TP 14356E

High Temperature Stress-Rupture Tests of Sample Tank-Car Steels

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by

Department of Mechanical and Materials Engineering
Queen’s University
Kingston, Ontario

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by

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December 2004

Since some of the accepted measures in the industry are imperial metric measures are not always used in this report.

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16. Abstract

This report contains tension and stress-rupture test data on various railway tank-car steels at room temperature and temperatures between 500ºC and 720ºC. It also describes the test facility, applicable standards, and procedures that were followed during the tests.

The stress-rupture testing was conducted at constant load (tensile force) conditions. A sample was heated to a specified temperature and the load was applied. The time to failure was then recorded. This testing was needed due to a general lack of available data for the high-temperature stress rupture of tank-car steels. This data is needed for the purposes of predicting tank failure when tank-cars are exposed to heating by fire. The steel samples were obtained from a recent train derailment and included both new and older steels. Samples were cut in both the hoop and longitudinal directions to see whether the steel was isotropic.

Excellent data was obtained with very little data scatter in each sample. Results show that stress-rupture properties vary from sample to sample. Some older steels were as good as new steels, some were not. However, all samples were isotropic when it came to high-temperature stress rupture.

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16. Résumé

Le rapport rend compte d'essais de traction et de rupture par fluage réalisés sur divers aciers pour wagons-citernes, à température ambiante et à haute température (de 500° C à 720° C). