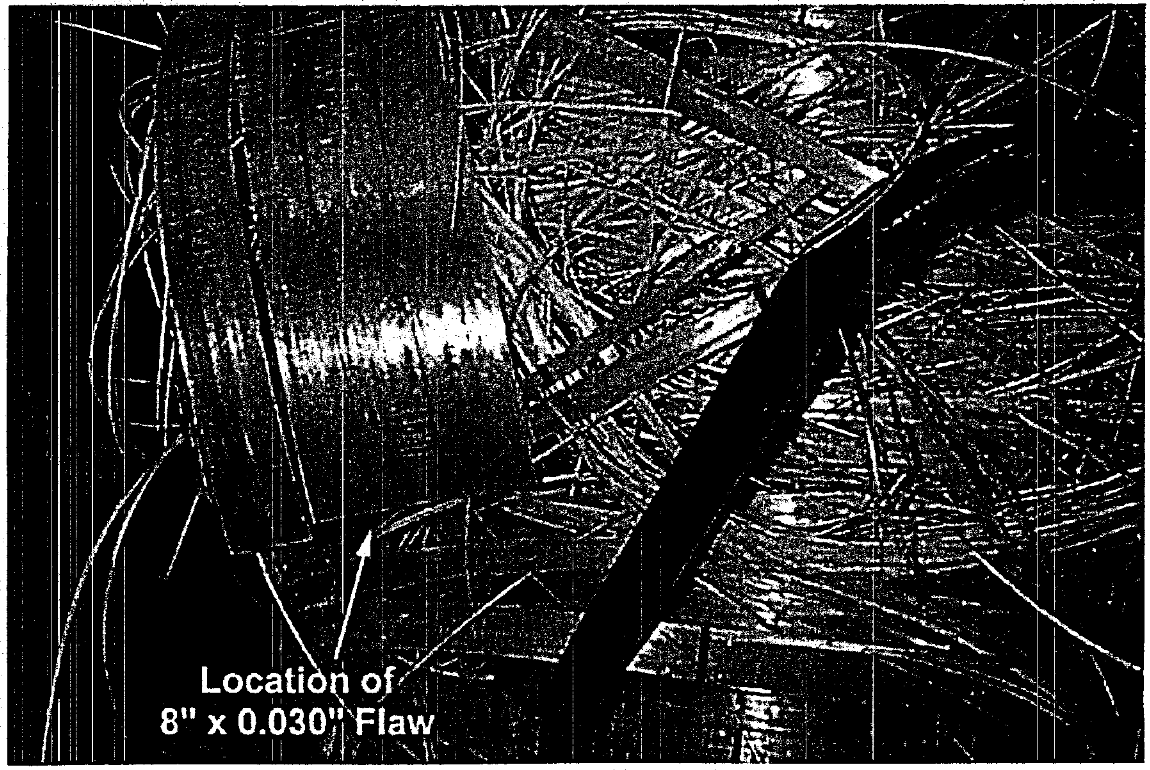
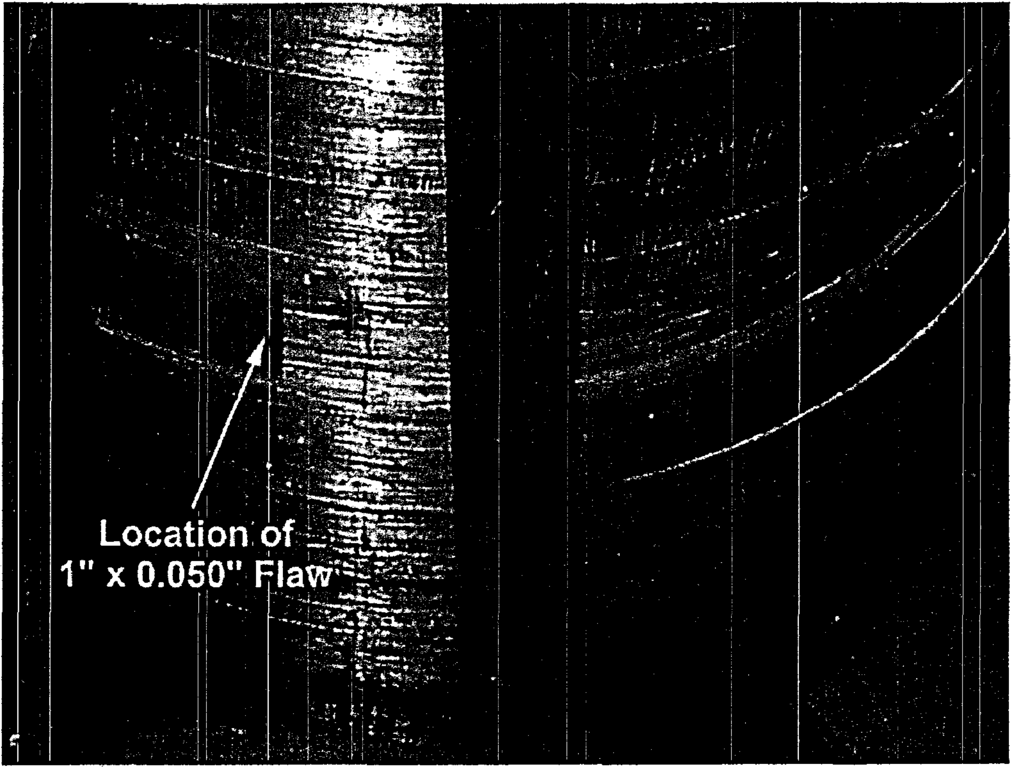


Figure 17. Cylinder B, Dome End



Environmental Testing Conclusions

According to Lucas, the burst strength of Cylinder B was nearly that of a virgin cylinder—no more than 10% lower. It is highly probable that the acid, as applied in this test, did not affect the composite in an appreciable manner. The degradation in burst strength could be attributable to the number of pressure cycles endured during the test. It could also be attributable to the cut induced in the cylinder at the start of the test. An informal inspection indicated that the failure might have initiated at this location. It is important to keep in mind that the cylinders tested were uncoated. Traditional E-glass cylinders, if uncoated, could be expected to fail either NGV2-98 or Draft 6 environmental tests.

Lucas and IGT made separate presentations to GM/Impco and to Ford at their facilities regarding the environmental testing of the Advantex-wrapped prototype cylinders. The test results were well received, though GM would still require production cylinders to pass Draft 6. The interim test report written by IGT was distributed to both organizations.

During the above meeting GM explained that they were reviewing Draft 6 to bring it more in line with NGV2 and that they may require additional cylinders for testing to both the existing and future versions of Draft 6.

DESIGN ISSUES

Starting stock plate thickness was established early in the project as it affected tooling design, the longest lead-time item. A review of end geometry using an elliptical design indicated no major improvement to the target project requirements. Design calculations for cylinder geometry were reviewed to establish the needed plate thickness. The press used for the first cupping operation fixed the maximum initial disc diameter. A larger diameter disc allowed some reduction in initial plate thickness and reduced the volume of the metal in the dome end of the cylinder. However, this did not markedly affect the target project requirements. Also, the existing Lucas cylinder design report for their existing line of Ford cylinders was reviewed to determine the necessary changes to optimize the design.

Lucas visited with potential customers to discuss targets for cylinder size, weight, and cost. As a result of these discussions, it was decided that the cylinders would have an outer diameter of 16.3 inches and lengths of 61 and 34 inches. In discussions regarding the impact of using Advantex versus carbon fiber composites, potential customers indicated that a slightly undersized cylinder could be accommodated whereas a slightly oversized cylinder would be undesirable. This topic was addressed with potential customers because a liner designed for a fiberglass composite would be smaller than one designed for a carbon fiber composite. Once a final decision was made regarding liner diameter and tooling development commenced, significant changes in liner diameter would result in costly and time consuming tooling redesign.

A finite element model was prepared and stress analyses were completed based on a process minimum steel strength of 140 ksi (150 ± 10 ksi). The design liner wall thickness was 0.250 inches for all fiber types. Three composite systems were examined—Table 7 lists the thickness of each system's composite wrap and an estimate of the specific weight of the resulting 16.3-inch diameter, 61-inch long cylinder. The design report appears in Appendix A.

Table 7. Composite Thickness and Estimated Cylinder Specific Weights

Composite System	Composite Thickness (inches)	Specific Weight (pounds per scf)
Advantex/Epoxy	0.250	0.173
T700/Epoxy	0.150	0.160
Twaron/Epoxy	0.225	0.163

Process tolerances for the liner were determined and led to reduction in wall thickness variability by approximately 50 percent compared to present Lucas production. The design wall variation at the cylinder's mid-length was fixed at 0.014 inches. Results from the units manufactured indicated a process variation of 0.012 inches was possible. Process drawings for the liner, composite overwrap, and label stages were issued.

Benchmarking

Lucas benchmarked competitors' manufacturing processes to support design and manufacturing decisions. The benchmarking effort included a comparison between Lucas's existing deep drawing and ironing processes and flow forming cylinders direct from hot drawn tube. It was found that the most cost effective and least technologically risky manufacturing method should remain deep drawing and ironing from steel plate stock. The benchmark effort also led to the development of a cost model that was used to derive the product cost and selling price for the project targets in terms of dollars per scf.

Lucas examined the feasibility of adding a flow forming process to better control wall thickness. As Lucas did not have flow forming equipment of the proper size in-house, the advantages gained from the flow forming step would be outweighed by the increased processing cost, time, and transportation cost. Also, the potential uncertainty of flow former availability from a third party was problematic.

TOOLING DEVELOPMENT

The tooling concept design was completed, which led to tool design and tool stress analysis. The draw reduction ratios were computed, enabling starting stock and draw concepts for the liner to be calculated. Lucas's first cup subcontractor (Royal Ordnance) assisted in the development of the early cupping stage (tool design, handling systems modification, and production development). Initial tooling design placed the maximum material on both the punch and die. During tooling and prototype development, material was removed from the die to achieve the desired container wall thickness.

A total of twelve discs were plasma cut, spheroidized, and phosphated in preparation for Cup 1 production at Royal Ordnance. This was the Tool Try Out (TTO) batch from which the three cylinders for long term testing were produced. The twelve initial discs were successfully advanced to the Cup 2 stage at Royal Ordnance. One unit was retained at Royal Ordnance for mechanical handling trials and the remaining eleven units were returned to Lucas for further processing.

The increased diameter hot-spin heating coil was installed. Lucas moved its ultrasonic testing to after the external shot blast process step. This change yielded more consistent results. The test piece used to calibrate the ultrasonic testing equipment had a known defect 0.012 inches deep. This was equivalent to only 4.5 percent of the liner wall thickness and an improvement on the BS5045[5] requirement of 5 percent. Machining was brought partially in-house and it was expected that the majority of machining would be performed in-house. The outside contractor was retained to provide backup machining capacity.

PROTOTYPE DEVELOPMENT

A dummy unit, simulating the new liner design, was manufactured and the unit successfully passed through the proposed production operations.

Following the completion of tooling development, eleven initial units successfully completed the Draw 3 operation. The Draw 4 punch was installed and these eleven units completed the Draw 4 operation. Two units were used to obtain the hot spin parameters and the remaining nine units passed through the hot spin, internal clean, and harden/temper processes. Hardness tests were performed at three places along the liners. The results from the nine units showed a hardness range of HB 293 to 300. This is equivalent to an ultimate tensile strength (UTS) range of 141 to 158 ksi. The target tolerance range was 140 to 160 ksi. Test samples taken from a liner after heat treatment showed a 151 ksi UTS. Three impact test pieces were also taken from the sample and yielded Charpy impact values of 105, 110, and 115 J/cm^2.

After neck machining, the nine units were internally cleaned, grit blasted externally, ultrasonically tested, weighed, dimensionally inspected, and primer coated prior to filament winding. The liner dimensional inspection indicated a wall thickness towards the top end of the required range. The average wall thickness mid-way along the liners was 0.275 inches. The filament winding program was confirmed by dry winding and the nine units were successfully filament wound and cured. Because the steel liner was towards the top end of the required range, the thickness of the overwrap was targeted to the minimum requirement (0.250 inches). The nine cylinders were autofrettaged, weighed, dimensionally inspected, and given a 0.001-inch top coat of polyurethane varnish. These nine cylinders were prepared for shipping to IGT.

One liner used for obtaining the hot spin parameters was heat treated and sent for neck machining prior to its use as a liner burst sample.

Twenty-nine additional discs were pressed into Cup 1 at Royal Ordnance. This, together with the Cup 2 unit previously retained at Royal Ordnance, provided sufficient units to complete the contract. Thirty units were progressed to Cup 2 should further cylinders be required.

PROTOTYPE TESTING

Due to Lucas's decision to discontinue NGV cylinder production (see **Other Considerations**), the planned qualification testing program was scaled back. It was felt that the prospects were slight for a sale of the entire plant. If, for instance, another company acquired only Lucas's design to produce with their own equipment and tooling, it would be necessary to qualify cylinders manufactured on that equipment. Thus it was established jointly between Lucas, IGT, and GRI that six cylinders would be used for evaluation and testing at IGT. Three cylinders were subjected to ambient cycling (section 18.3 of NGV2-98) and three others to hydrostatic burst testing (section 18.5 of NGV2-98).

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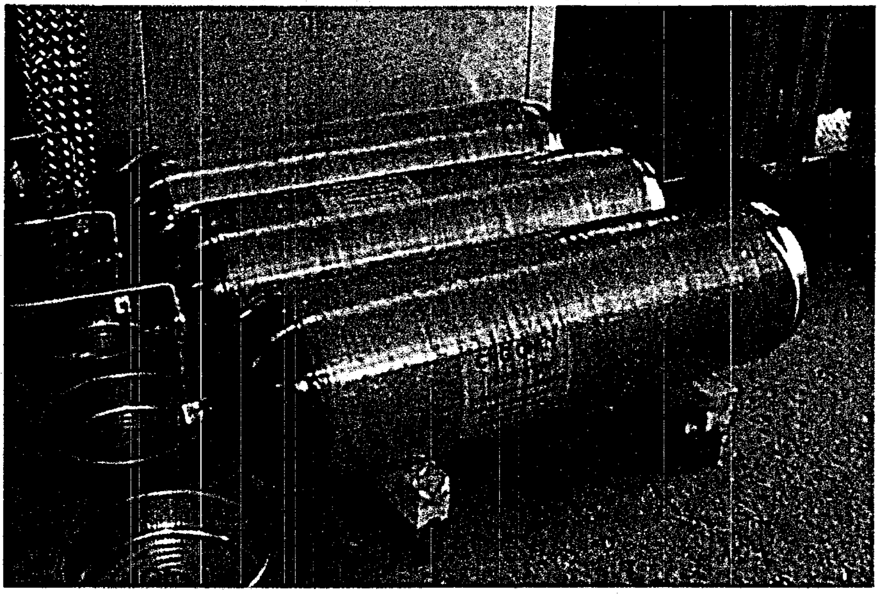
[5] *Transportable Gas Containers*, British Standards Institution (BS5045, Part 1), 1982.

Ambient Cycling

The NGV2-98 ambient cycling test requires that finished containers be pressure cycled at ambient temperature to failure or 45,000 cycles. The pressure range for cycling is from 12.5 to 125 percent of service pressure. The cycling rate is limited to no more than ten cycles per minute. The containers shall not fail before reaching a number of cycles equal to 750 times the design life of the containers in years (e.g., 15,000 cycles for a container with a 20-year design life). After this point, the containers may fail by leakage but the composite fibers are not allowed to fail. To expedite testing, all three cylinders were cycle tested simultaneously (Figure 18).

Figure 18. Prototype Cylinders (F, G, H)



The cycling rate was rather slow due to the large size of the containers and that three were being cycled simultaneously. Figure 19 shows the typical pressure profile versus time approximately 2,000 cycles into the test.

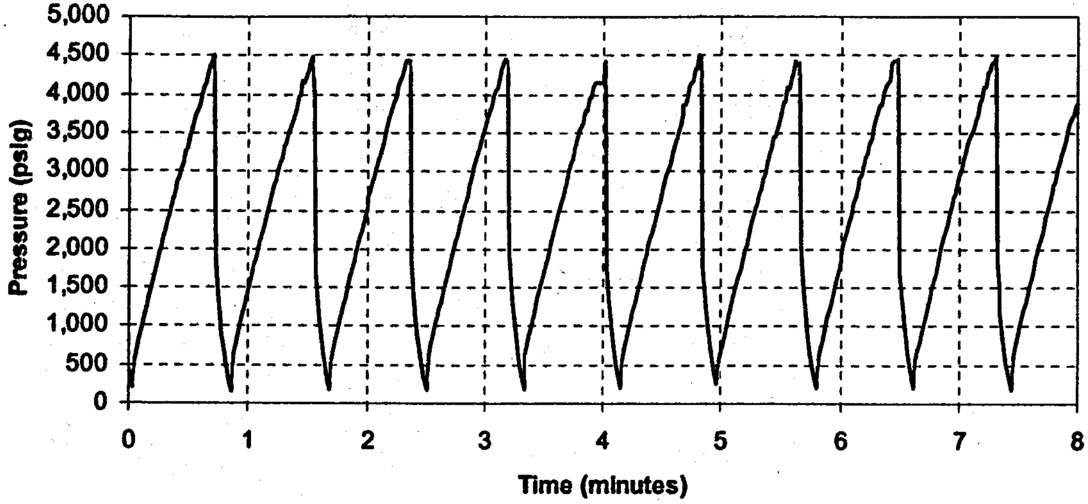
All three cylinders successfully completed 15,000 cycles. At approximately 24,520 cycles, one of the cylinders developed a leak under the composite approximately one foot from the edge of the composite wrap. The composite structure was intact. A second cylinder failed in a similar fashion at approximately 30,690 cycles. The remaining cylinder successfully completed 45,000 cycles. All three cylinders met the requirements of the ambient cycling test of NGV2-98.

Hydraulic Burst

The hydraulic burst test in NGV2-98 requires that containers be pressurized to failure at a rate not exceeding 200 psi per second at pressures below 80 percent of minimum required burst pressure, and not exceeding 50 psi per second at pressures above. For Type 2 cylinders, a liner is also burst and must achieve 125 percent of service pressure (4,500 psig for a 3,600 psig service pressure cylinder).

The burst pressure for the liner was 5,829 psig. If the minimum UTS were to be encountered, a burst pressure of 5,440 psig would be expected (5,829 x 140 / 150). If, in addition, the minimum wall thickness were encountered, a burst pressure of 4,945 psig would be expected (5,440 x 0.25 / 0.275). Therefore, the margin of safety at minimum UTS and minimum liner wall thickness is 1.1 (4,945 / 4,500).

Figure 19. Ambient Cycling Profile, Early Testing



Three cylinders were pressurized to failure—failure here meaning failure of the composite. Typically, the composite of a Type 2 cylinder will rupture, causing a slight increase in the volume of the liner that results in a sudden and large pressure drop (assuming that the pumping equipment does not have so much flow capacity to very quickly catch up). Once this pressure drop is observed, the test is halted. The liner is usually intact at this point. If pressurization were to continue, the maximum pressure realized after the initial composite rupture will not be greater than the pressure realized at the time of composite failure.

Figure 20 shows the pressure profile for Cylinder F, which achieved a maximum recorded pressure of 9,435 psig. The slight dip just past 2,000 seconds was attributable to the test equipment, not any change in the cylinder. Figure 21 shows the same profile for Cylinder G, which achieved a maximum recorded pressure of 9,206 psig. Finally, the profile for Cylinder H appears in Figure 22. Cylinder H reached a maximum recorded pressure of 9,430 psig. Minimum burst pressure for this design was 9,000 psig, thus all cylinders met the test requirements.

Figure 20. Burst Pressure Profile, Cylinder F

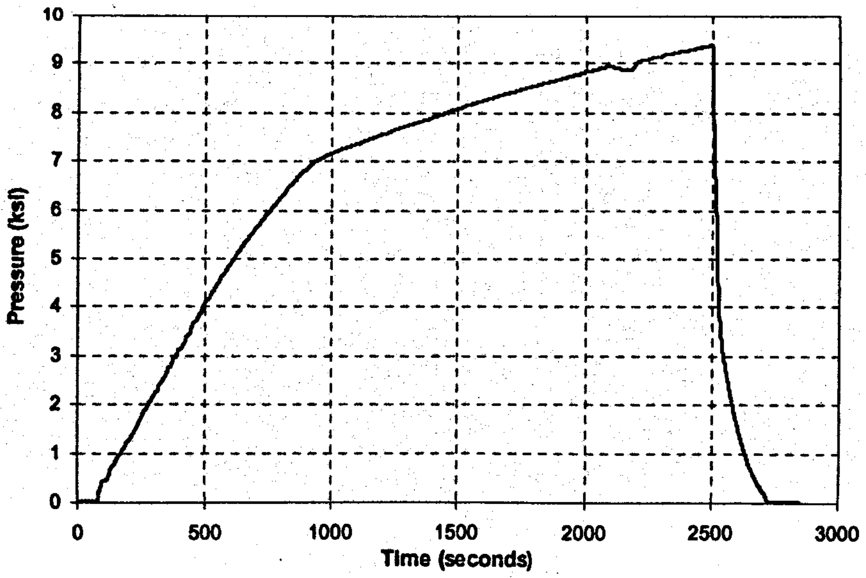


Figure 21. Burst Pressure Profile, Cylinder G

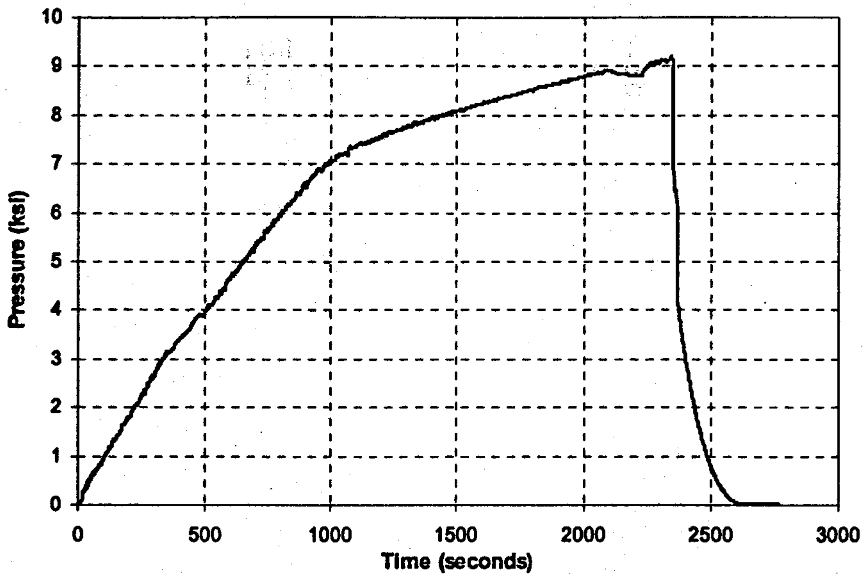


Figure 22. Burst Pressure Profile, Cylinder H

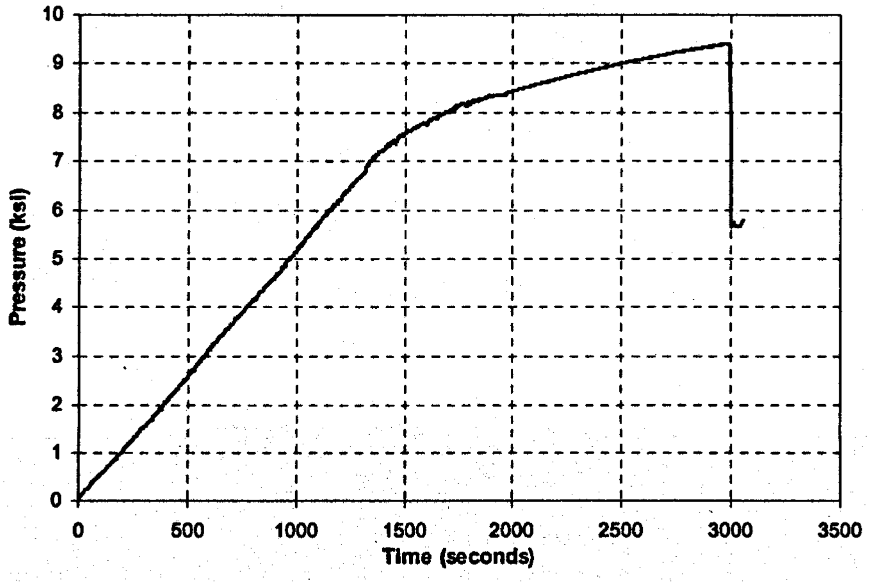


Figure 23 through Figure 25 show Cylinders F, G, and H after completion of the burst tests.

Figure 23. Cylinder F After Burst Test

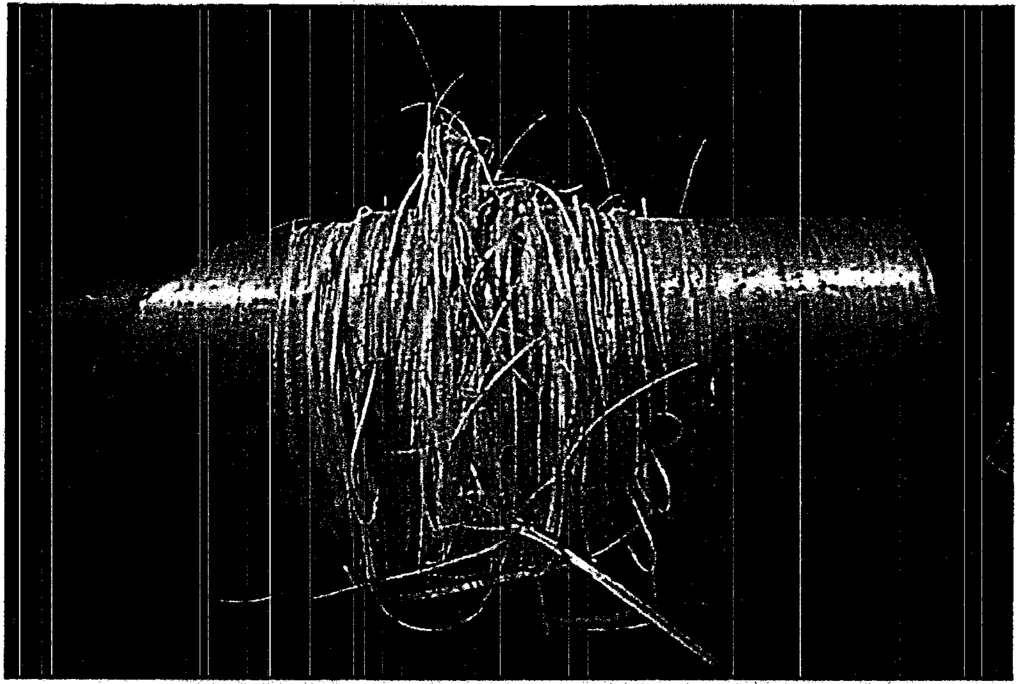


Figure 24. Cylinder G After Burst Test

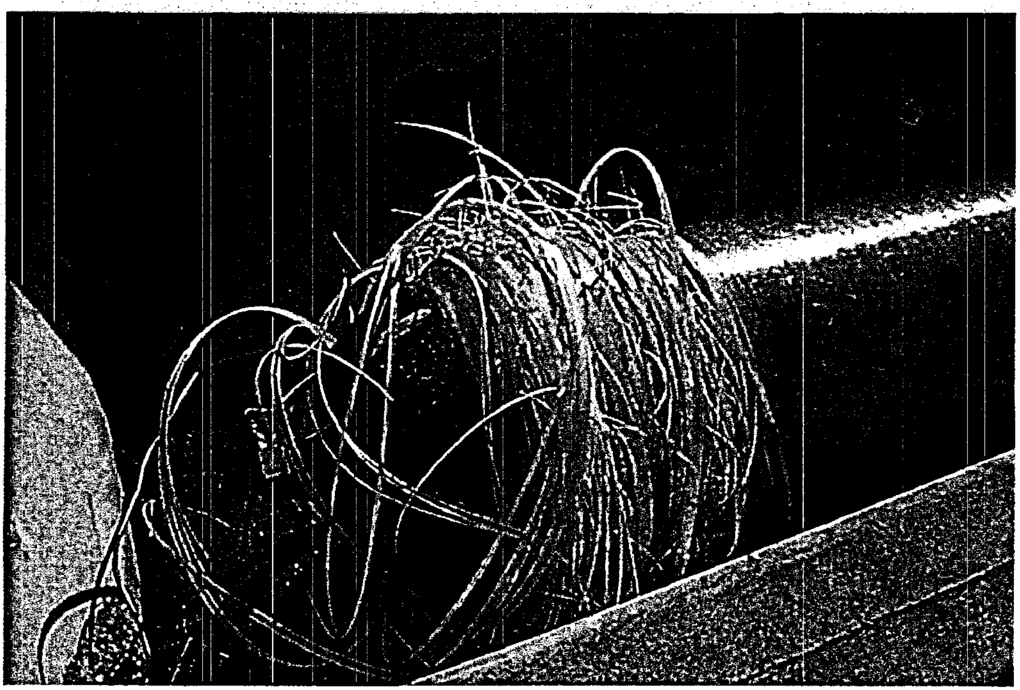
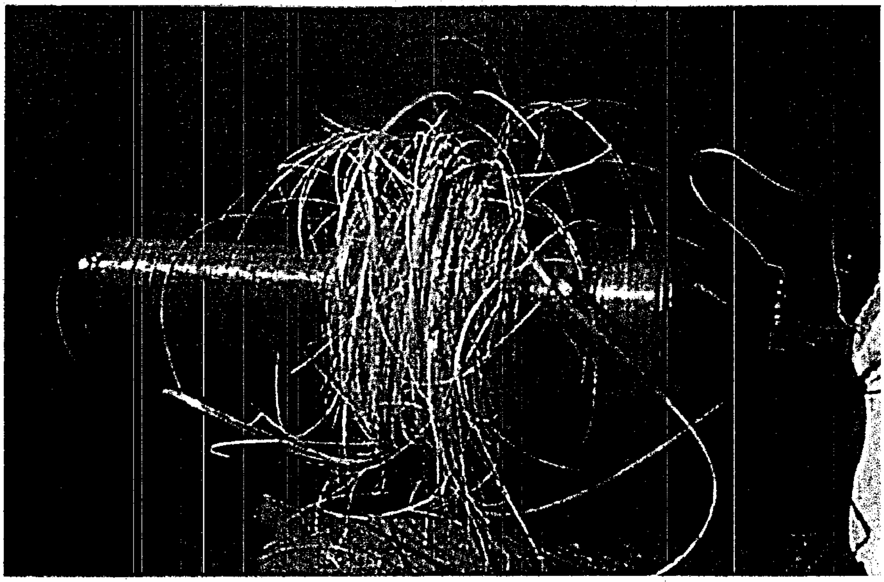


Figure 25. Cylinder H After Burst Test



OTHER CONSIDERATIONS

On May 22, 1998, Lucas informed their workforce that the Group had decided to withdraw from both the industrial gas and NGV cylinder markets and close that area of the business situated in Burnley. IGT (and others) were informed that Lucas would complete a number of cylinders for this contract but would not take the project forward into commercial production.

A conference call took place on June 4, 1998. Representatives from Lucas, IGT, GRI, and DOE participated. The purpose of the conference call was to discuss Lucas's decision to exit the NGV and industrial gas cylinder markets and to discuss possible avenues of commercialization for the cylinders developed during this project. At the completion of the project, Lucas held the rights to the design. The disposition of the plant and tooling is not known at this time, though some of the equipment may not be completely unrestricted with respect to its sale or transfer. Lucas has been discussing the transfer of the design and some equipment/tooling with interested parties though the talks have been preliminary in nature. GRI and IGT developed a list of potential container manufacturers who may be interested in acquiring Lucas's design and equipment. The list was forwarded to Lucas.

CONCLUSIONS

Although the project did not immediately lead to a commercial product, important progress was made towards improving the cost and performance of NGV cylinders. The testing of Advantex glass fibers will be of benefit to the industry in general and the frequent discussions with OEMs will likely lead to their acceptance of cylinders made with Advantex once they become available.

Based on the nine finished cylinders produced (16.3-inch diameter, 61-inch length), the final weight was 0.18 pounds per scf which met the target of the RFP and exceeded the project goal. The expected cost was somewhat above the RFP target. The expected "factory gate" cost (excluding packing, transportation, and U.S. import duty costs) was $0.45 per scf.

Table 8. Final Cost and Weight Estimates

	RFP Target	Project Goal	Final (Expected) Value
Weight (lb/scf)	0.18	0.19	0.18
Cost ($/scf)	0.46	0.40	0.49

Appendix A

Lucas Aerospace CNG Cylinder 3600 psi 16.3 Inch Diameter Design Summary

POWERTECH LABS INC.

FINAL REPORT

LUCAS AEROSPACE CNG CYLINDER
3600 PSI 16.3 INCH DIAMETER
DESIGN SUMMARY

Subtask of
Gas Research Institute High Strength Steel
Type 2 Cylinder Project

Powertech Project 9081-32

Principle Investigators:

Joe Wong
Livio Gambone
Craig Webster

TABLE OF CONTENTS

1.0 INTRODUCTION

The purpose of this report is to summarize the design and optimization of the Lucas Aerospace 16.3-inch diameter NGV cylinder for use at a service pressure of 3600 psi. The cylinder design will utilize a steel liner hoop-wrapped with a composite wrap. Designs were developed using fibers made of glass, carbon, and aramid.

2.0 DEVELOPMENT OF MODEL

2.1 Computer Model

Nonlinear finite element analysis techniques using the COSMOS/M analysis software package, developed by Structural Research and Analysis Corporation, were used to estimate the stresses and strains in the cylinder at various pressures.

The finite element model was developed using the minimum cylinder dimensions taken from the drawing in Appendix 1. The cylinder was discretized using 4 node axisymetric isoparametric two-dimensional planar elements.

2.2 Steel Properties

The material properties for the steel are based on the results of the tensile tests performed on cylinders produced to date (see Appendix 1):

Yield strength - 125 – 135 ksi
Tensile strength - 140 – 160 ksi
Elastic Modulus - 30 Msi
Plastic Modulus - 133,333 psi (bi-linear stress strain curve)
Shear Modulus - 12.0 Msi

Poisson's Ratio - 0.32

2.3 Laminate Properties

Three types of reinforcing fibers were used for this study:

1. glass fibers
2. carbon fibers
3. aramid fibers

The mechanical properties of the fibers used for this analysis are shown in Table 1

Table 1
Mechanical Properties of Reinforcing fibers

Property	Glass	Aramid	Carbon
Filament elastic modulus (Msi)	11.5	18	33
Fiber volume (%)	.62	.62	.62
Laminate hoop modulus (Msi)	6.8	10.9	20.5
Transverse modulus (Msi)	.01	.01	1.2
Axial modulus (Msi)	.01	.01	1.5
Shear modulus (Msi)	.01	.01	1.04
Poisson ratio	0.25	.32	.28

The tensile strengths of fibers vary depending on the type of fiber, the fiber manufacturer, the grade of fiber, and the translation efficiency when the fiber is filament wound. The selection of fibers is addressed in a separate report (1).

2.4 Pressures

Calculations were performed for the following design pressures:

Autofrettage pressure	-	7000 psi
Zero pressure	-	0 psi
Min operating pressure	-	360 psi
Service pressure	-	3,600 psi
Test pressure	-	5,400 psi
Minimum burst pressure	-	9,000 psi

The minimum burst pressure of the cylinder design is determined by the stress ratio requirements for the particular fiber. The stress ratio in CSA B51-95 Part 2 for a type NGV-2 E-glass fiber design is set at a value of 2.75. For a working pressure of 240 bar (3,480 psi) at 15°C, the 2.75 value is equivalent to the ANSI/AGA NGV2-92 stress ratio requirement of 2.65 at a service pressure of 248 bar (3,600 psi) at 21°C. Similarly, the stress ratio in CSA B51-95 Part 2 for a type NGV-2 carbon fiber design is set at a value of 2.35. For a working pressure of 240 bar (3,480 psi) at 15°C, the 2.35 value is equivalent to the ANSI/AGA NGV2-92 stress ratio requirement of 2.25 at a service pressure of 248 bar (3,600 psi) at 21°C. The calculations for this analysis were performed at 248 bar (3,600 psi) at 21°C.

3.0 STEEL LINER THICKNESS

Burst pressures were estimated for various liner thicknesses using the following formula:

$$P = S\,(D^2 - d^2)\,/\,(1.3\,D^2 + 0.4d^2)$$

Where:
P = pressure
S = tensile strength
D = outside diameter of liner
d = inside diameter of liner

Figure 1 shows the range of burst pressures for the 140 ksi and 160 ksi UTS steel liners at different wall thickness. The minimum burst pressure for the liner is 4,500 psi. At 140 ksi UTS, a liner with 0.215 wall thickness will burst at 4,500 psi. With a liner wall thickness of 0.25 inch, the burst pressure is estimated to be 5,209 psi at 140 ksi UTS and 5,950 psi at 160 ksi UTS.

A wall thickness of 0.25 inch was chosen to allow a 15% margin of safety over the minimum liner burst. Note that the burst pressure for the current 14.6-inch diameter 3,600 psi design is approximately 6,300 psi (134 ksi UTS).

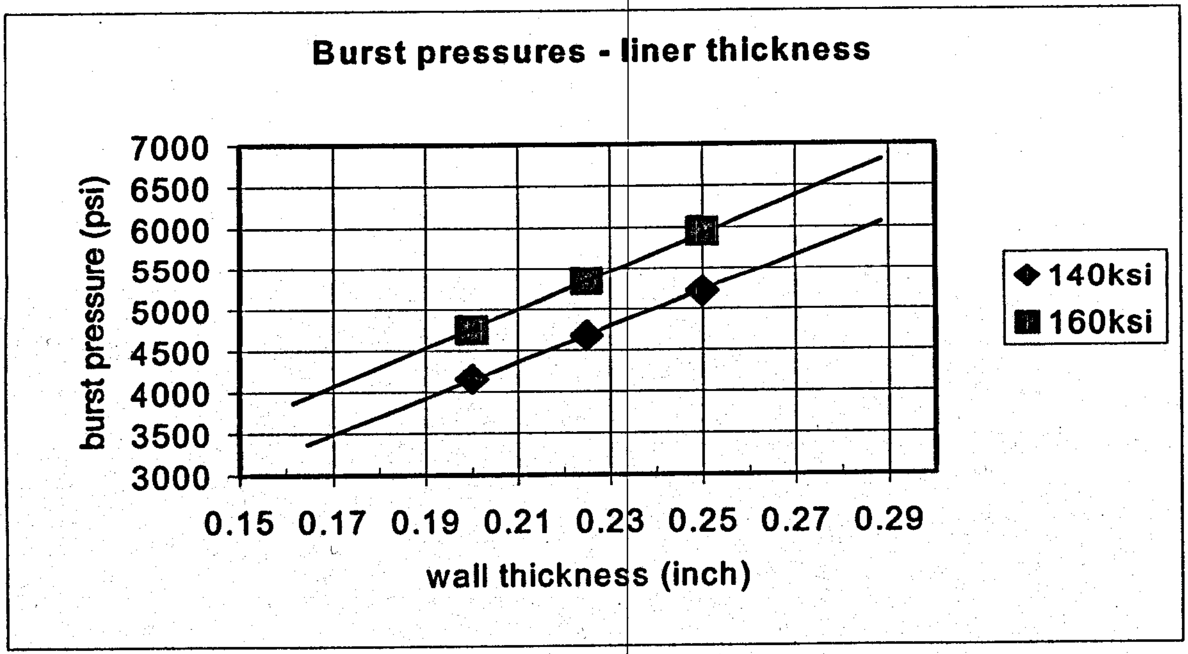


Figure 1. Burst pressure calculations of the steel liner

4.0 FIBER WRAP THICKNESS

A simplified finite element model of the cylinder sidewall was used to establish the wall thickness of the composite wrap using the three types of fibers. Keeping the outer diameter at 16.3 inches, the FE model was adjusted for different wrap thicknesses while maintaining a liner wall thickness of 0.25 inches. An autofrettage pressure of 7,000 psi was used.

4.1 Carbon Fiber Design

Figure 2 shows the results of the stress analysis for the carbon fiber cylinder design. The selection of the wall thickness will depend on the tensile strength of fiber chosen. It can be seen that the fiber stress at a minimum burst pressure of 9,000 psi is approximately 450 ksi at a wrap thickness of 0.150 inch. This wrap thickness may be adequate for a higher-grade fiber such as the Toray T700. The lower grade "big tow" carbon fibers will require a thicker wrap. Prototype cylinders will have to be burst tested in order to obtain the tensile strength of the fibers in the laminate.

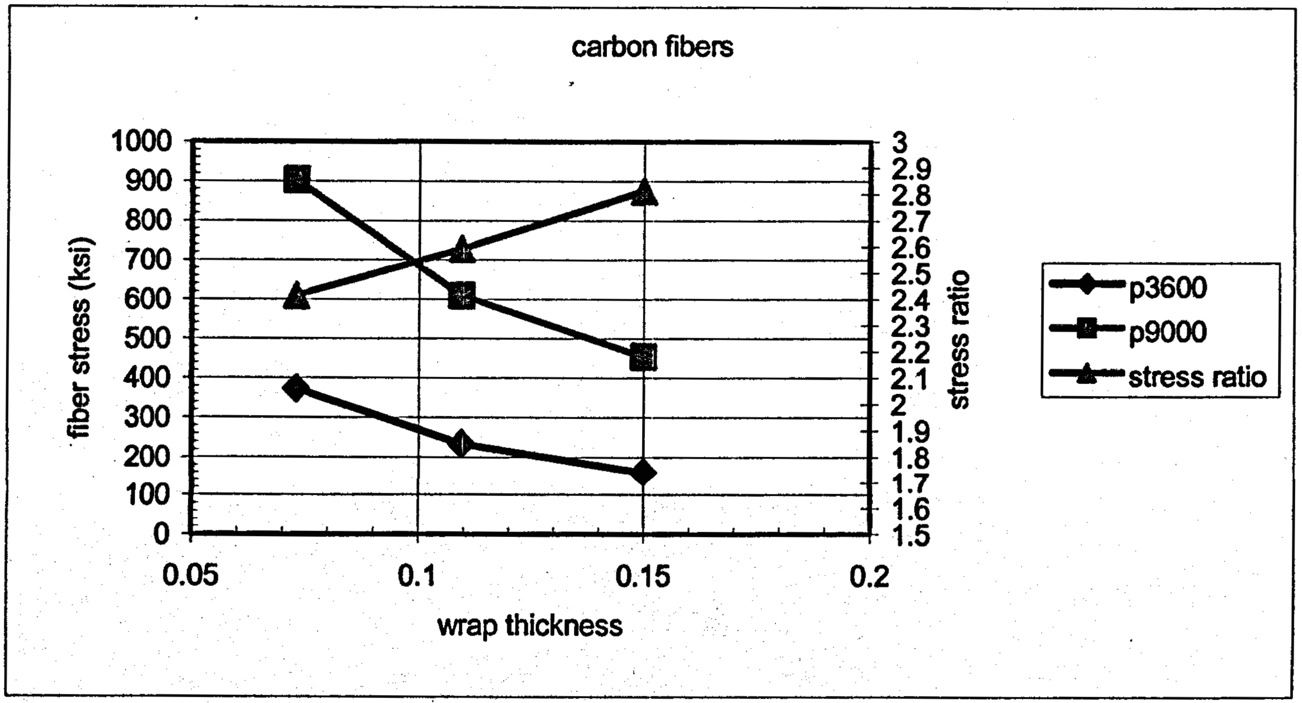


Figure 2. Stress analysis of carbon fiber cylinder

4.2 Aramid Fiber Design

Figure 3 shows the results of the stress analysis for the aramid fiber cylinder design. As in the carbon fiber design, the selection of the wrap thickness will depend on the tensile strength of the fibers. Assuming that the tensile strength of the fiber in the laminate will achieve 400 ksi, the wrap thickness required in the design is 0.225 inch.

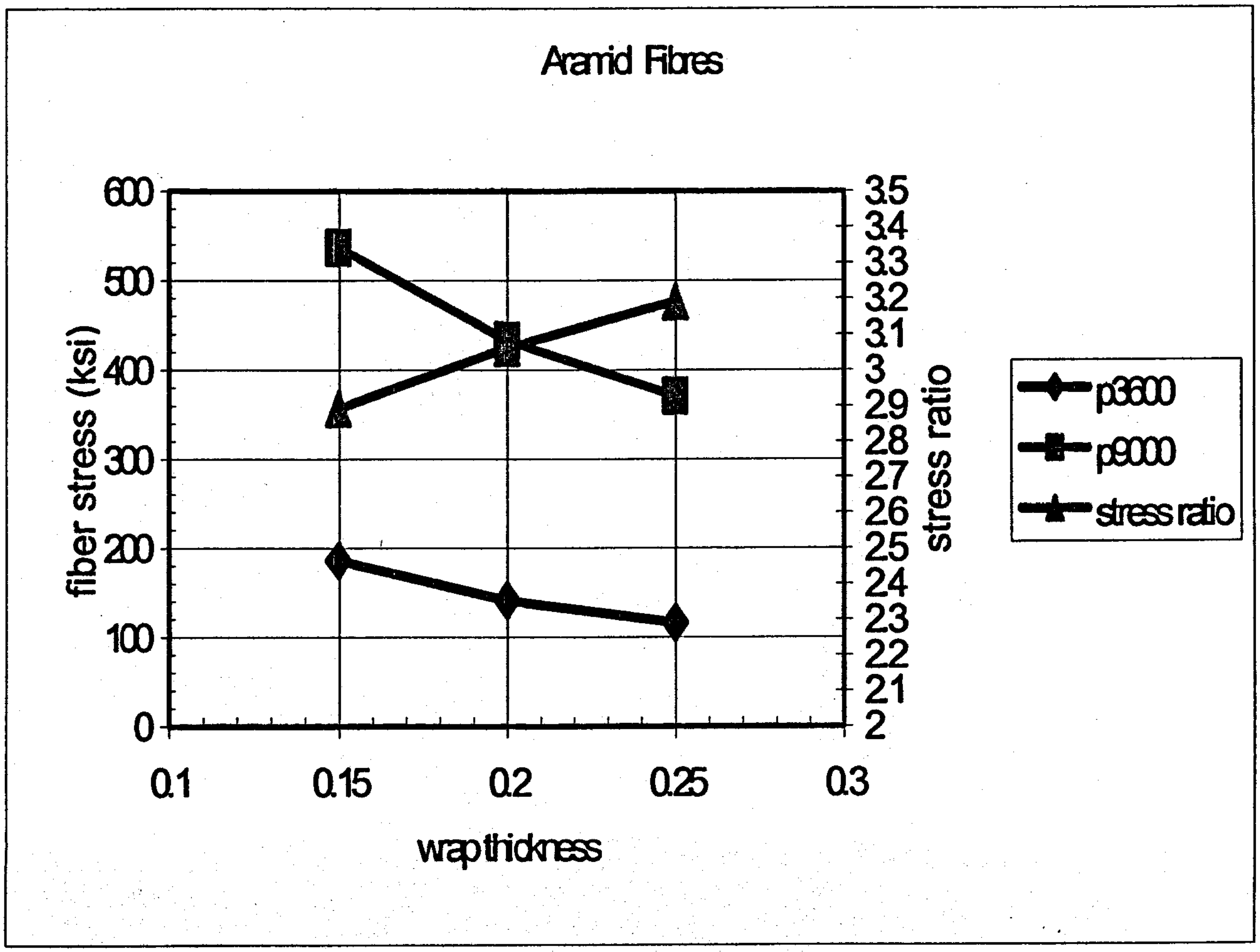


Figure 3. Stress analysis of aramid wrap

4.3 Glass Fiber

Figure 4 shows the results of the stress analysis for the glass fiber cylinder design. It can be seen that the fiber stresses at the burst pressure decreased to the ultimate tensile strength of the fiber (330 ksi) at a wrap thickness of 0.25 inch. However, the stress ratio did not improve substantially when the wrap thickness was increased from 0.2 to 0.25 inches. The stress ratio may improve if the autofrettage pressure is lowered.

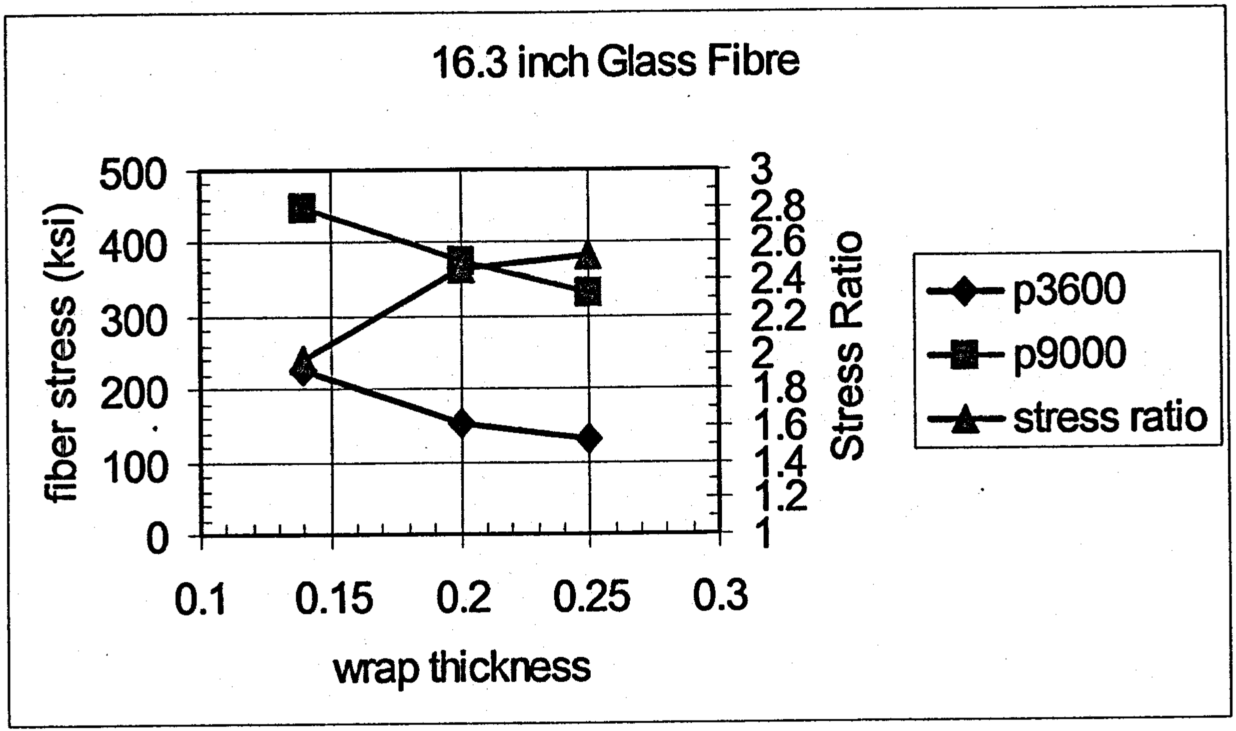


Figure 4. Stress analysis of glass fiber wrap

5.0 OPTIMIZED GLASS FIBER DESIGN

A full finite element model including the end domes was generated for the 16.3 inch OD glass fiber design with a wrap thickness of 0.25 inch. The autofrettage pressure was lowered to 6750 psi.

Table 2 summarizes the maximum stresses and strains at various cylinder pressures.

Table 2
Summary of Maximum Stresses and Strains

Pressure	Steel Yield (ksi)	Liner Hoop (ksi)	Liner Long. (ksi)	Von Mises. (ksi)	Inner Fiber Strain	Fiber Stress (ksi)	Long. Strain
Autofrettage 6750 psi	125	141	71	128	0.01189	136.7	0.005094
	145	165	138	146	0.007569	87.0	0.003227
Zero 0 psi	125	-48	-26	49	0.007375	84.8	0.003621
	145	-23	-17	24	0.003059	35.1	0.001754
Min. Oper. 360 psi	125	-39	-21	43	0.007616	87.5	0.003699
	145	-13	-12	14	0.0033	38.0	0.001832
Fill 3600 psi	125	84	28	76	0.00978	112.5	0.004407
	145	92	80	84	0.005465	62.8	0.002539
Cycling/Max 4500 psi	125	100	40	90	0.01038	119.3	0.004603
	145	112	97	101	0.006066	75.9	0.002736
Hydro Test 5400 psi	125	117	52	104	0.01098	126.3	0.004799
	145	133	113	119	0.006667	76.6	0.002932
Min. Burst 9000 psi	125	113	132	133	0.02682	308.4	0.02059
	145	165	159	152	0.02131	213.1	0.009638

5.1 Maximum Liner Stresses

The stresses in the liner at 3,600 psi will be used for the fracture mechanics assessment to determine the minimum fatigue life and leak-before-burst assessment.

5.2 Maximum Fiber Stresses

At the minimum burst pressure, the maximum fiber stress was calculated to be 308.4 ksi.

5.3 Maximum Liner Strains

The cylinder will exhibit an increase in diameter after undergoing autofrettage. The amount of change will depend on the yield strength of the steel liner. Based on the strains calculated by the FE model at zero pressure, figure 5 shows the diameter of the cylinder prior to autofrettage such that the final liner diameter will be 15.8 inches.

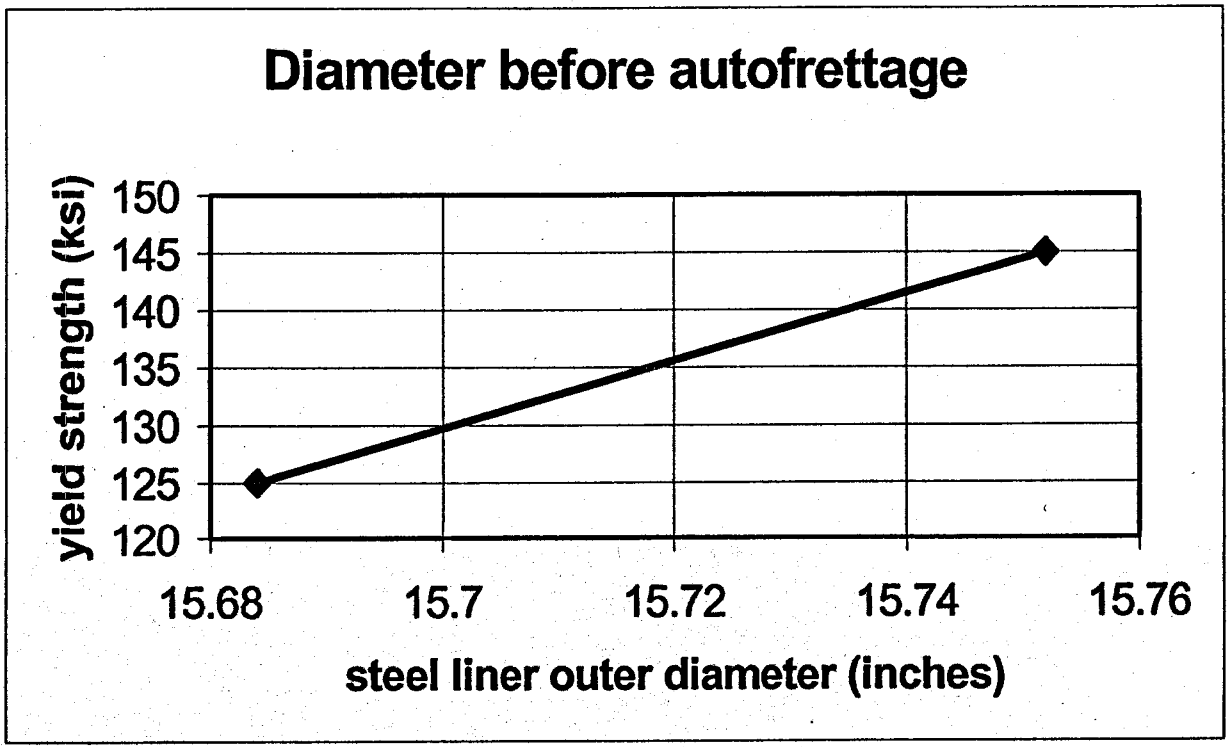


Figure 5. Diameter change due to autofrettage

6.0 STRESS CONTOURS

The stress contours in the cylinder with liner yield strength of 140 ksi and 160 ksi at various pressures are included in Appendix 2. It can be seen that the maximum stresses in the liner are located near the end dome transition zone and the maximum stresses in the composite are located near the liner composite interface.

7.0 RECOMMENDATIONS

Based on the preliminary design analysis of the 16.3 inch cylinder the following recommendations can be made:

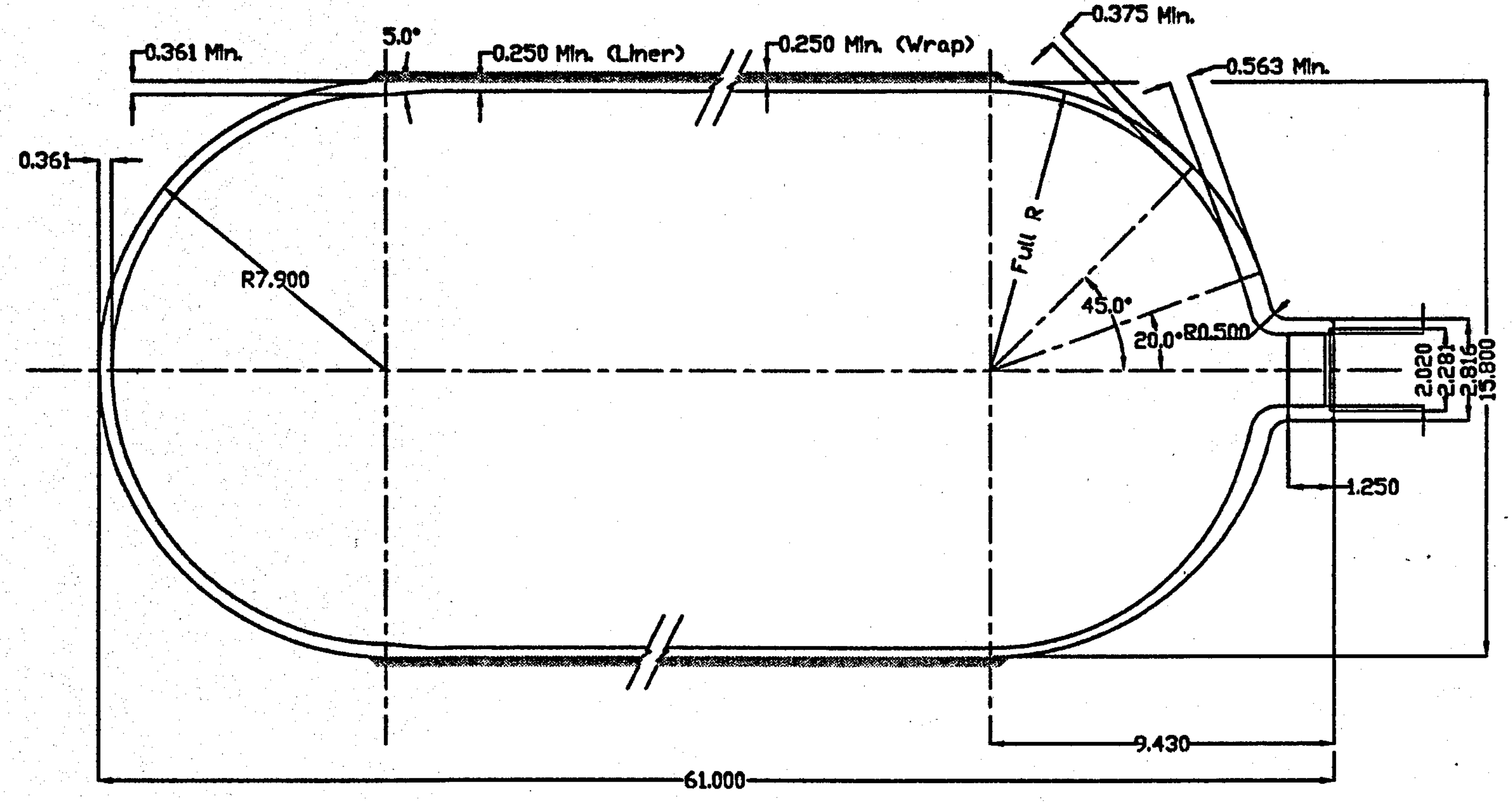
1. The liner thickness of the cylinder should be 0.250 inch.
2. The minimum thickness for the glass wrap should be 0.250 inch.
3. The autofrettage pressure for the glass wrap design should be 6750 psi.
4. The minimum thickness for the carbon wrap should be 0.15 inch.
5. The minimum thickness for the aramid wrap should be 0.225 inch.
6. The wrap thickness for the cylinders cannot be finalized until prototype cylinders have been burst tested to obtain the strength of the laminate.

8.0 REFERENCES

1. Powertech report PR165-lrg " Lucas Aerospace CNG Cylinder Fiber Reinforcement Study"

Appendix 1

Drawings



NOTE:
ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED.
DO NOT SCALE DETAIL DRAWING.

POWERTECH LABS INC.
LUCAS 16.3 INCH DESIGN

PREPARED BY RCL	DATE 06/11/97	SCALE NTS	
CHECKED BY	DRAWING NO. 9081-32-01		
APPROVED BY			

Appendix 2

Stress Contour Plots

Steel Liner Properties

Elastic Modulus	30	Msi
Plastic Modulus	133,333	Psi
Yield Stress	125	Ksi
Poisson's Ratio	0.32	

Composite Properties

Laminate Hoop Modulus	6.8	Msi
Transverse Modulus	0.01	Msi
Axial Modulus	0.01	Msi
Shear Modulus	0.01	Msi
Poisson's Ratio	0.25	

Pressures at Time Step

Calculations were performed for the following pressures with designated time steps.

Pressure	Value		Time Step
Initial	0	psi	0
Autofrettage pressure	7,000	psi	40
Zero pressure	0	psi	60
Minimum operating pressure	360	psi	70
Service pressure	3,600	psi	80
Service pressure	4,500	psi	90
Test pressure	5,400	psi	100
Minimum burst pressure	9,000	psi	130

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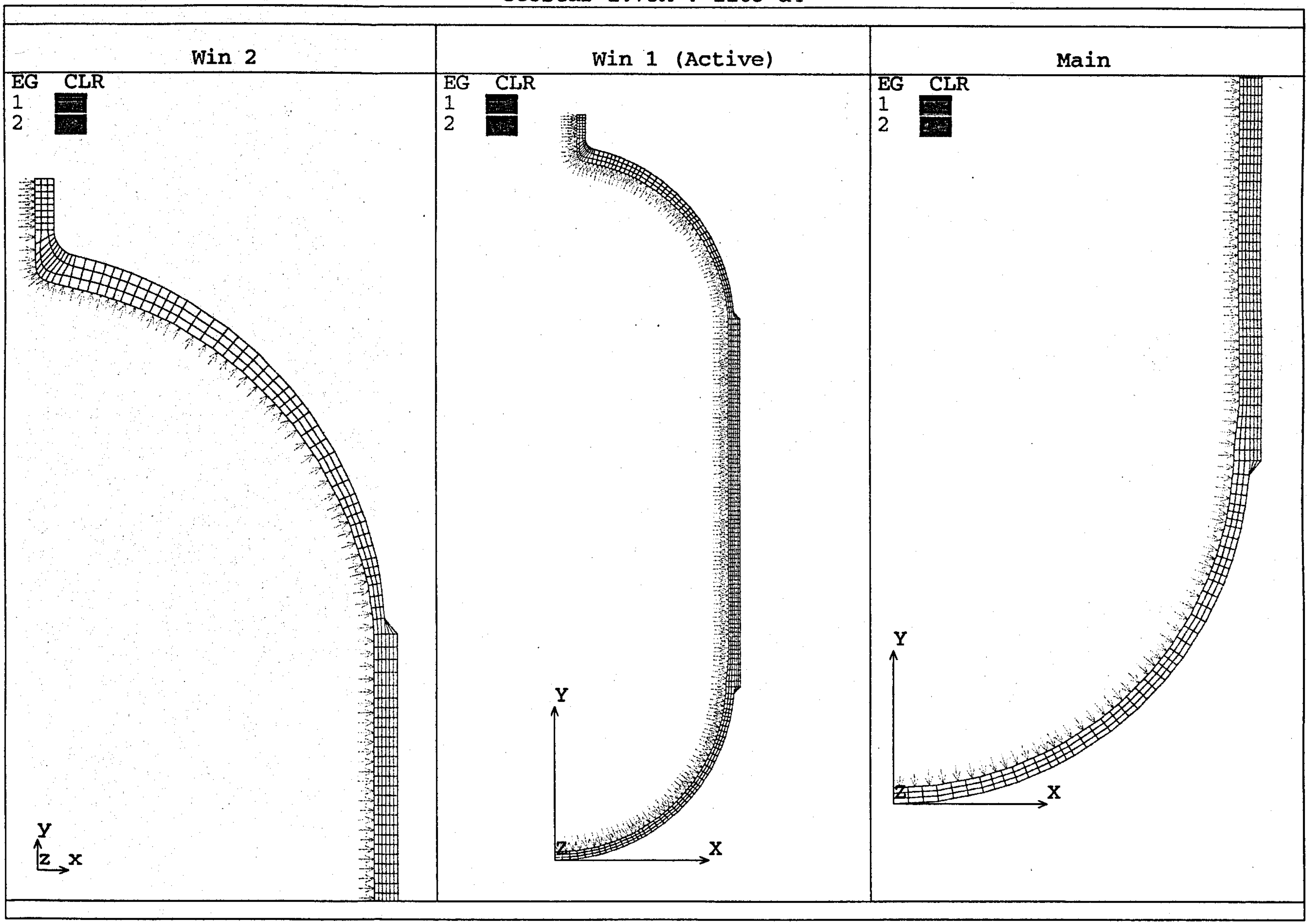

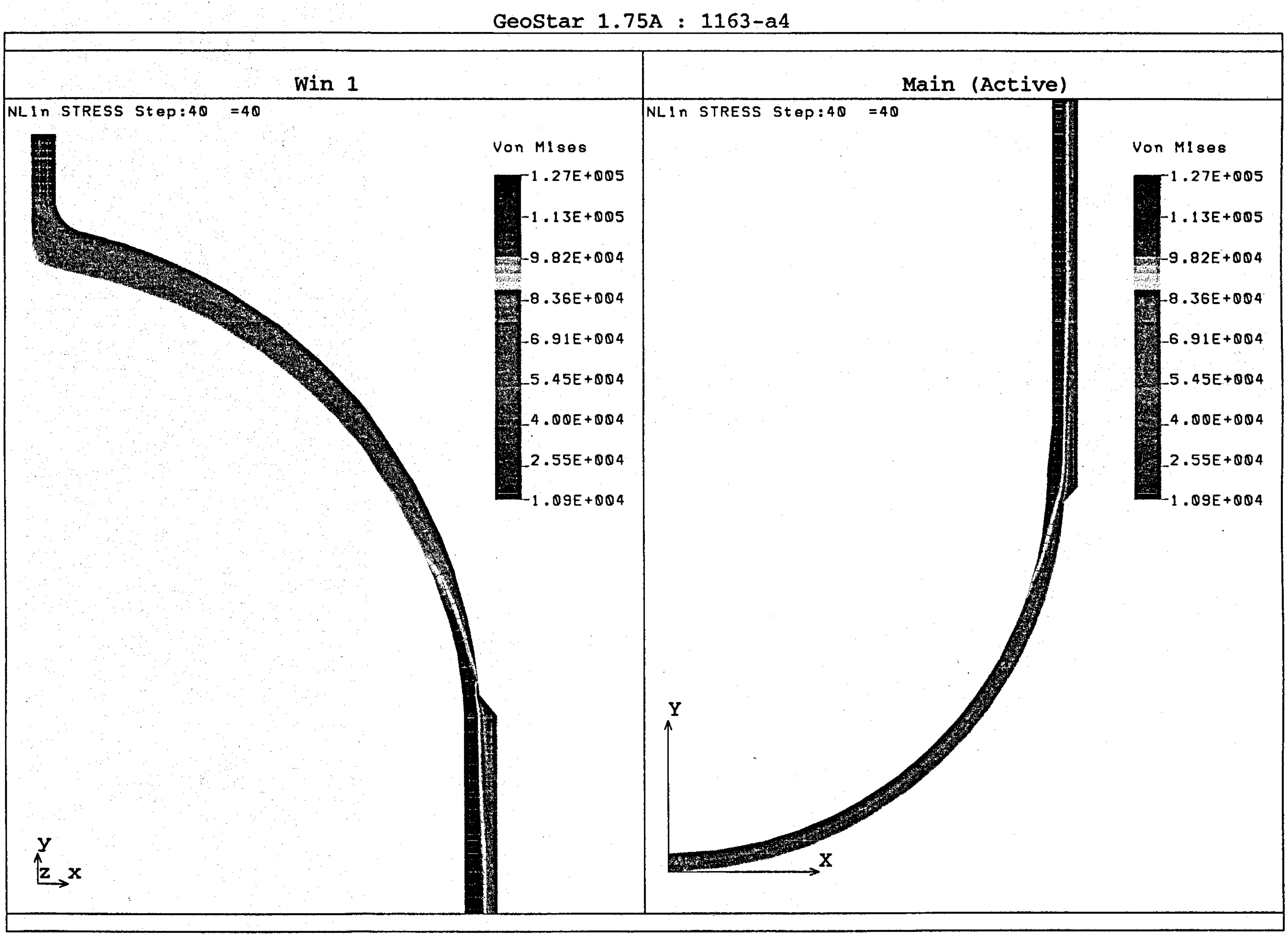
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Von Mises
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1.13E+005
9.82E+004
8.36E+004
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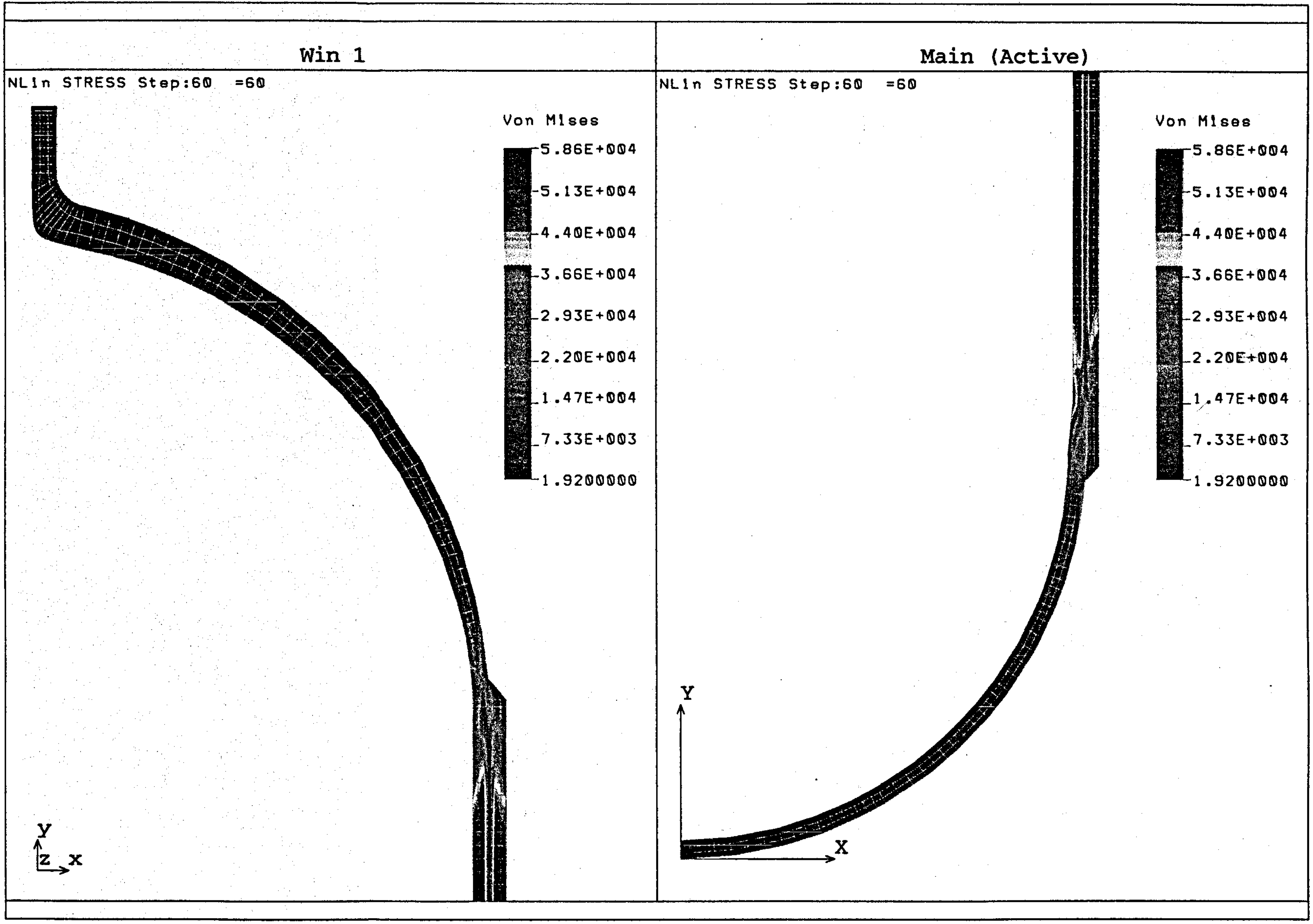

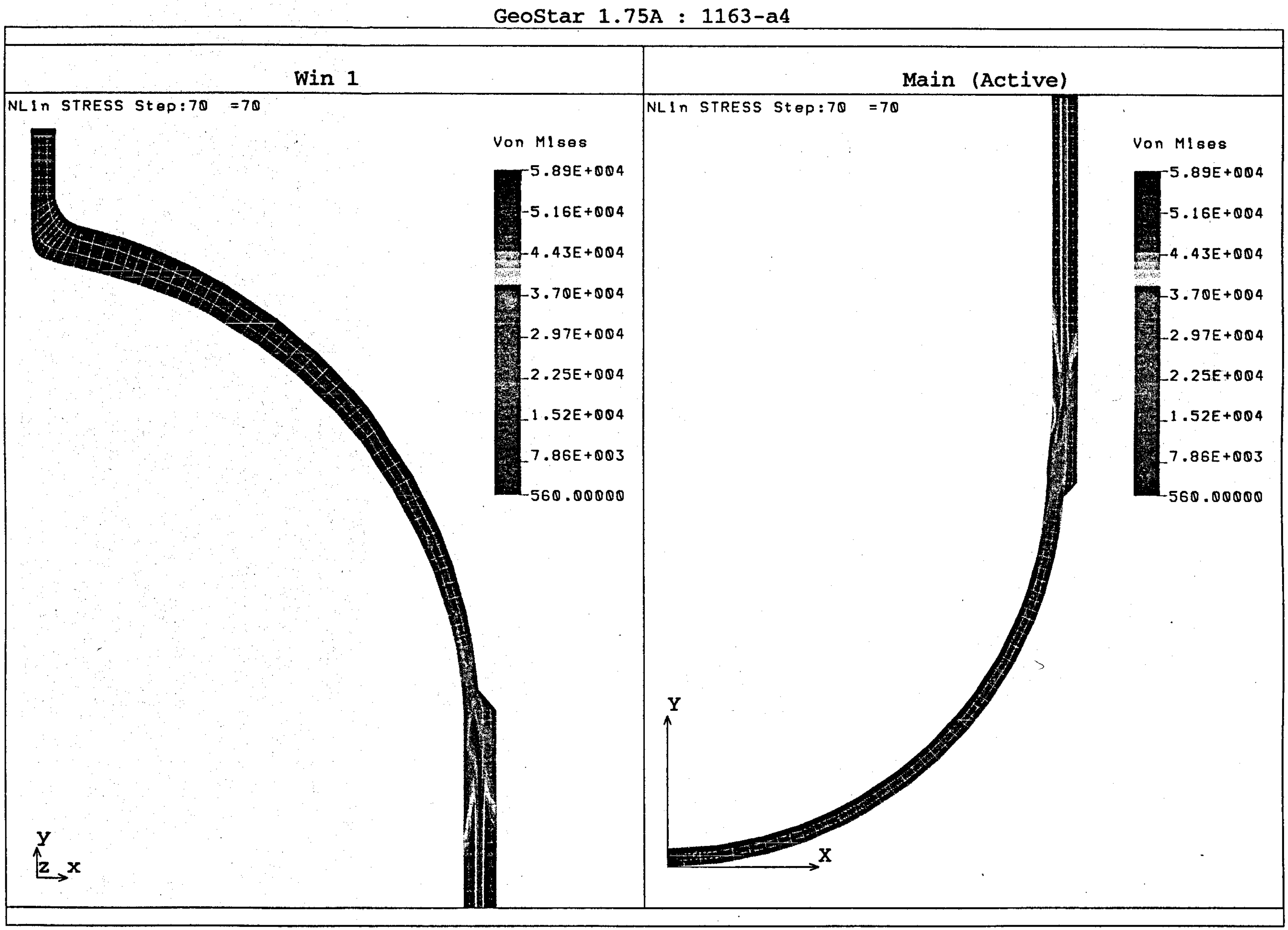
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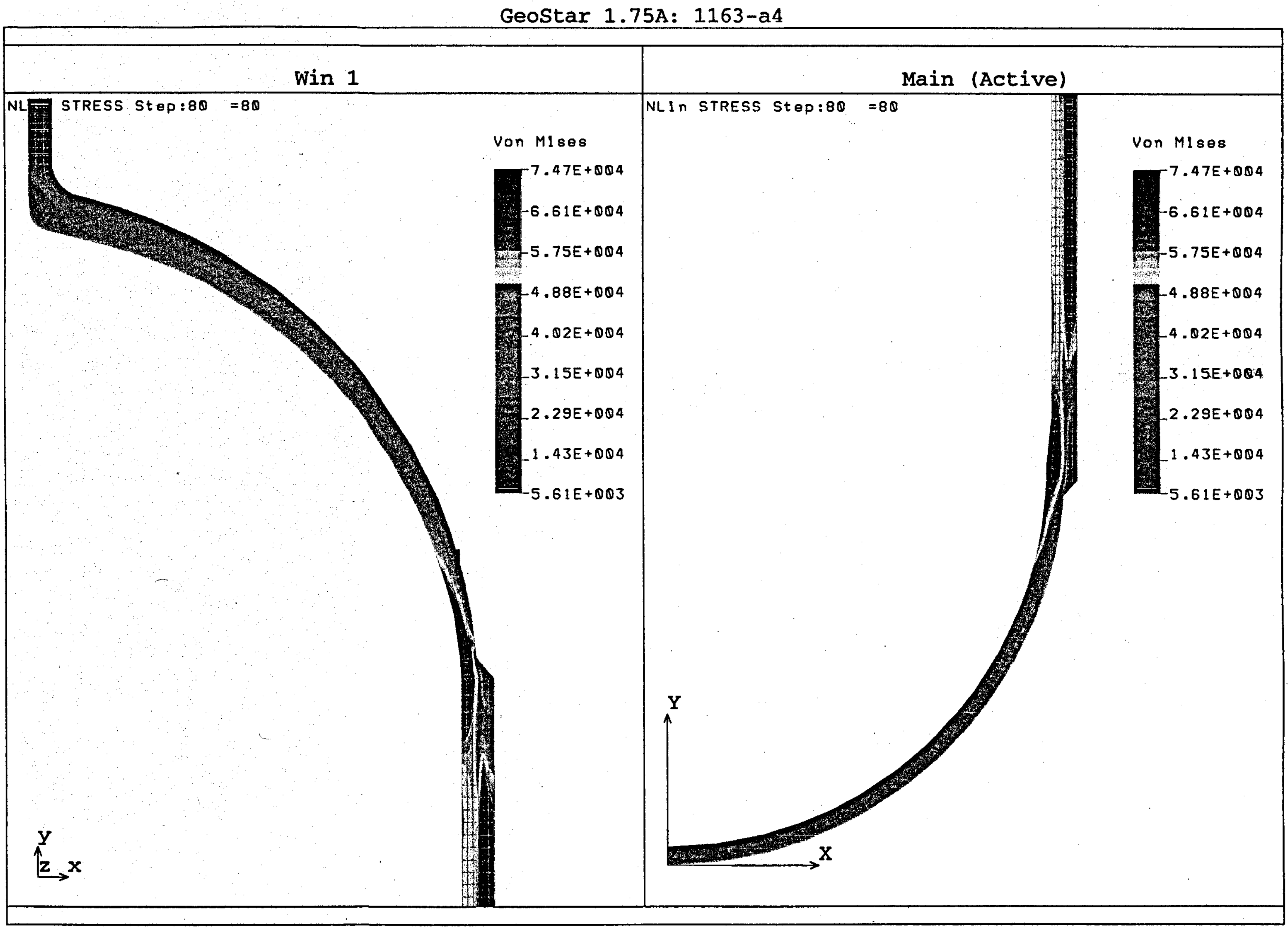
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1.43E+004
5.61E+003
Y
Z
X
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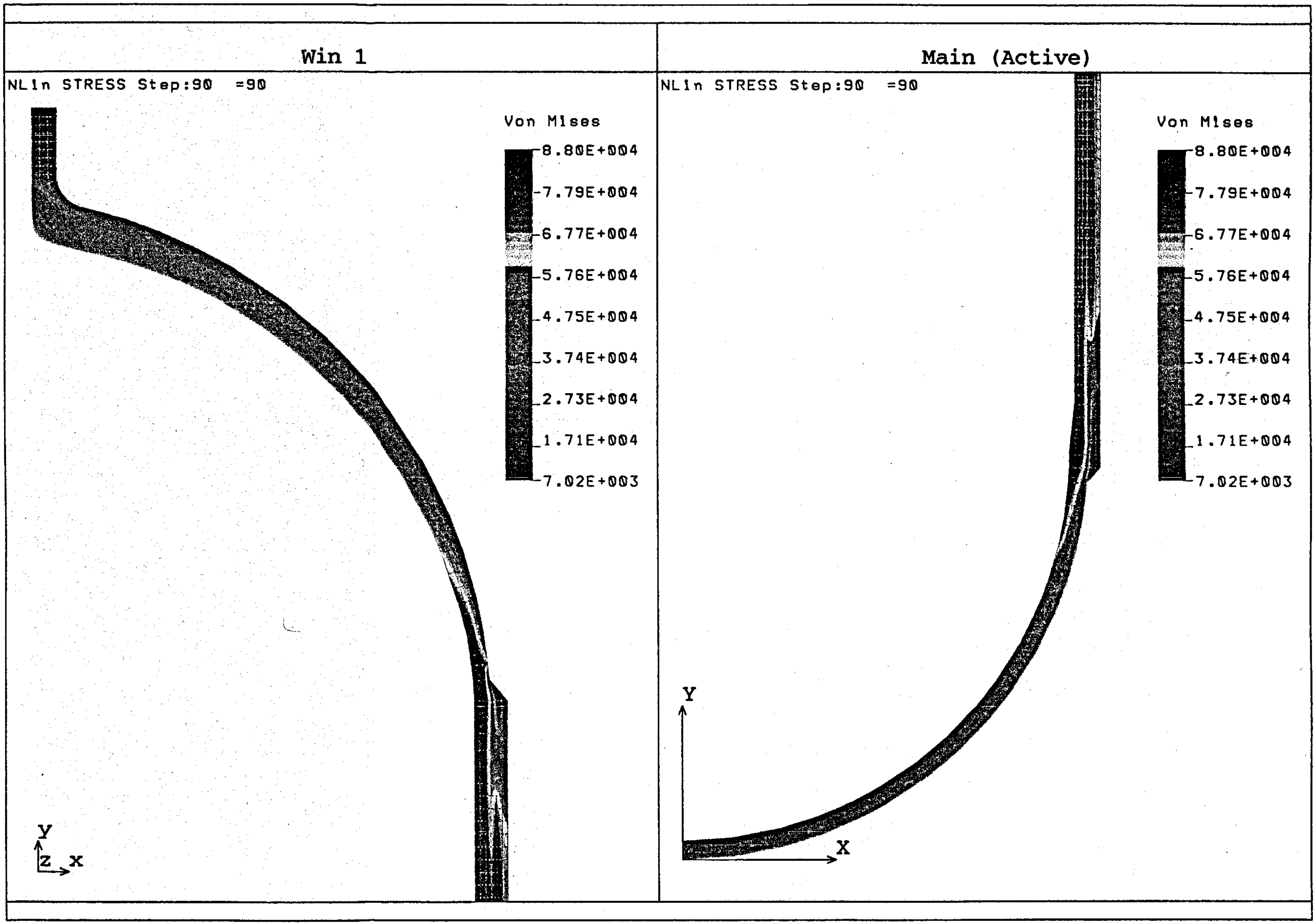

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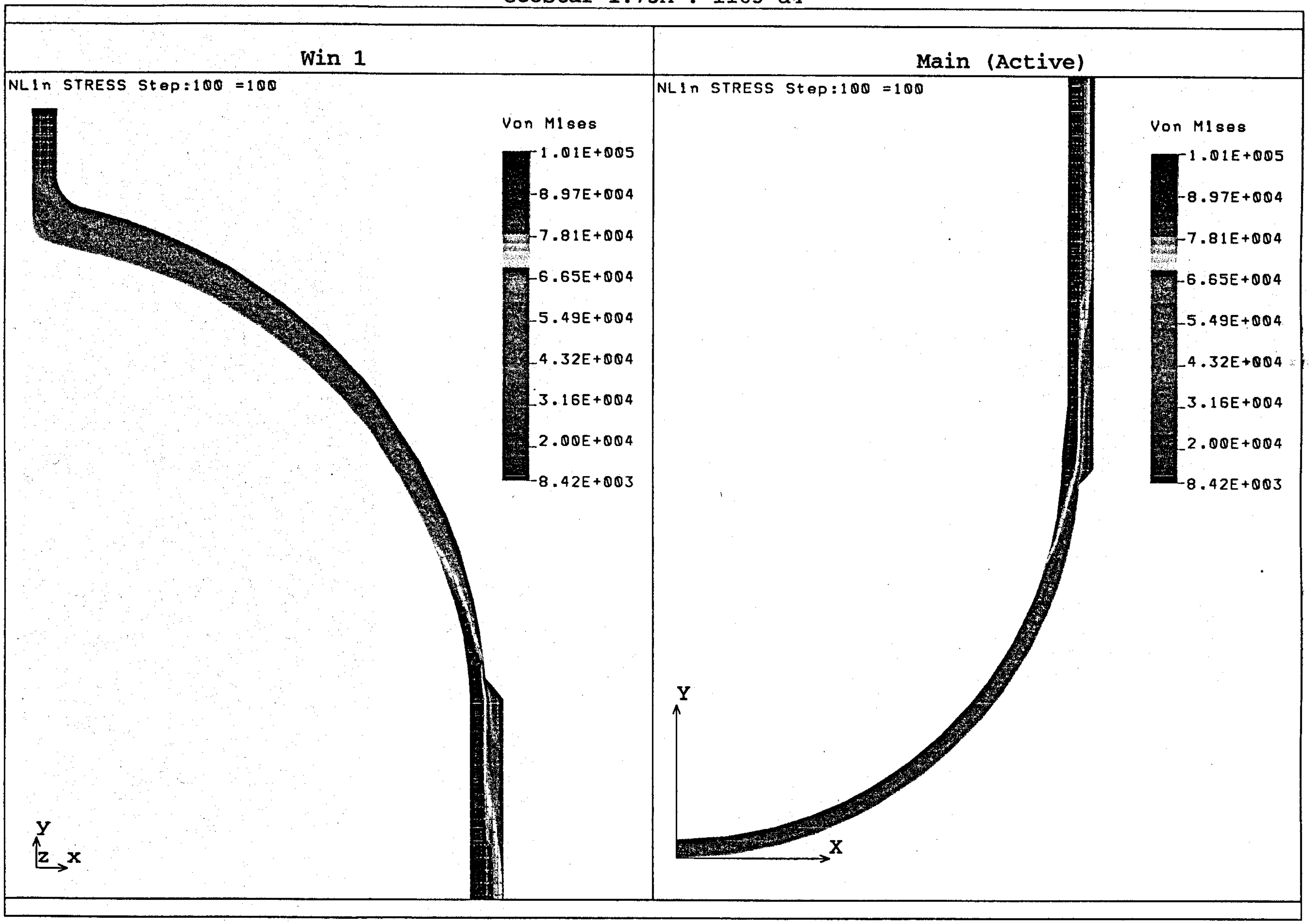

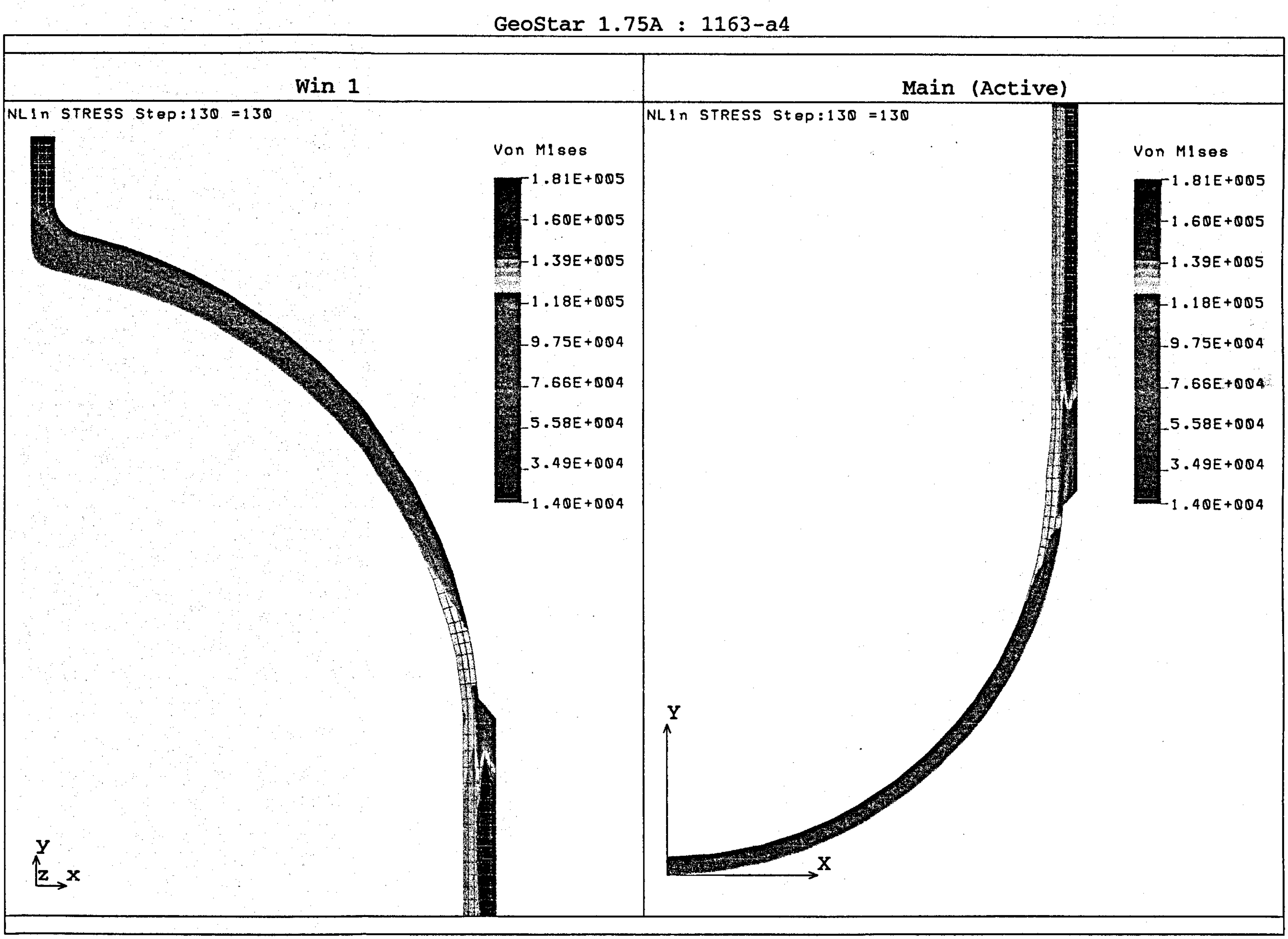
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Z
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7.66E+004
5.58E+004
3.49E+004
1.40E+004
Y
X

Steel Liner Properties

Elastic Modulus	30	Msi
Plastic Modulus	133,333	Psi
Yield Stress	135	Ksi
Poisson's Ratio	0.32	

Composite Properties

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Shear Modulus	0.01	Msi
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Pressures at Time Step

Calculations were performed for the following pressures with designated time steps.

Pressure	**Value**		**Time Step**
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Minimum operating pressure	360	psi	70
Service pressure	3,600	psi	80
Service pressure	4,500	psi	90
Test pressure	5,400	psi	100
Minimum burst pressure	9,000	psi	130

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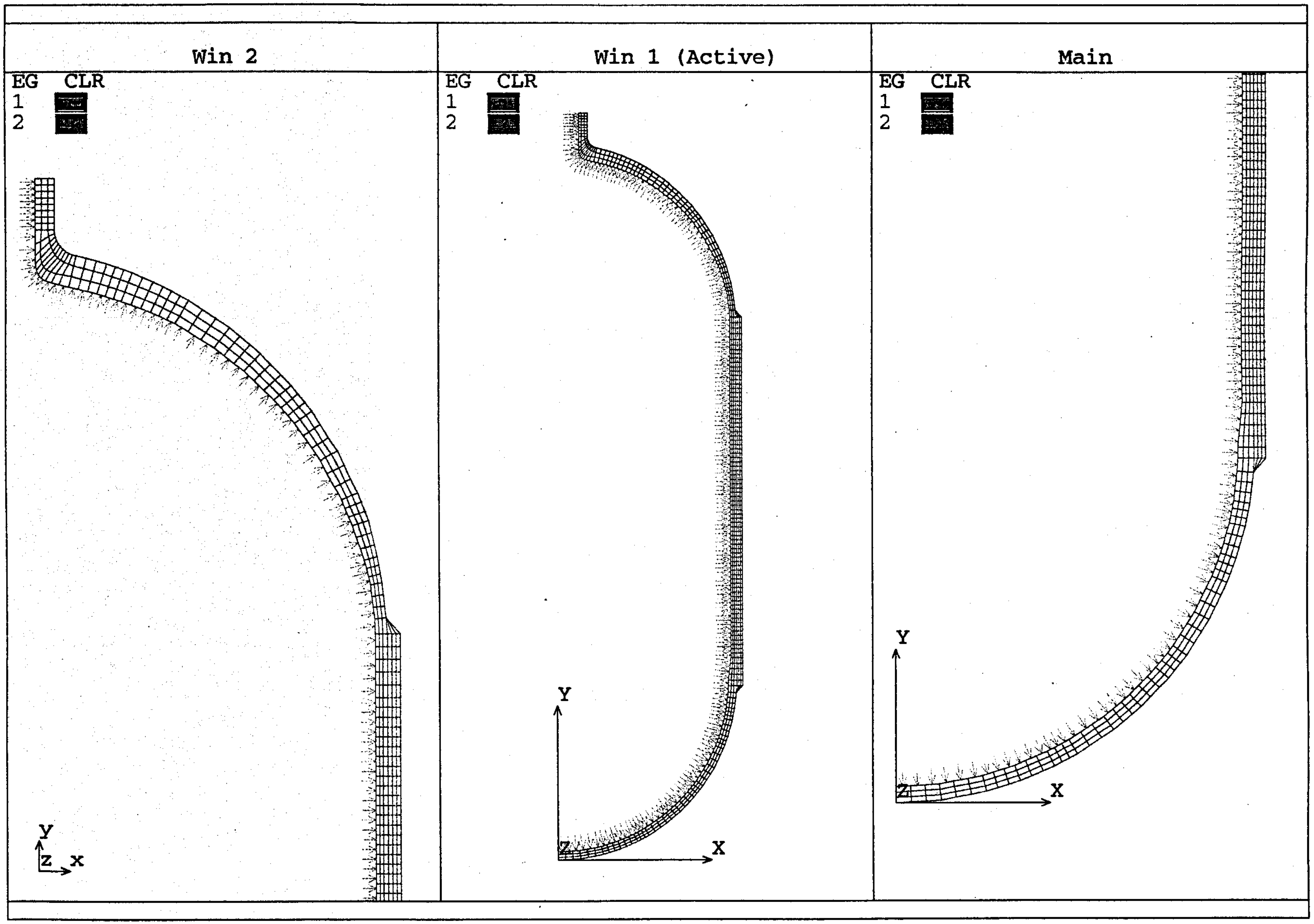

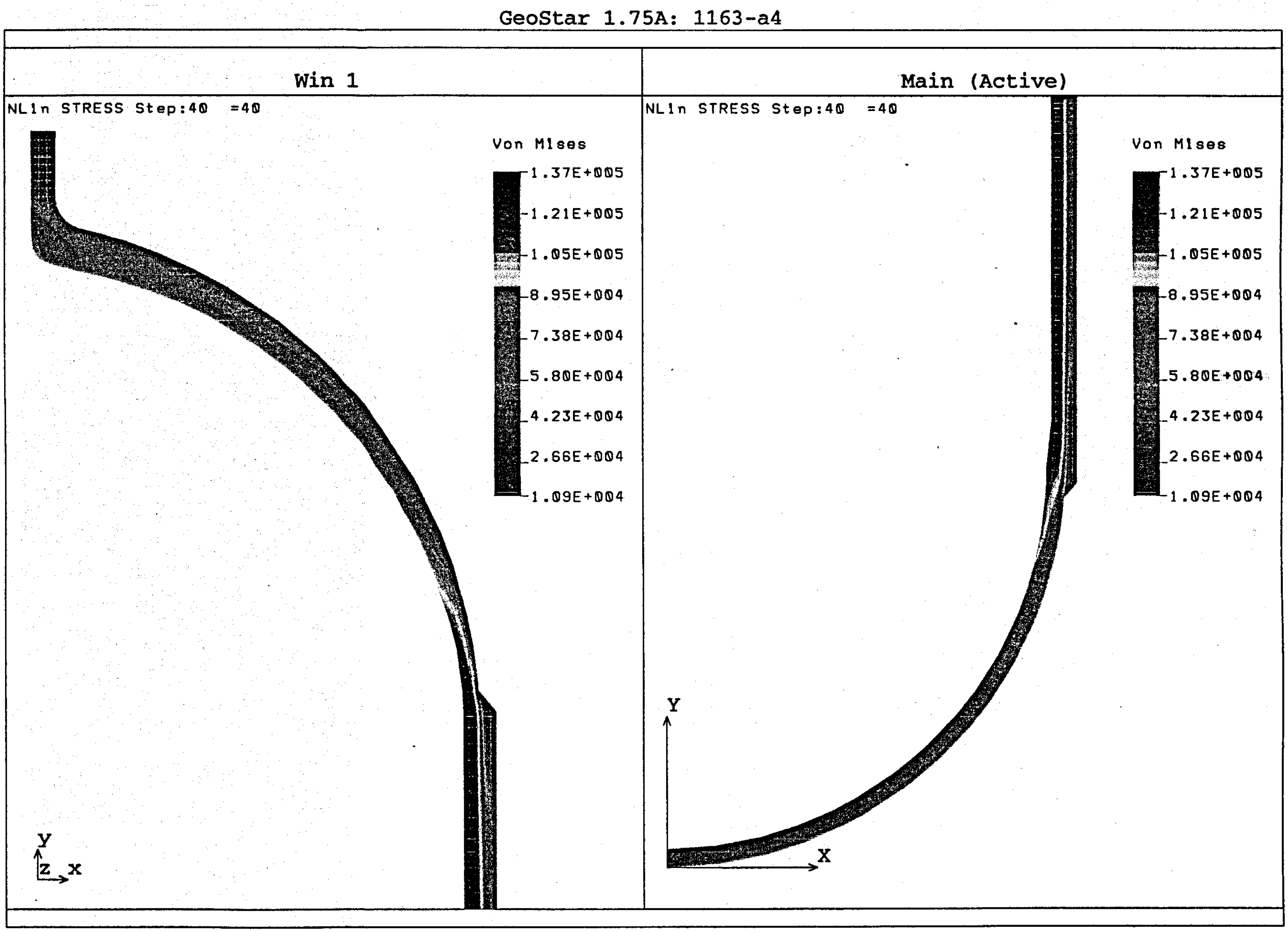
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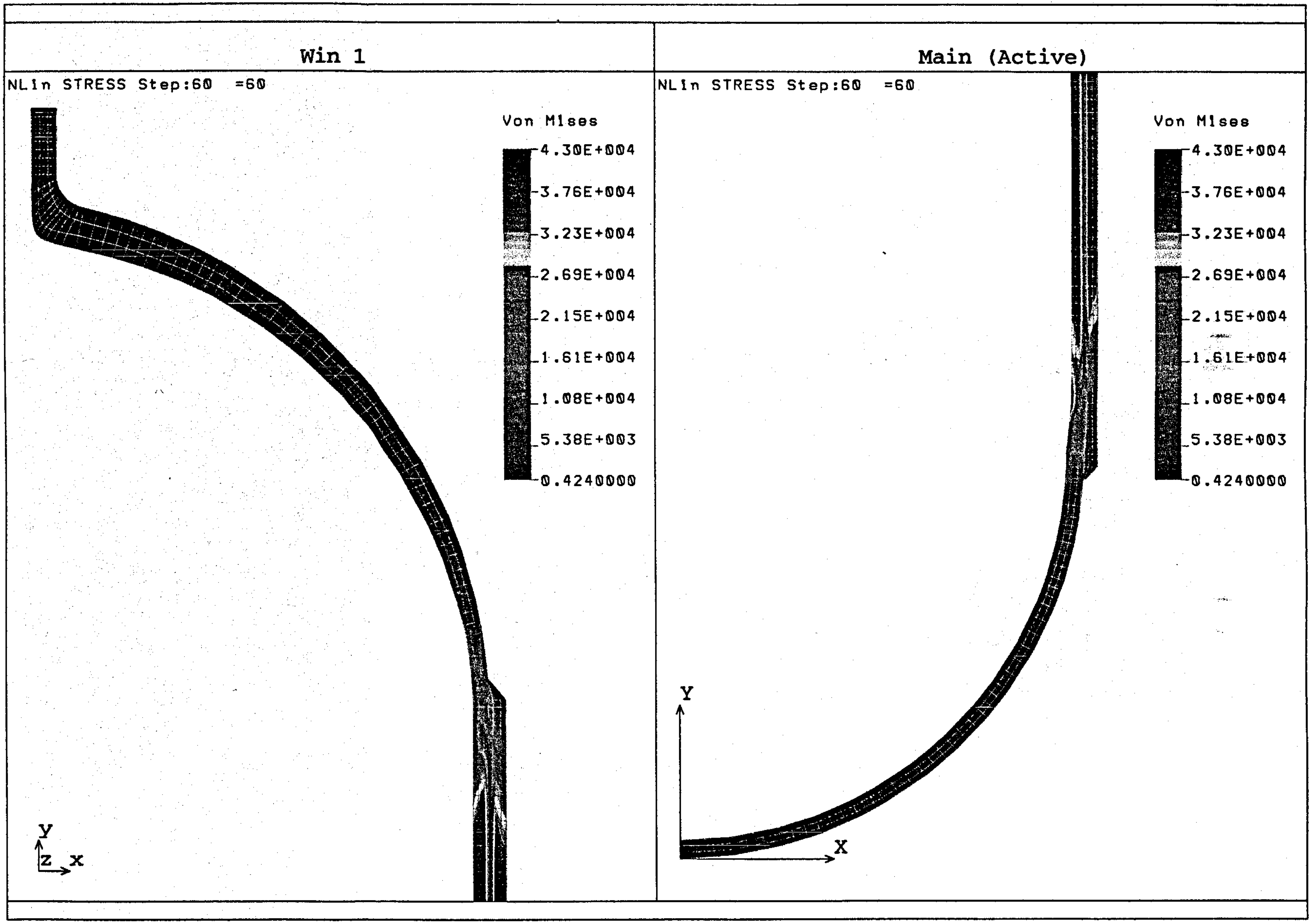

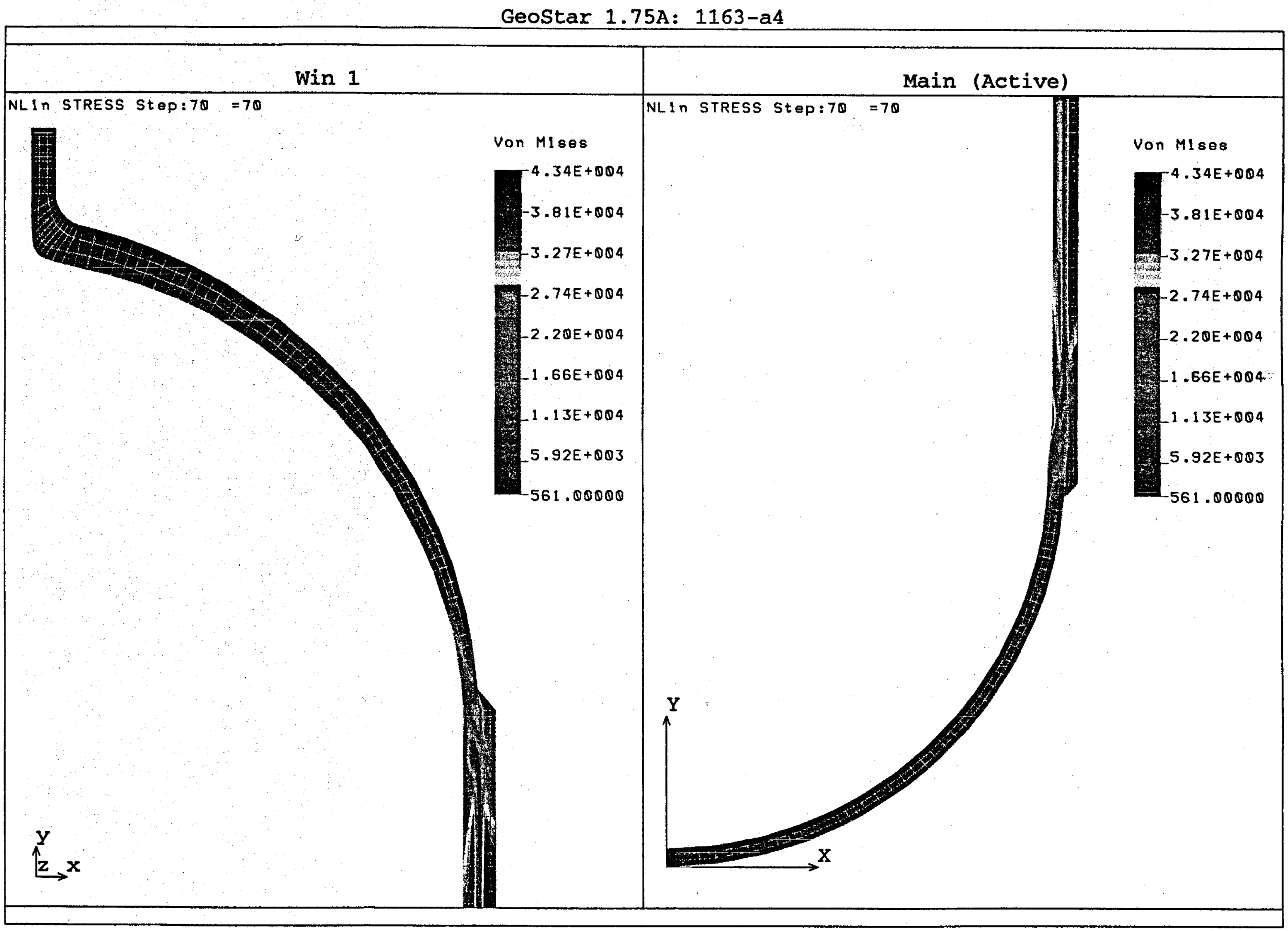
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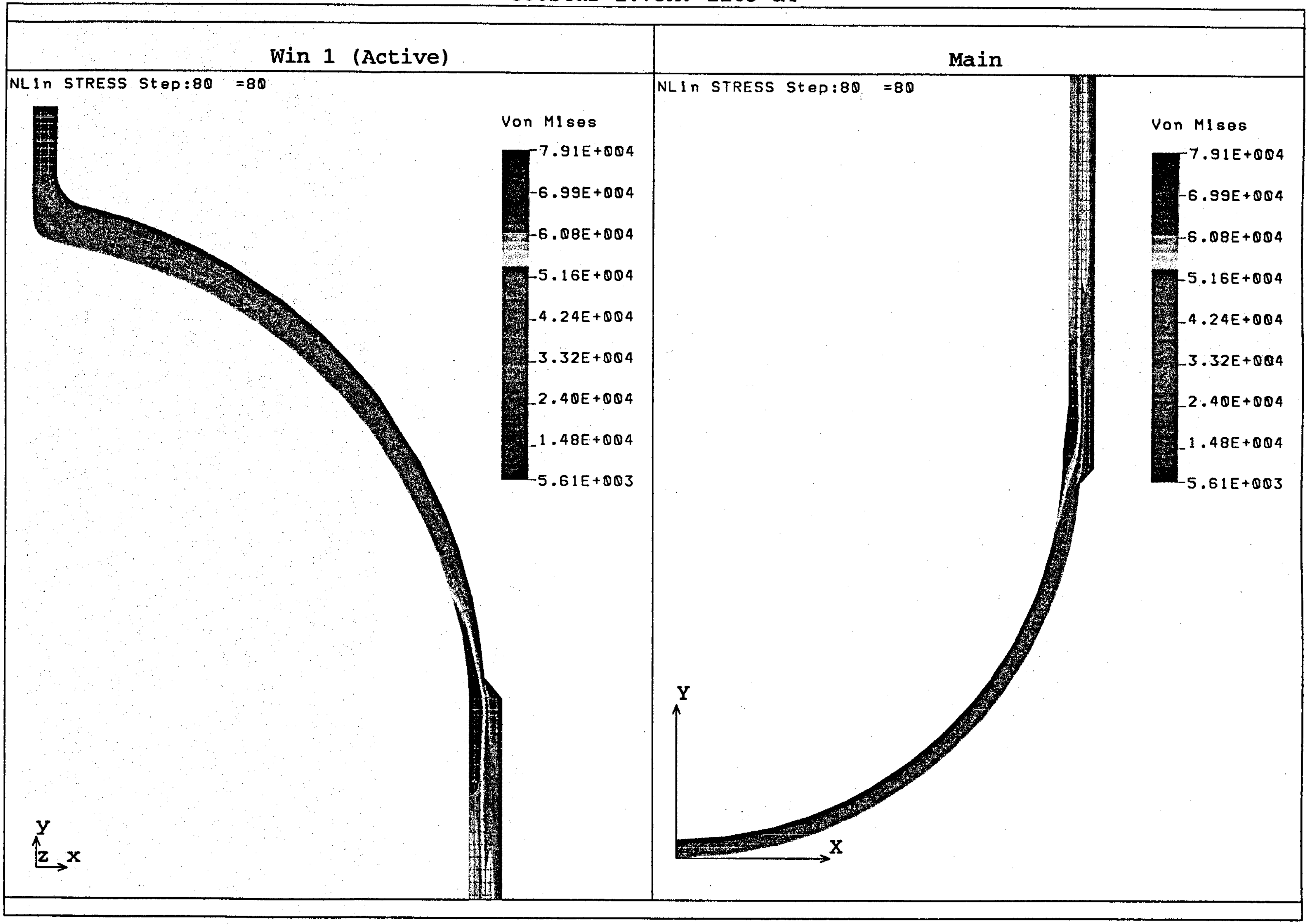

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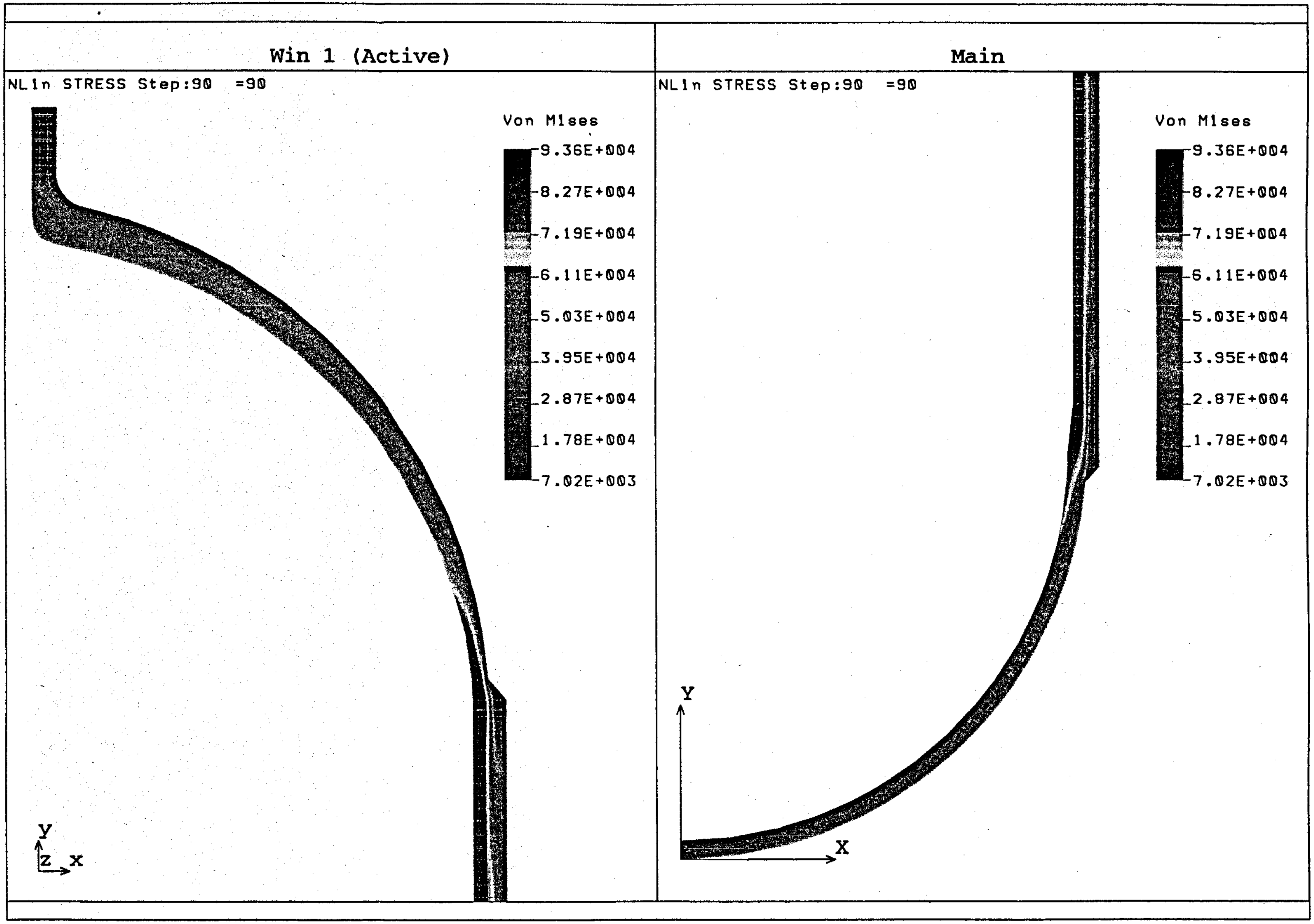

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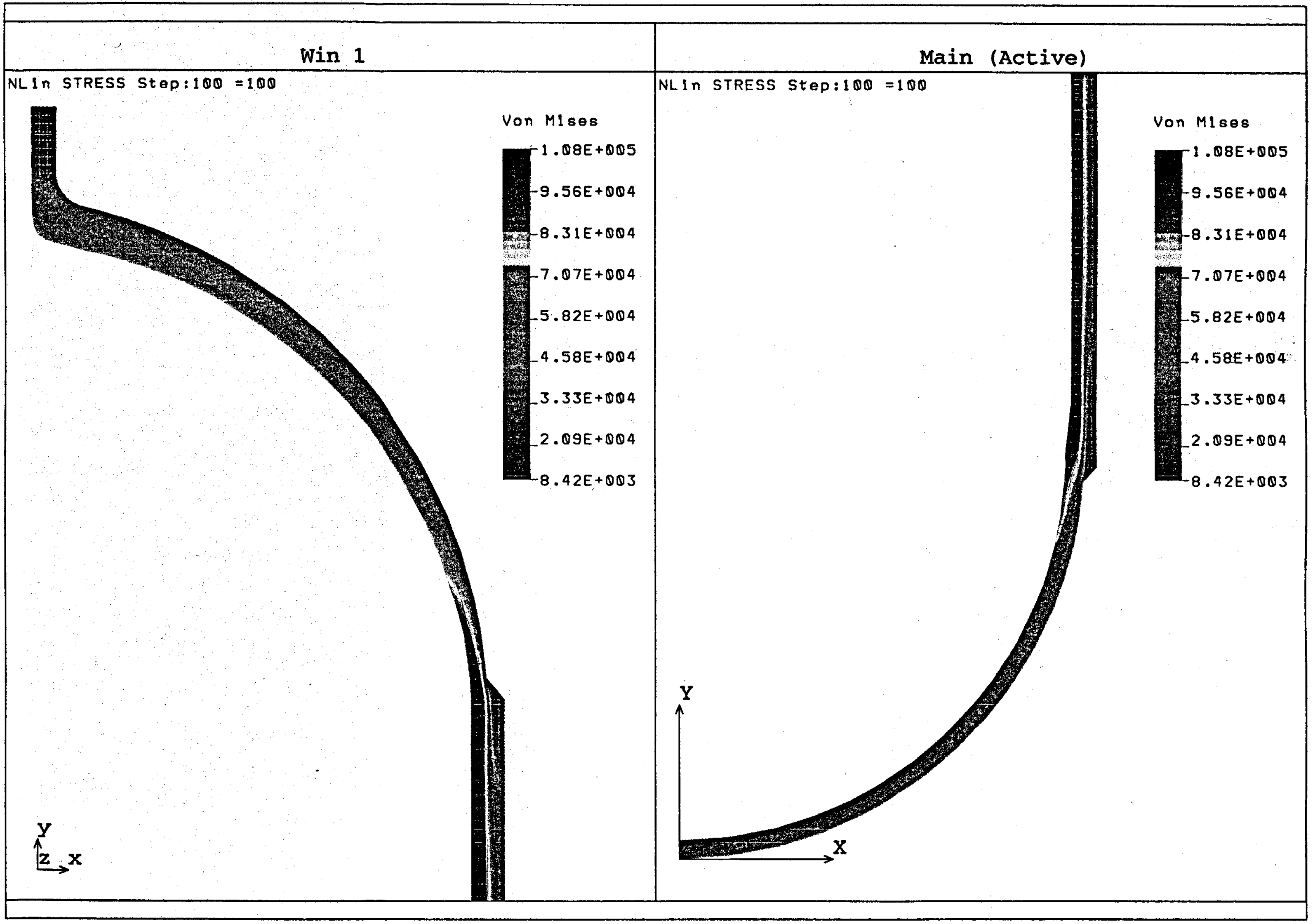

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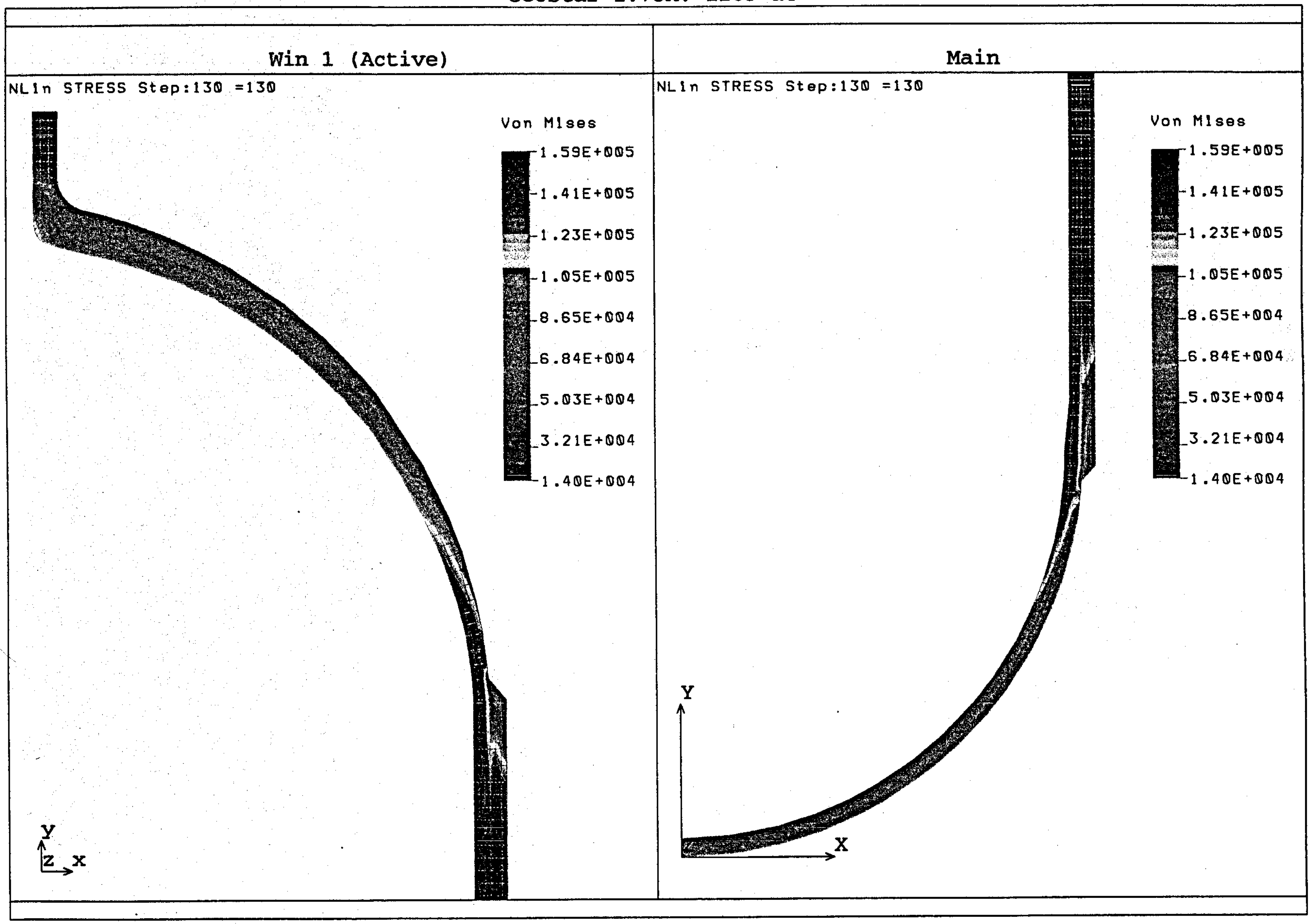

Appendix B

Lucas Aerospace CNG Cylinder Fiber Reinforcement Study

POWERTECH LABS INC.

FINAL REPORT

LUCAS AEROSPACE CNG CYLINDER FIBER REINFORCEMENT STUDY

Sub-Task
of
Gas Research Institute
High Strength Steel
Type 2 Cylinder Project

Powertech Project 9081-32

Principle Investigators:
Joe Wong
Livio Gambone
Craig Webster

TABLE OF CONTENTS

1.0 INTRODUCTION

The objective of the current program is to develop an optimized high strength steel hoop-wrapped (Type 2) compressed natural gas (CNG) cylinder for Lucas Aerospace. The new design will incorporate a high strength steel liner as permitted in the proposed revision (July 1997) to the ANSI/AGA NGV2 standard. Fiber reinforcement will be selected based on the results of the current fiber study.

Technical information pertaining to the performance of fibers under CNG service conditions was gathered from several fiber suppliers in an effort to determine which fiber system would be most suitable for the optimized Type 2 cylinder design. The fiber types considered included glass, carbon and aramid and encompassed the following specific manufacturers and products:

Glass Fibers	Carbon Fibers	Aramid Fibers
Vertrotex R099 P122 E-glass	Toray T700	Akzo Nobel Twaron® 2200
Owens Corning ZenTron™	Akzo Nobel Fortafil ® 3(C)	
Owens Corning Advantex™	Zoltek PANEX ® 33	

Consideration was given only to the above products since they appeared to offer the greatest potential for the intended application [1]. Where possible, the performance characteristics of Vetrotex R099 P122 E-glass fibers were used as a basis for comparison since these fibers are utilized in the present Lucas Aerospace CNG cylinder design.

2.0 FIBER PERFORMANCE

2.1 Glass Fibers

2.1.1 General

Glass fibers are the most widely used reinforcement for the manufacture of CNG cylinders due to their mechanical properties and attractive selling price. The inherent low cost of glass fibers is achieved by virtue of the simplicity of the manufacturing process, which in essence can best be described as the drawing of filaments from molten sand.

The most common and least expensive glass fiber type used is E-glass, which is a calcium alumino-borosilicate glass. S-glass is a magnesium alumino-silicate glass originally developed for aerospace/aircraft applications due to its higher strength and excellent thermal stability. A lower cost version (S2-glass®) manufactured by Owens Corning using less stringent (non-military) specifications is also available and offers similar mechanical performance. ZenTron™ is a new high strength glass fiber product line developed by Owens Corning, which has a similar formulation to S2-glass® and offers comparable performance.

The susceptibility of E-glass fibers to stress corrosion cracking (SCC) in the presence of acidic environments led to the development of ECR-glass, a boron-free version of E-glass. Owens Corning currently markets a glass fiber (Advantex™) that combines the mechanical properties and lower cost of traditional E-glass with the acid corrosion resistance of ECR-glass. The Advantex™ fiber system replaces Owens Corning's existing E-glass and ECR-glass product line.

2.1.2 Mechanical Properties

The mechanical properties of the glass fiber products under consideration are included in Table 1.

Table 1
Mechanical Properties of Glass Fibers [2 - 4]

Property	Vetrotex R099 P122 E-glass	Owens Corning Advantex™	Owens Corning ZenTron™
Strand Tensile Strength ksi (MPa)	493 (3400)	500 (3450)	575 (3970)
Strand Tensile Modulus Msi (GPa)	10.6 (73)	11.7 (81)	13.5 (94)
Strand Elongation at Break (%)	4.5	4.6	4.2
Composite Strength Translation Efficiency (%)	71*	70†	52†

* Impregnated single strand (measured)
† Unidirectional laminate in epoxy (measured)

2.1.3 Environmental Resistance

Glass fiber reinforced composites are susceptible to a number of moisture-induced degradation mechanisms [5 - 14]. For example, exposure to moisture causes a decrease in glass transition temperature and plasticization of the resin, which leads to reductions in strength, stiffness, and impact properties. Resin swelling attributed to moisture introduces stresses into the composite laminate, particularly at the fiber/resin interface. In addition, microcracking, void formation, crazing, and fiber/resin debonding have been reported. Researchers have confirmed that silane coupling agents used to promote interfacial bonding between the glass fibers and epoxy can dissolve in water.

Water can also cause the chemical degradation of glass fibers resulting in lower fracture energies. This degradation mechanism reportedly involves an ion exchange mechanism whereby acidic hydrogen ions present in water or dilute acid solutions are exchanged with the larger alkali metal cations in the glass fiber surfaces. This causes surface shrinkage, which in turn creates tensile stresses leading to new surface flaws. In the presence of service loading this can lead to SCC. A great deal of study has been devoted to examining the brittle fracture of glass fiber reinforced materials due to SCC [15 - 21]. In general, the evidence indicates that acids such as sulfuric, nitric, hydrochloric, and to a lesser extent, hydrogen bromide, hydrogen iodide, and some organic acids such as oxalic, promote the corrosion of glass fibers. In addition, alkali chemicals such as sodium hydroxide have been shown to be aggressive corrosion agents at high pH levels.

A number of failures of metal-lined composite CNG cylinders have been attributed to SCC of the glass reinforcing fibers [1]. In all cases reported, the type of fibers used in the cylinder designs was E-glass. Accordingly, the NGV industry has shown significant interest in the potential substitution of E-glass with glass fibers more resistant to the environmental service conditions to which CNG cylinders are exposed.

Owens Corning has subjected both their Advantex™ and ZenTron™ glass fibers to validation tests in water and acidic environments. Table 2 lists glass fiber weight loss as a function of exposure time to sulfuric acid. Both Advantex™ and ZenTron™ fibers exhibit significantly less weight loss than E-glass fibers under these conditions.

Table 2
Glass Fiber Weight Loss Due to Acid Exposure [3,22,23]

Exposure Time (Days)	**Fiber Weight Loss (%) (10% H_2SO_4, 96°C)**		
	Owens Corning E-glass	**Owens Corning Advantex™**	**Owens Corning ZenTron™**
1	39	6	--
7	42	10	4

Results from tensile strength retention tests performed by Owens Corning also confirm that Advantex™ fibers outperform E-glass fibers in water and mild acid exposure (see Table 3). Similar performance has been confirmed with respect to flexural strength retention. More information regarding the Owens Corning test specimens, exposure conditions and test results is available in Appendix A.

It is important to note that the data in Table 3 was generated by first exposing glass fiber reinforced panels to the given environment for the specified time, then performing tensile tests on samples prepared from these panels. These test conditions are not representative of the SCC failure mechanism observed in NGV service. As a result, Powertech Labs has performed a number of true SCC tests on both the Vetrotex E-glass and Owens Corning Advantex™ fiber systems. Details regarding the test procedure and test results are summarized in Section 3.0.

Table 3
Glass Fiber Reinforced Composite Tensile Strength Retention in Water and Acid [24,25]

Exposure Time (Days)	Composite Tensile Strength Retention (%)			
	Water (50°C)		Acid (5% H_2SO_4, 20°C)	
	Owens Corning E-glass	Owens Corning Advantex™	Owens Corning E-glass™	Owens Corning Advantex™
7	94	95	--	--
21	87	90	96	100
91	--	--	89	86
500	--	--	78	86

2.1.4 Availability and Cost

The glass fiber industry has three major global producers: Owens Corning, PPG Industries and St. Gobain (Vetrotex in the U.S.). Together, these companies contribute 60% of the glass fibers to the global market. The remainder of the market is served by a number of regional suppliers.

Glass fiber production is capital intensive, making sufficient plant loading critical to profitability. The industry has recently been operating near full capacity due to the growth in composites use. In support of this growth, the glass fiber industry is expected to add more than one-half million tons of capacity in the next four years. Owens Corning will account for about 50% of this total.

Current prices for E-glass fibers are about $0.85 to $1.00/lb. Owens Corning Advantex™ fibers are priced at the same level as E-glass fibers. In contrast, Owens Corning high strength ZenTron™ fibers range from $5.50 to $6.75/lb depending on order volumes.

Owens Corning manufactures its Advantex™ glass fiber product in North America (Guelph, Ontario) and in Europe (Battice, Belgium and L'Ardoise, France). ZenTron™ glass fibers are available from the North American Specialty Fibers Division in Huntington, Pennsylvania.

2.1.5 Filament Winding Considerations

Owens Corning's Advantex™ and ZenTron™ fibers are equally compatible with all of the most widely used resin systems for filament winding. In addition, a glass fiber sizing system has been developed to provide good cyclic and burst strength performance for filament wound epoxy pressure vessels. Both fiber systems are available in center-pull and outside-pull spools.

2.2 Carbon Fibers

2.2.1 General

Carbon fibers are produced by the thermal decomposition of various organic fiber precursors such as cellulose, polymerized acrylonitrile (PAN) and mesophase pitch. More than 90% of all carbon fibers on the market are manufactured from PAN precursors. These precursors provide a carbon fiber yield of 45 to 50% (typically 2.2 lb PAN per lb carbon fiber produced). The current price of commercial grade carbon fibers is approximately $12.00 to $20.00/lb. The capital-intensive nature of the manufacturing process coupled with the high cost of raw material (PAN precursor) and relatively low conversion yield is primarily responsible for its high cost.

In general, carbon fibers offer the highest modulus and strength of all reinforcing fibers. The fibers have high fatigue strength and do not suffer from SCC or stress rupture failures. However, carbon fiber exhibits low failure strain, a property which imparts low impact resistance to carbon fiber reinforced composites.

2.2.2 Mechanical Properties

The mechanical properties of the carbon fiber products under consideration are included in Table 4.

Table 4
Mechanical Properties of Carbon Fibers [26-28]

Property	Toray T700	Akzo Nobel Fortafil® 3(C)	Zoltek PANEX® 33
Strand Tensile Strength ksi (MPa)	700 (4825)	550 (3800)	525 (3620)
Strand Tensile Modulus Msi (GPa)	33.4 (230)	33.0 (227)	33.0 (227)
Strand Elongation at Break (%)	2.1	1.7	1.5
Composite Strength Translation Efficiency (%)	65*	48*	--

* Unidirectional laminate in epoxy (measured)

2.2.3 Environmental Resistance

In general, carbon fibers are unaffected by moisture, solvents, bases and weak acids at room temperature [29]. In addition, they are essentially immune to SCC and stress rupture at room temperature. They also offer outstanding strength and modulus retention over long periods at elevated temperatures (>150°C).

2.2.4 Availability and Cost

Worldwide carbon fiber shipments totaled over 17 million pounds in 1995. Military and commercial aerospace applications consumed nearly half of that amount, while the U.S. consumed over 40% over all applications [1]. Worldwide PAN-based nameplate capacity is approximately 22.7 million pounds, which misleadingly suggests an excess market capacity. In actuality, the carbon fiber industry is currently operating in the oversold condition. This condition has been exacerbated by the exit of Courtaulds and BASF from the carbon fiber industry due to the reduction and/or elimination of military programs in the early 1990s.

As a result, several carbon fiber manufacturers have plans to expand their production capacity [1,30]. Akzo Nobel has already expanded their plant by about 3.3 million pounds a year. Amoco is planning to start the old BASF plant, which will contribute 2 million pounds per year. R.K. Carbon is considering an expansion of between 1 and 2 million pounds, while Hercules is initiating several de-bottlenecking efforts to expand capacity. Toray plans to boost its production capability at its Ehime plant to 10.4 million pounds by the spring of 1998. In addition, Toray is considering new carbon fiber production capacity of about 4 million pounds for the U.S. by 1999. The total increase in carbon fiber capacity represented by these potential expansions is approximately 15 million pounds (prior to the year 2000).

The high cost of carbon fiber has limited its entry into the commercial marketplace and this has limited any potential price reduction from increased market exposure. The current price of commercial grade carbon fibers ranges from $12 to $20/lb, whereas the price of aerospace grade fibers can be as high as $55/lb. The cost of PAN raw material is partly responsible for this high cost since it is produced from propylene, which is a hydrocarbon derived from the catalytic cracking of crude oil. Another major factor in the cost of carbon fibers is the very high level of investment required of producers due to manufacturing capital and operating requirements.

A number of carbon fiber suppliers such as Akzo Nobel, Zoltek, and R.K. Carbon offer an industrial grade large tow (48K or 50K) low cost carbon fiber product manufactured using a textile acrylic fiber-based PAN precurser. Additional research is required to investigate whether this product is technically equivalent to the high strength 12K tow products used in current CNG cylinder designs. Technical issues which remain to be resolved include fiber windability, resin wetting, fiber tension and flatness. Carbon fiber costs as low as $10 to $12/lb are achievable for these lower cost textile-based fibers.

2.2.5 Filament Winding Considerations

The availability of inexpensive large tow carbon fibers such as Akzo Nobel's Fortafil® 3(C) is attractive to the current CNG cylinder optimization program due to the potential for finished cylinder cost reduction and increased filament winding through-put. As discussed previously in Section 2.2.4, the wet winding of CNG cylinders using large tow fibers requires considerable future experimentation. In addition, the manufacturing process reportedly incurs the risk of carbon particulate contamination of sensitive electrical equipment. In contrast, pre-impregnated (prepreg) unidirectional composite tapes made from large tow fibers offer the possibility of cost competitive and solvent free processing, ambient temperature storage, and improved composite strength translation efficiency. This latter feature is particularly helpful for the Fortafil® 3(C) carbon fiber system as it suffers from a low translation efficiency (see Table 4).

Thiokol's TCR™ prepreg product, which is available for carbon, aramid, and glass fiber systems, may be suitable for the optimized Lucas Aerospace hoop-wrapped CNG cylinder [33]. A detailed prepreg fiber feasibility study comparing the finished weight and cost parameters of the large tow Fortafil® fiber and the conventional 12K or 24K Toray T700 fiber would be essential to the manufacturing selection process. Thiokol's preliminary estimates for carbon fiber weight per cylinder (12 inch diameter x 60 inch long) and associated cost using TCR™ prepreg are shown in Table 5.

The preliminary estimates in Table 5 suggest that TCR™ prepregs manufactured with Fortafil® 3(C) carbon fibers offer both a minimal cost savings and incur a significant weight penalty compared to those manufactured with Toray T700 fibers.

For completeness, a similar weight and cost study should be prepared for the case of wet winding of conventional 12K or 24K Toray T700 fibers.

Table 5
Thiokol TCR™ Prepreg
Preliminary Weight and Cost Estimates [33]

	Akzo Nobel Fortafil® 3(C) 50K	**Toray T700 24K**
Carbon Fiber Weight (lb)	16.5	11.8
Carbon Fiber Cost ($/lb)	13.97	20.06
Total Carbon Fiber Cost ($)	230.51	236.71

2.3 Aramid Fibers

2.3.1 General

Aramid is a generic term for a class of aromatic polyamide fibers introduced commercially during the 1970s. Organic fibers such as Kevlar® aramids were developed by E.I. DuPont de Nemours. Akzo Nobel also manufactures an aramid fiber product under the trade name Twaron®. As a result of their highly aligned polymer chain, these fibers offer high tensile strength and modulus with moderate elongation. Aramid fibers exhibit excellent fatigue resistance and they are resistant to flame, high temperatures and chemicals such as organic solvents, fuels and lubricants. Their limitations include a tendency to absorb moisture, a susceptibility to ultraviolet degradation and poor adhesion to matrix resins.

2.3.2 Mechanical Properties

The mechanical properties of the aramid fiber product under consideration are included in Table 6.

Table 6
Mechanical Properties of Aramid Fiber [31]

Property	Akzo Nobel Twaron® 2200
Strand Tensile Strength ksi (MPa)	457 (3150)
Strand Tensile Modulus Msi (GPa)	16.7 (115)
Strand Elongation at Break (%)	2.6
Composite Strength Translation Efficiency (%)	46*

* Unidirectional laminate in epoxy (estimated)

2.3.3 Environmental Resistance

Twaron® aramid fibers generally offer good resistance to most organic chemicals, and acids and bases in the pH range 3 to 10 [31]. As with most fiber-reinforced composites, the limiting factor for chemical resistance is usually the less resistant polymer matrix. Aramid fibers alone can absorb significant amounts of moisture when exposed to high humidity. However, the total moisture absorbed by an aramid/epoxy composite may not be substantially greater than that absorbed by other epoxy composites [32].

The ultraviolet resistance of bare unprotected Twaron® aramid fibers is relatively poor [31]. However, this behavior has limited impact on fiber reinforced systems since the fibers are embedded in an epoxy or polyester matrix. Resin-rich topcoats, which offer high ultraviolet absorption, can protect aramid fibers more than adequately [32].

Twaron® aramid fibers exhibit minimal creep behavior at 85°C [31].

2.3.4 Availability and Cost

The global market for aramids is approximately 20,000 tons annually and U.S. demand is expected to grow 6 to 8% per year for several years. The largest use for aramid fibers is for the reinforcement of firefighter's breathing apparatus bottles. Other uses include aircraft oxygen bottles and a variety of aerospace applications.

There are only a handful of suppliers of aramid fibers: DuPont, Akzo Nobel, Teijin, and Hoechst Celanese. DuPont (Kevlar®) and Akzo Nobel (Twaron®) dominate the market. DuPont's share of the world market is above 60%, while Akzo Nobel holds about a 30% share. Prices for aramid fibers have recently settled to the $7 to $9/lb range.

2.3.5 Filament Winding Considerations

Akzo Nobel's Twaron® aramid fiber can be filament wound using wet processing methods at rapid speeds (up to 325 ft/min.). This is facilitated by the use of a conical pultrusion-type die through which the aramid fibers are forcibly wetted. Although the resulting winding speeds would likely be too high for the manufacture of CNG cylinders, some increased throughput can be expected. Prior to winding, the aramid fibers are pre-heated in a ceramic infrared heater to 250 to 300°C to remove moisture from the fibers, thereby improving fiber wetting. This latter processing feature shortens curing time since the initial cure temperature can be higher due to reduced moisture in the composite.

Twaron® aramid fibers would also be suitable prepreg candidates for the Thiokol TCR™ prepreg tape system.

3.0 POWERTECH ACID TEST RESULTS

In order to complement the acid test work performed by Owens Corning (see Section 2), Powertech initiated a series of SCC tests for the Vetrotex E-glass and Owens Corning Advantex™ fiber systems. The test involved subjecting epoxy resin impregnated tows of each fiber system to a range of constant loads in a sulfuric acid environment and monitoring the time to failure of individual samples. The test was designed to duplicate the exposure of a Lucas Aerospace hoop-wrapped CNG cylinder to battery acid.

The fiber tows were impregnated with a Shell Epon 8132 epoxy resin/Ancamide 506 hardener and cured at room temperature for 16 hours followed by a post-cure of 2 hours at 100°C. Cross-sections of several cured glass fiber tows were examined in the scanning electron microscope (SEM) to confirm adequate resin distribution/fiber wetting. In addition, the image analyzer attachment to the SEM was used to estimate fiber cross-sectional area.

The acid solution consisted of 19% by volume sulfuric acid. The test was conducted at room temperature. The effects of elevated temperature acid exposure and varying acid concentration were not evaluated in the current test program.

The Powertech acid test results are presented graphically as fiber stress versus log time-to-failure in Figure 1. Based on the consistent but limited data, the Advantex™ fibers clearly outperformed the Vetrotex E-glass fibers under these exposure conditions. At fiber stresses associated with typical Lucas Aerospace hoop-wrapped CNG cylinder operating pressures (60 to 100 ksi), the SCC data suggests that Lucas cylinders hoop-wrapped with Vetrotex fibers are affected by acid exposure, whereas those hoop-wrapped with Advantex™ fibers may be unaffected.

Figures 2 and 3 are SEM micrographs of fracture surfaces of broken Vetrotex and Advantex™ glass fibers showing the characteristic features of brittle fracture due to SCC. The fracture surfaces consist of a small fracture mirror (indicative of high applied stress), and small ridges oriented in a direction parallel to crack propagation, which eventually merge into similar but larger ridges.

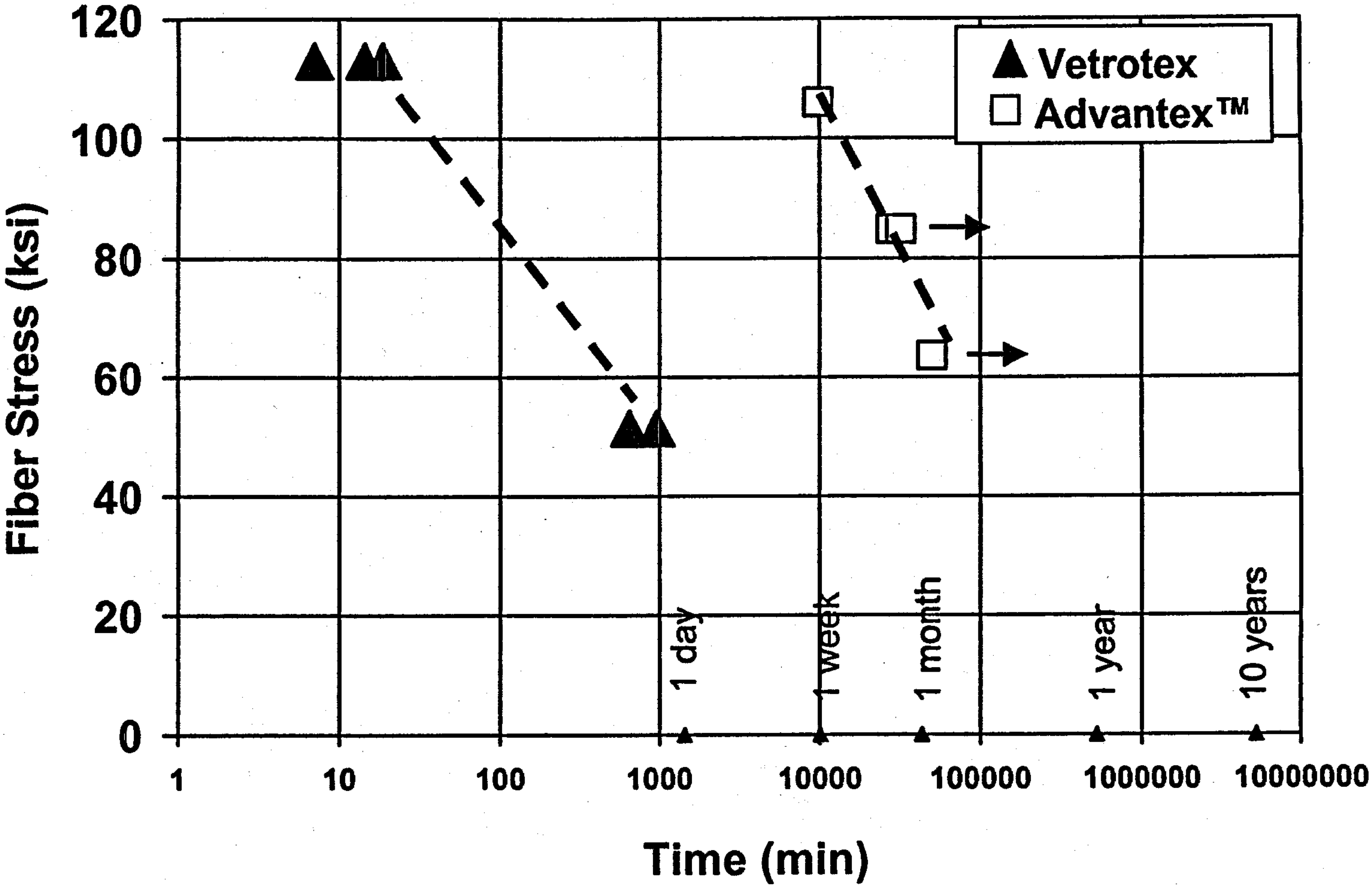

Figure 1: Plot of fiber stress versus log time-to-failure in 19% by volume sulfuric acid solution.

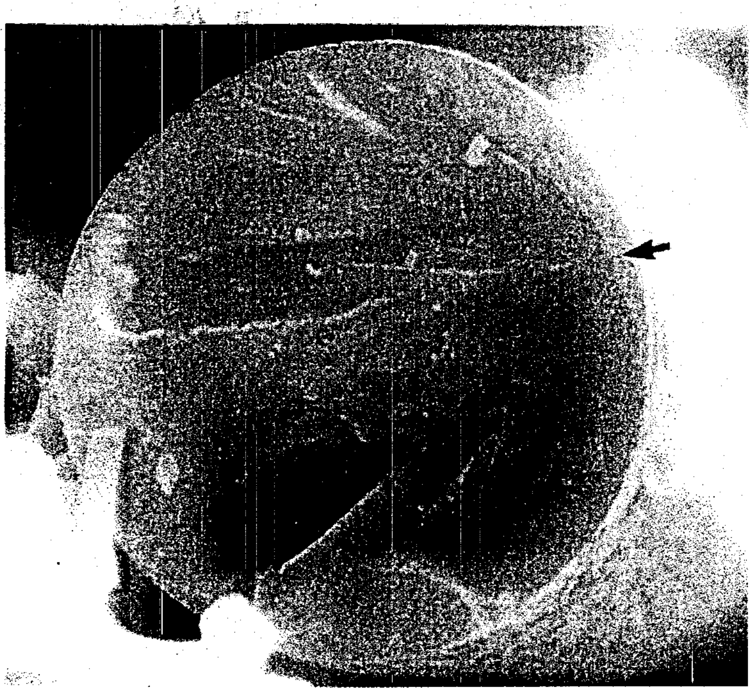

Figure 2: SEM micrograph of broken Vetrotex E-glass fiber after 646 minutes exposure to 19% by volume sulfuric acid at 51.4 ksi. Characteristic brittle fracture surface features caused by SCC are visible (fracture mirror identified with an arrow). Magnification: 3500X

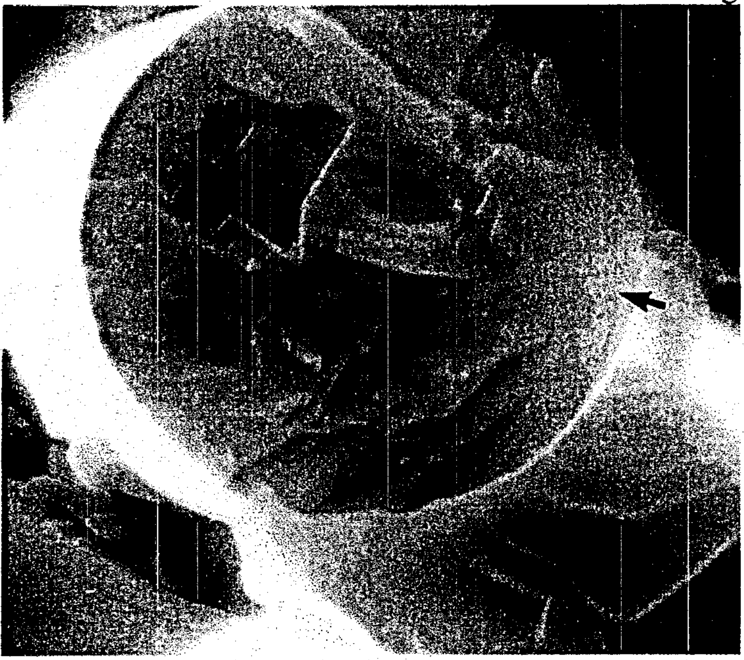

Figure 3: SEM micrograph of broken Owens Corning Advantex™ glass fiber after 24,480 minutes exposure to 19% by volume sulfuric acid at 84.8 ksi. Characteristic brittle fracture surface features caused by SCC are visible (fracture mirror identified with an arrow). Magnification: 5000X

4.0 RECOMMENDATIONS

A review of the technical information pertaining to the performance of selected glass, carbon, and aramid fiber systems under CNG service conditions has been performed. With respect to fiber reinforcement selection for an optimized Lucas Aerospace Type 2 CNG cylinder design, the following course of action is recommended:

1. Given the favorable cost, superior acid performance, and European availability of Owens Corning Advantex™ fibers, it is recommended that prototype cylinders be fabricated and tested using this fiber system. The prototype cylinders should be subjected to the environmental, accelerated stress rupture and flaw tolerance tests as described in the latest draft (July 1997) of the ANSI/AGA NGV2 standard.

   In order to expedite the test program, the prototypes should be wet wound using Lucas' existing process parameters (e.g. resin system, fiber tension, wind speed, etc.). Should this fiber system prove successful in cylinder prototype tests, these process parameters can be fine tuned in consultation with Owens Corning at a later date. In addition, to improve fiber wetting and increase throughput, the use of a conical pultrusion-type fiber feed die should be considered.

2. Concurrent with the above recommendation, tests should be conducted on Advantex™ fibers to confirm their elevated temperature acid performance and the effect of varying acid concentration. In addition, it is recommended that the Owens Corning Application Development Center in Granville, Ohio be contacted for more information regarding their existing acid exposure test program.

3. Should the Owens Corning Advantex™ fiber system prove unsuitable for the optimized Lucas Aerospace CNG cylinder, then additional prototype cylinders should be fabricated using Toray T700 carbon fibers in either prepreg tape format or through a wet winding process, pending favorable results from a detailed weight and cost study as suggested in Section 2.2.5. Further investigation will be required to determine if sensitive electrical equipment can be protected from carbon fiber particulate contamination for the case of wet winding of Toray T700 fibers, should this approach prove more weight/cost effective than the prepreg processing of these fibers.

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Appendix A

Owens Corning Advantex ™ Acid Test Results

Guelph Tso Corrosion Study

Raw Materials:

1. Chopped Strand Mat - 3 layers each [approximate thickness 0.12"]
   - a) E glass - M723 from Mexico 450 gm/sq m
   - b) 3709 glass - M723 from Guelph Feb 1995 production
   - c) 5075 glass - M723 from Guelph March 1995 production

2. Continuous roving [approximate thickness 0.30"]
   - a) E glass - Amarillo 1) 357B AC 211 (2400 TEX)
     2)495 DF 208 (2362 TEX)
   - b) 3709 glass - Guelph 1) 357B AC 2400
     2)495 AA 2400
   - c) 5075 glass - Guelph 1) 357B AC 2400
     2)495 AA 2400

3. Resin - Alpha-Owens Corning E704-BI Isophthalic Polyester

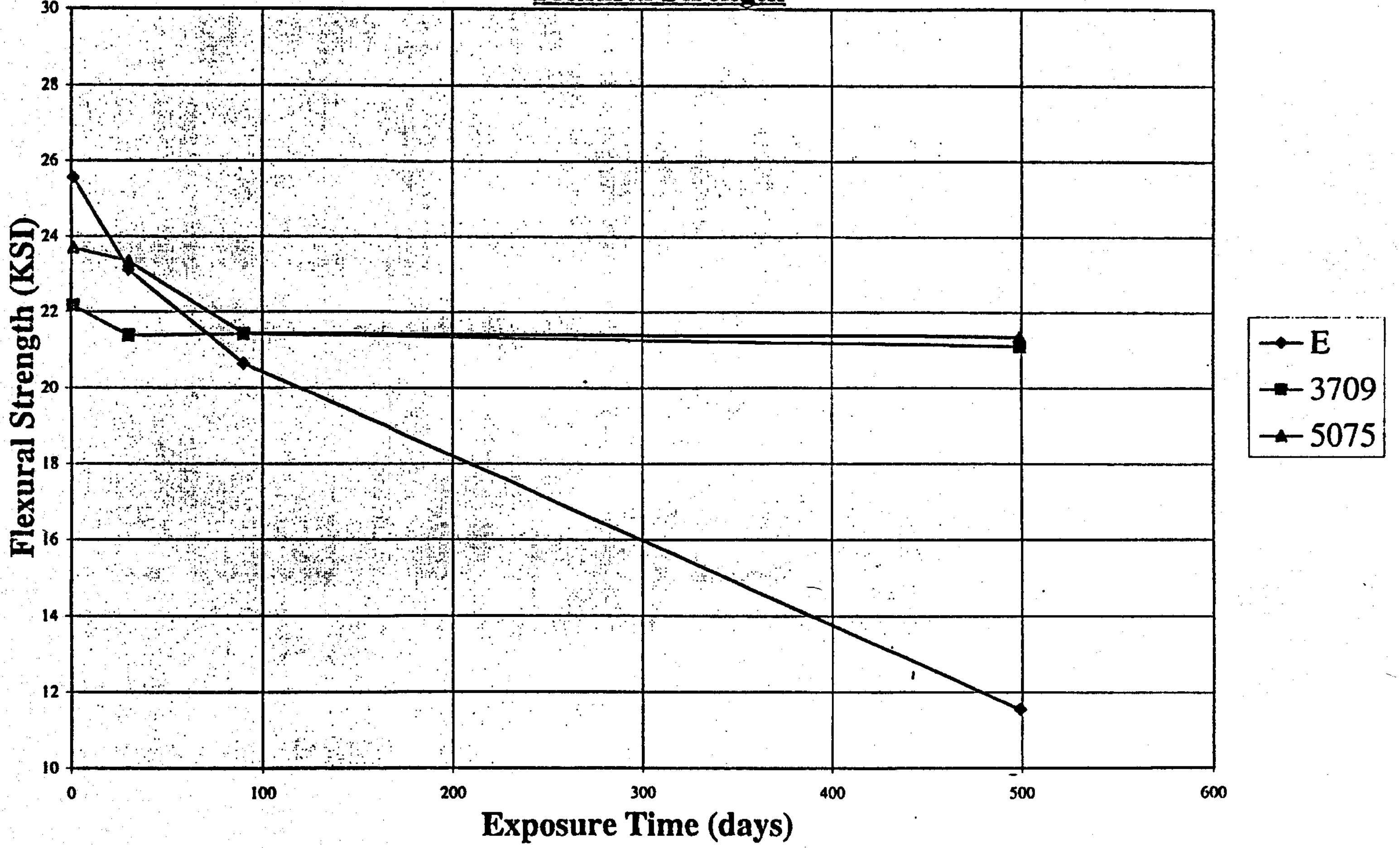
Exposure: 1 Normal Sulfuric Acid (about 5%) at 20 deg.C

Note: All laminates were post cured at 90 deg.C for 3 hrs.

Tests:
1. Tensile - ASTM D638 - Test Type I
2. Flexural - ASTM D790
3. Glass Fibre Content - ASTM D2584
4. Density - ASTM D792
5. Weight Loss
6. Barcol Hardness

The exposure began May 24, 1995. Testing dates in days are 0, 1, 30, 120, 500, and 1440.

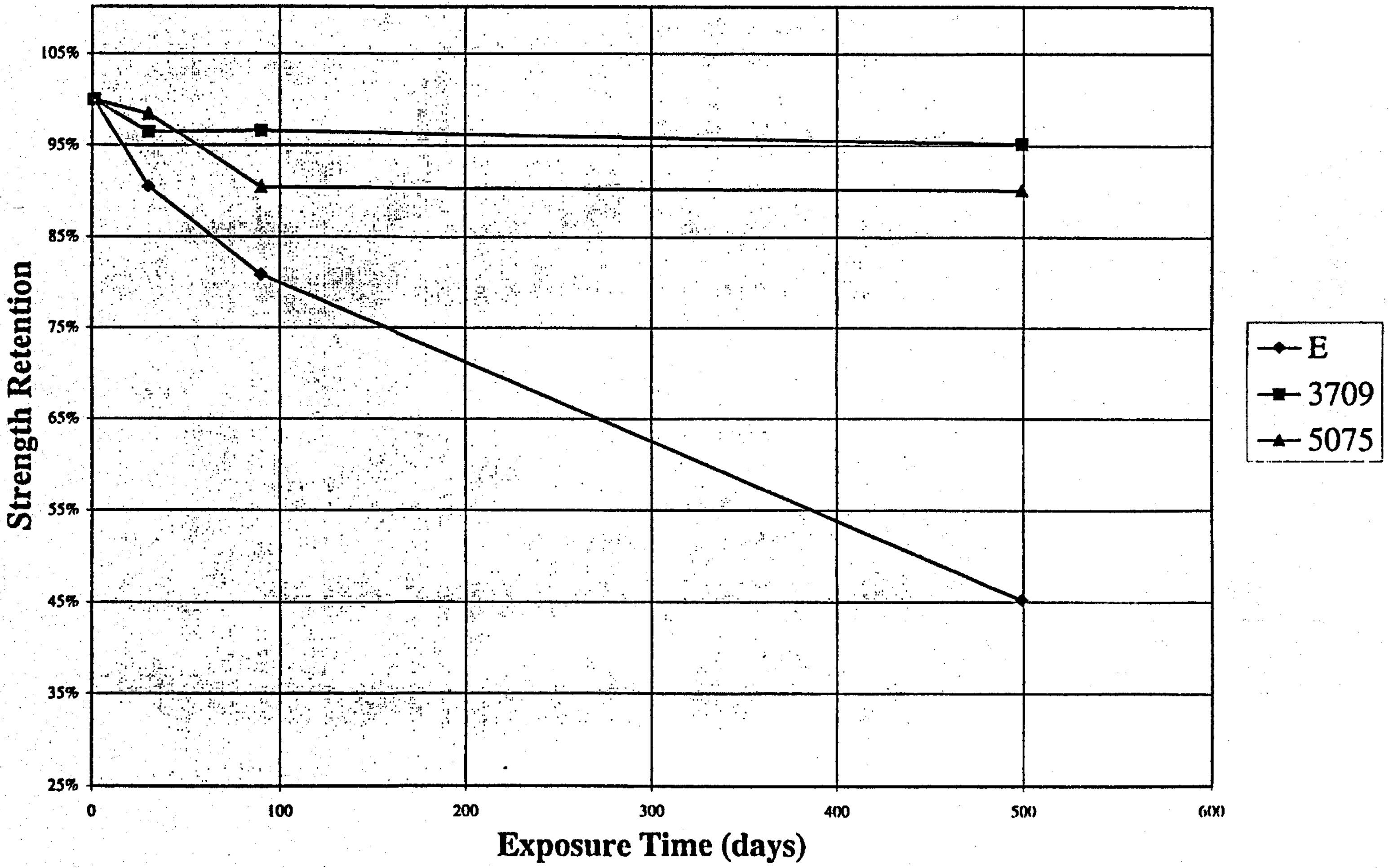
357 Continous Roving
Flexural Strength



Normalized to 30 Weight % Glass

Prepared by Rick Matzeg 27/11/96

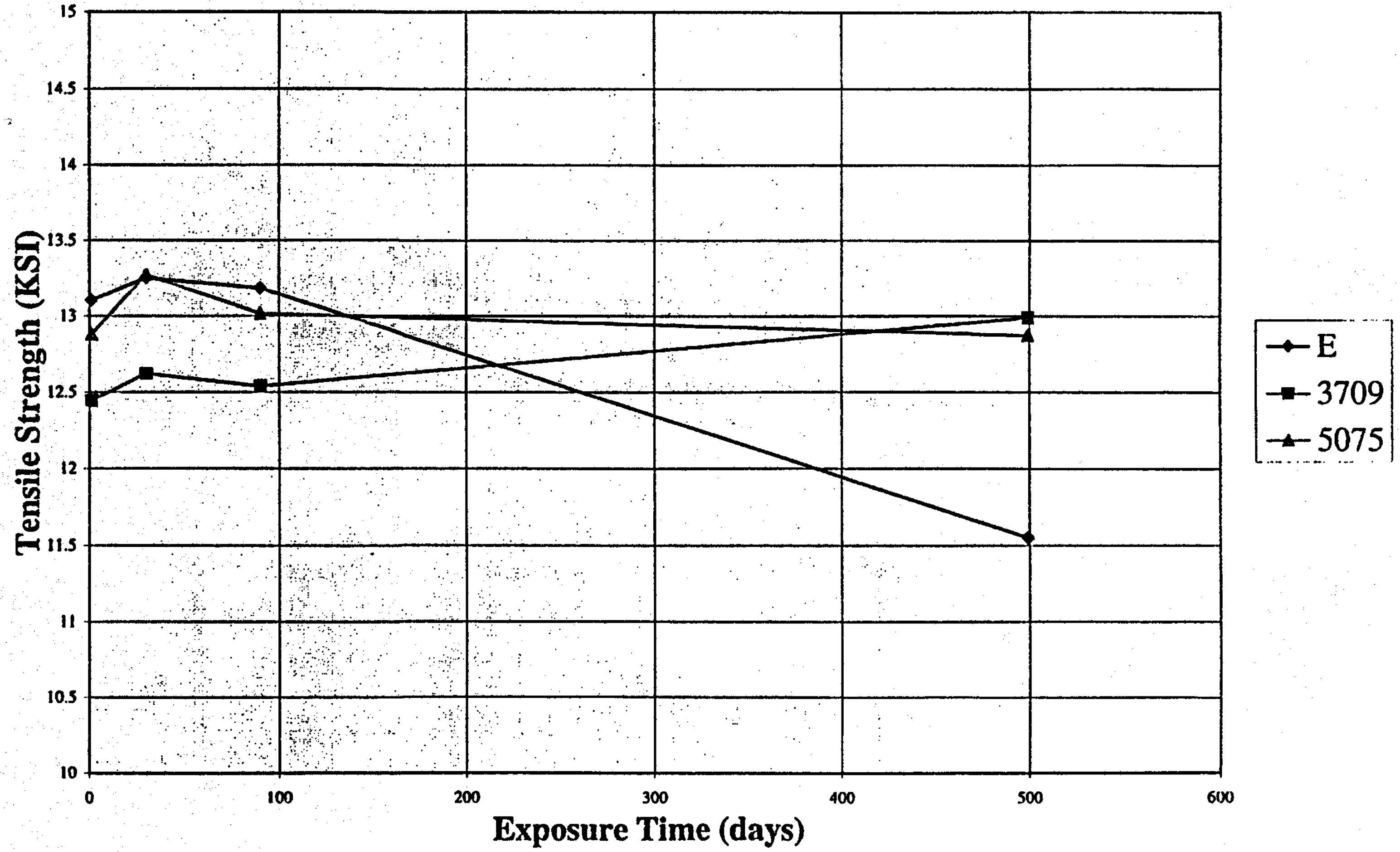
357 Continous Roving Flexural Strength Retention



Normalized to 30 Weight % Glass

Prepared by Rick Matzeg 27/11/96

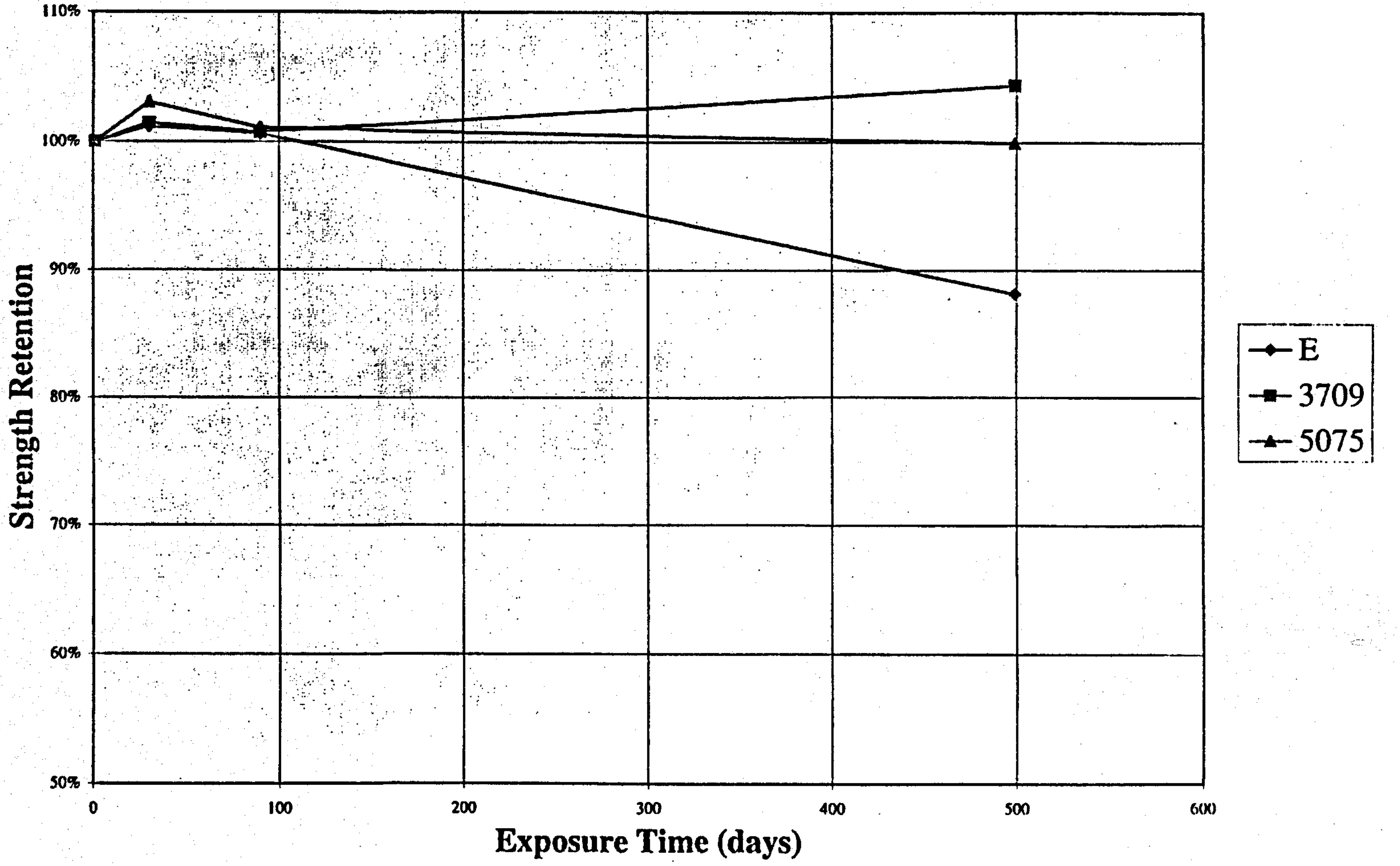
357 Continous Roving Tensile Strength



Normalized to 30 Weight % Glass

Prepared by Rick Matzeg 27/11/96

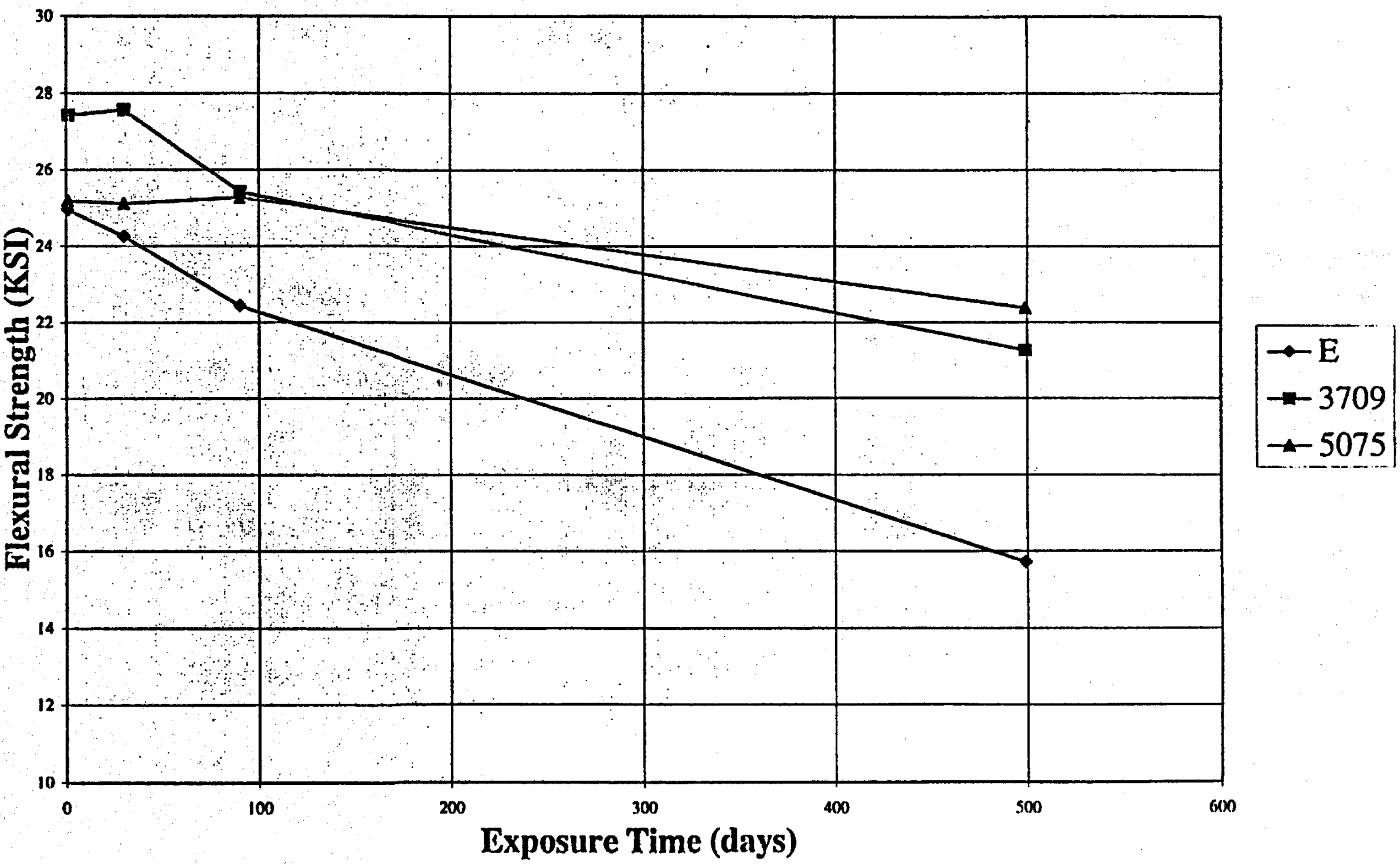
357 Continous Roving Tensile Strength Retention



Normalized to 30 Weight % Glass

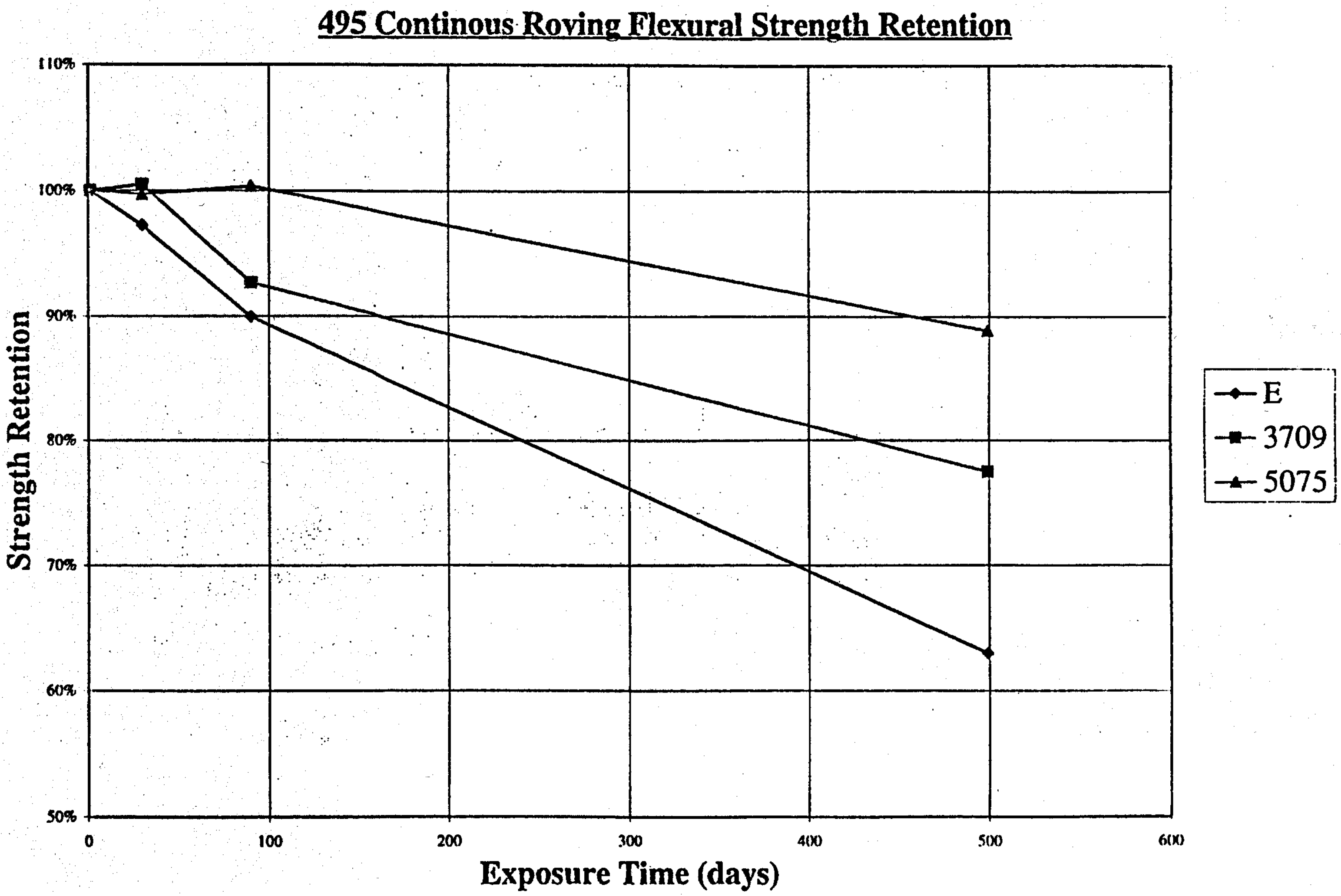
Prepared by Rick Matzeg 27/11/96

495 Continous Roving Flexural Strength



Normalized to 30 Weight % Glass

Prepared by Rick Matzeg 27/11/96

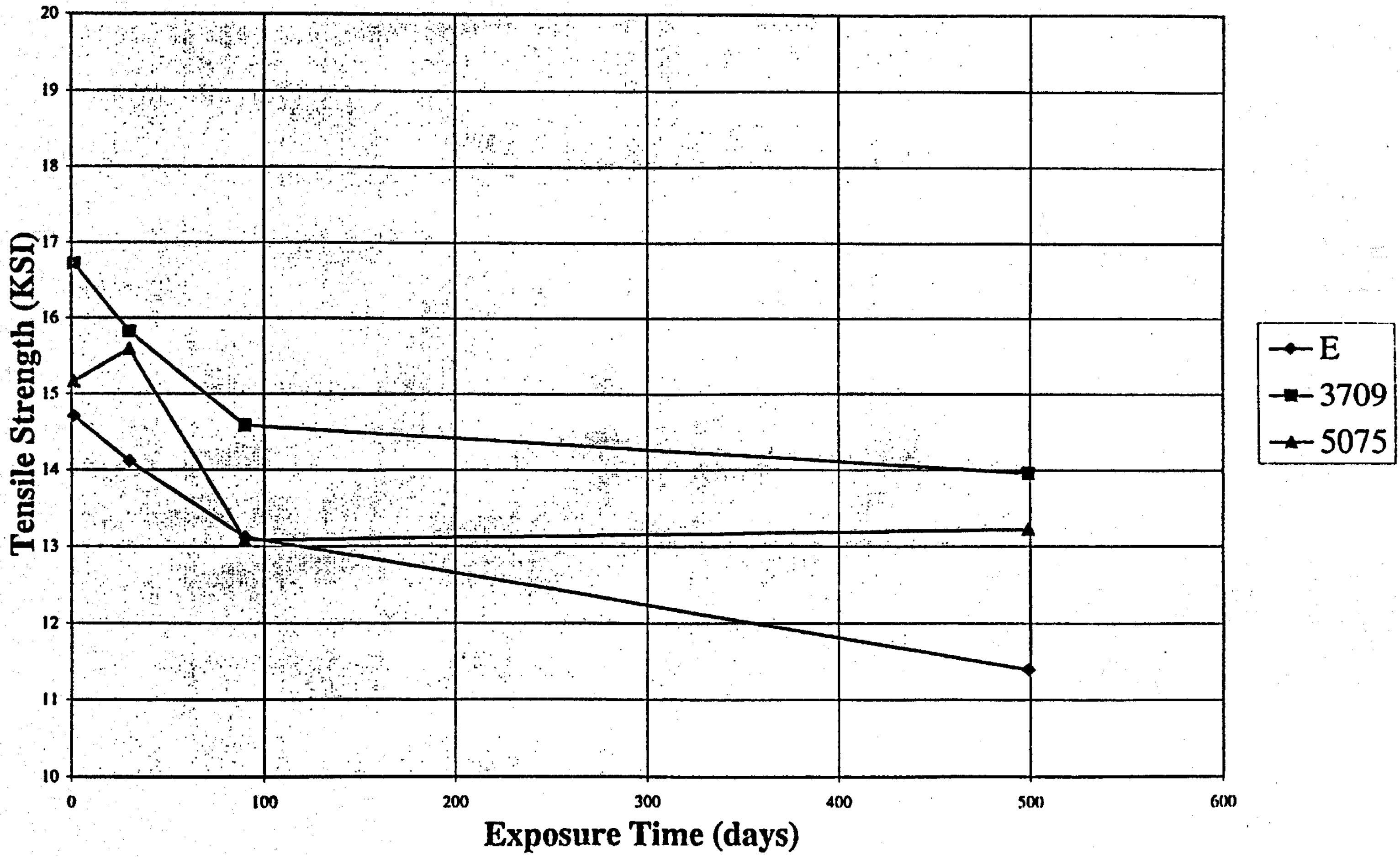


495 Continous Roving Flexural Strength Retention

Normalized to 3O Weight % Glass

Prepared by Rick Matzeg 27/11/96

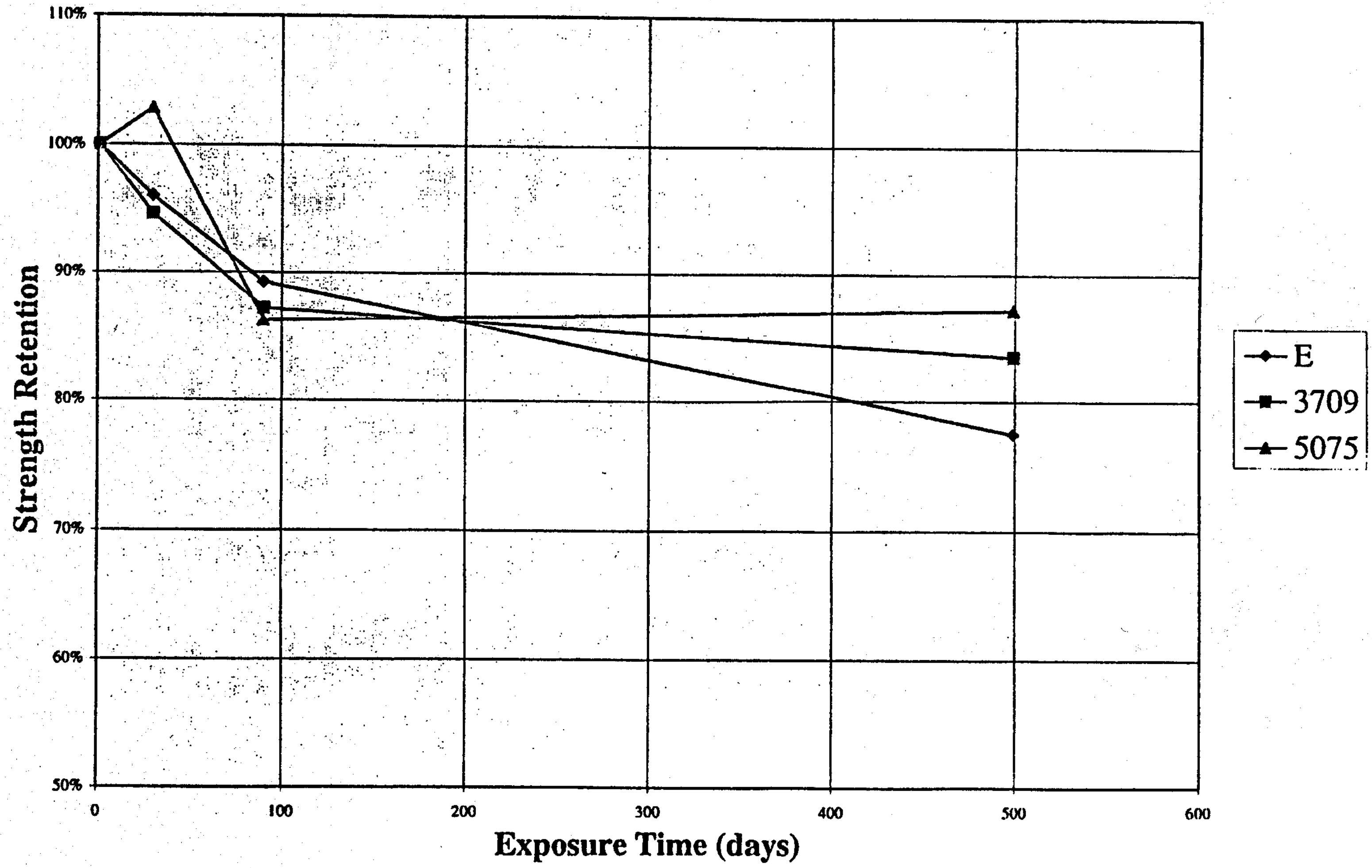
495 Continous Roving Tensile Strength



Normalized to 30 Weight % Glass

Prepared by Rick Matzog 27/11/96

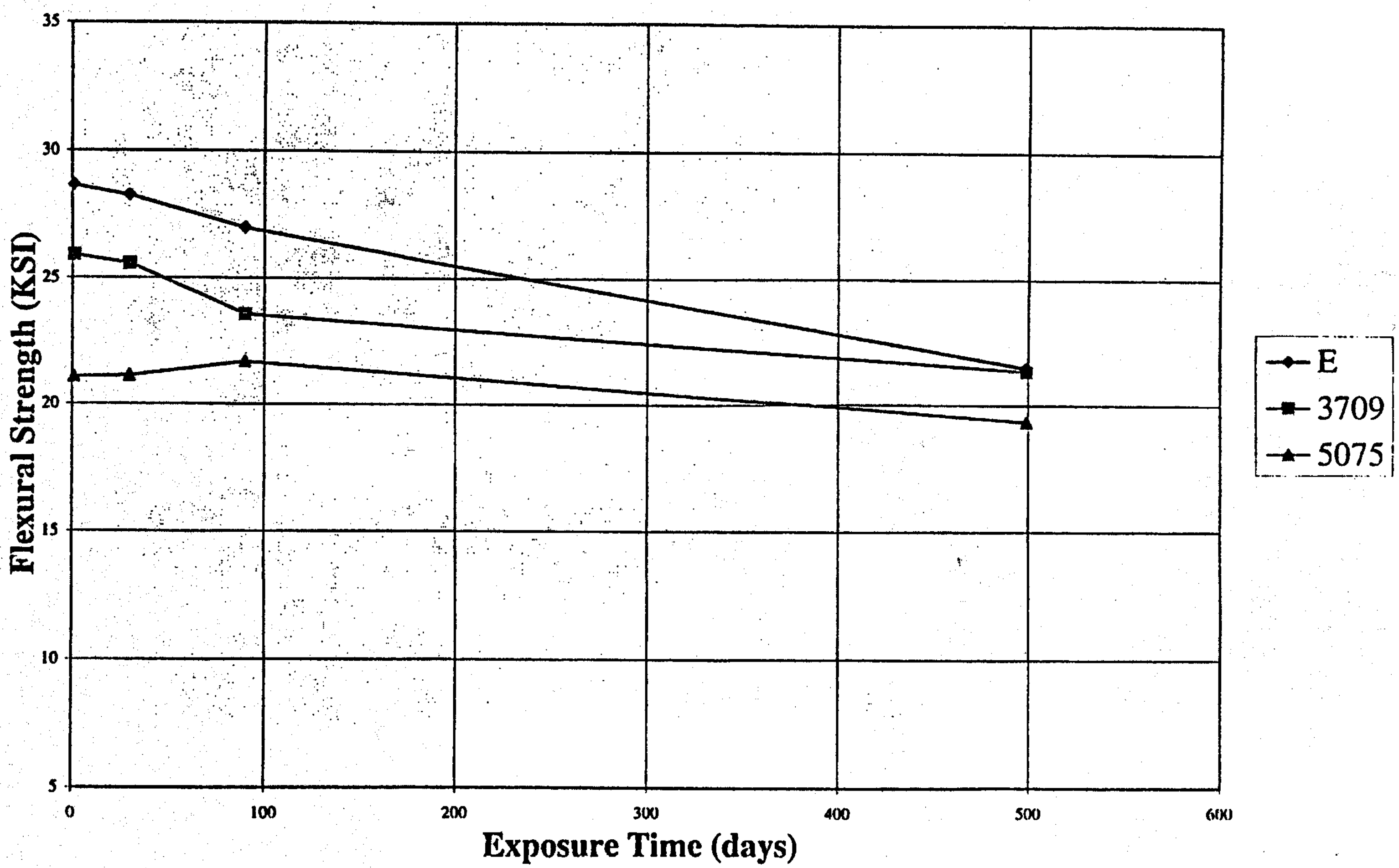
495 Continous Roving Tensile Strength Retention



Normalized to 30 Weight % Glass

Prepared by Rick Matzeg 27/11/96

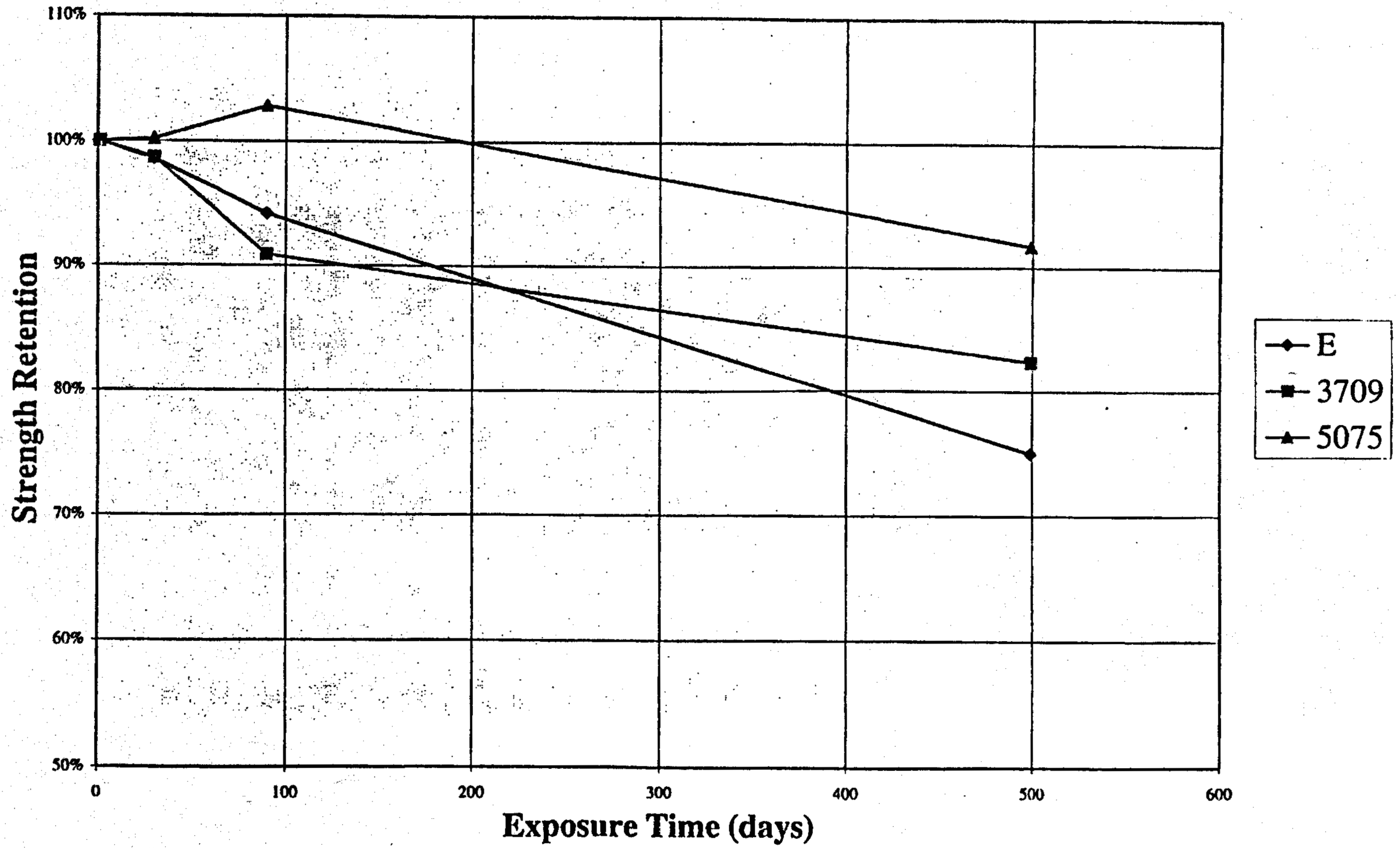
Mat Flexural Strength



Normalized to 33 Weight % Glass

Prepared by Rick Matzeg 26/11/96

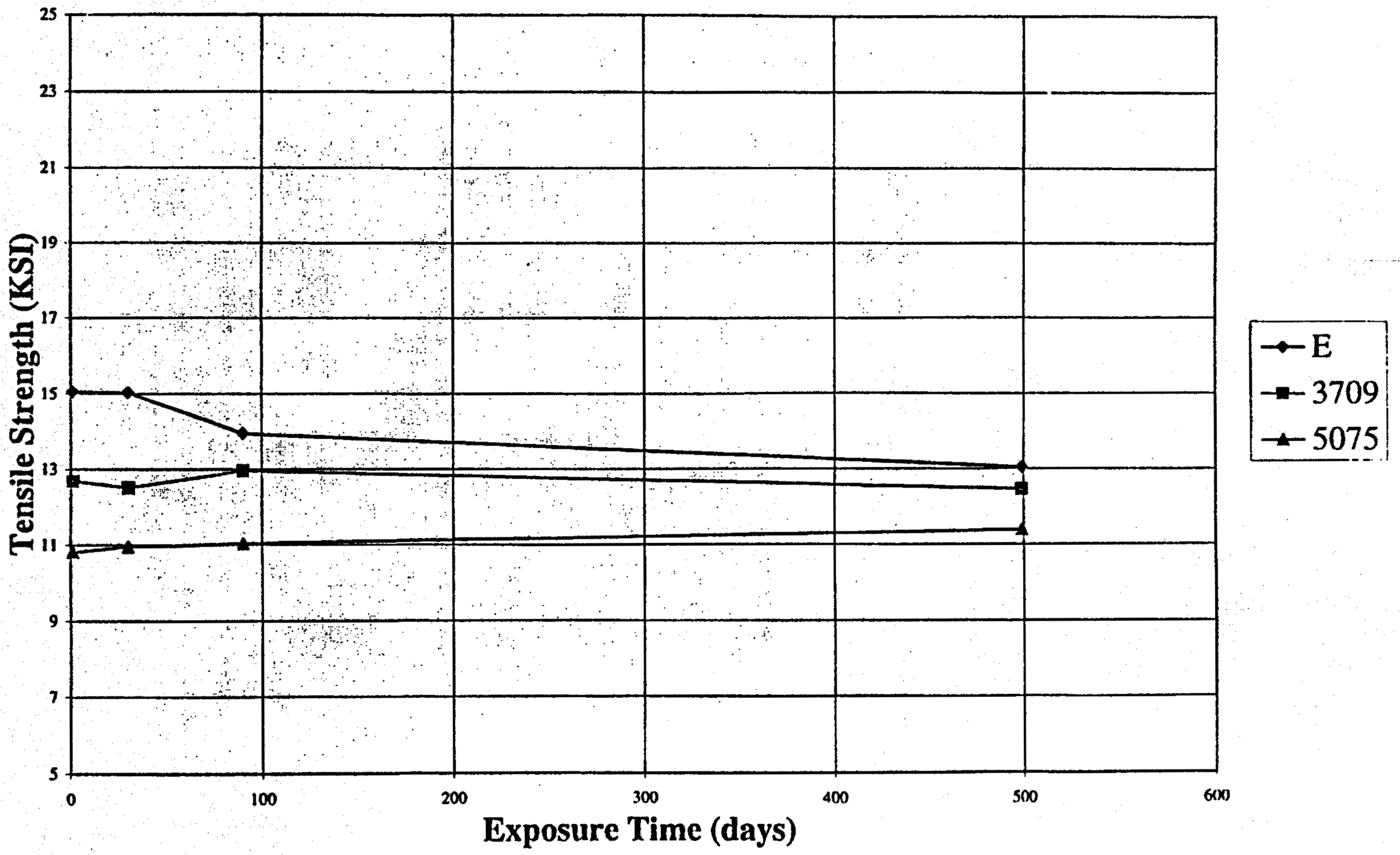
Mat Flexural Strength Retention



Normalized to 33 Weight % Glass

Prepared by Rick Matzeg 26/11/96

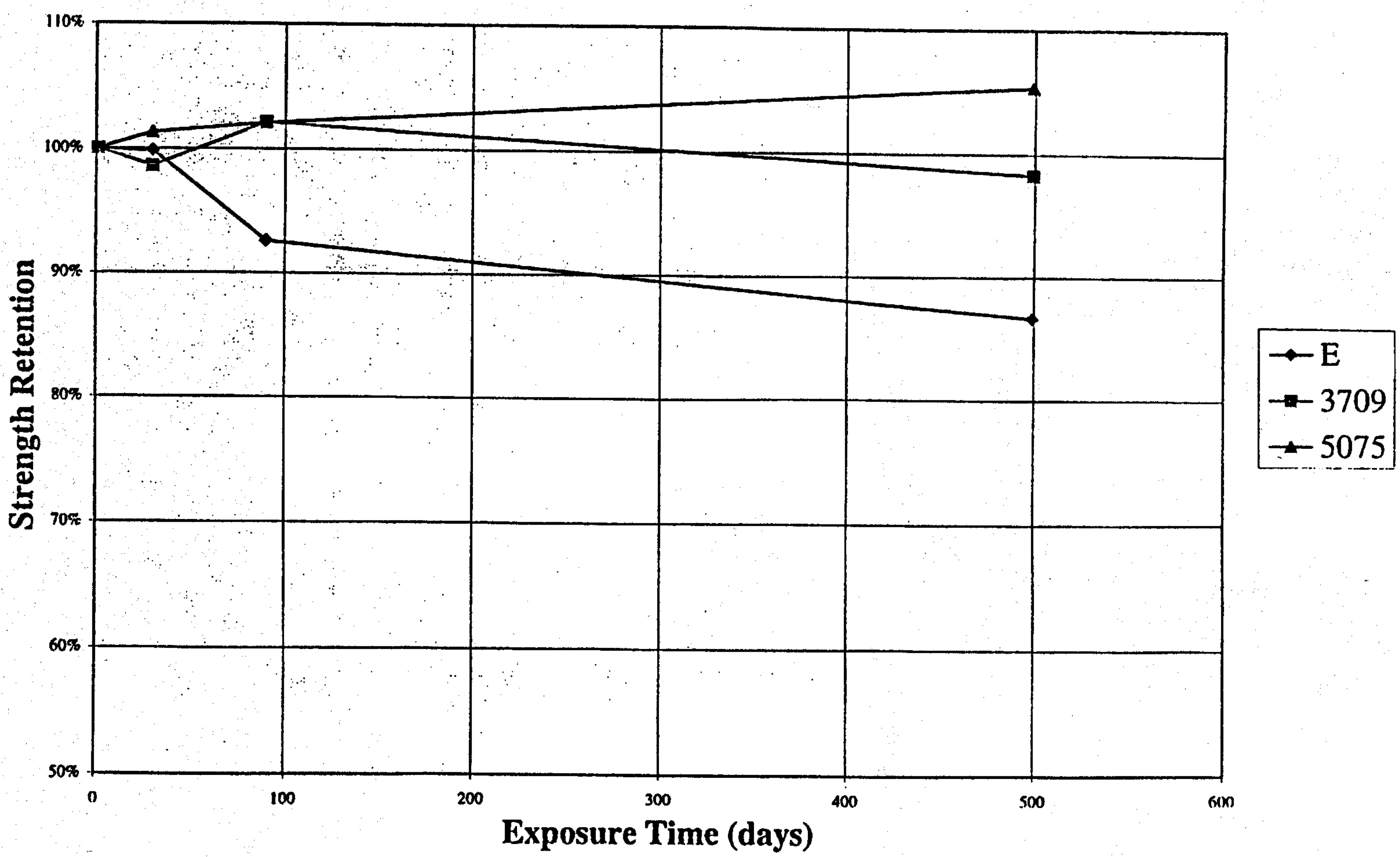
Mat Tensile Strength



Normalized to 33 Weight % Glass

Prepared by Rick Matzeg 26/11/96

Mat Tensile Strength Retention



Normalized to 33 Weight % Glass

Prepared by Rick Matzeg 26/11/96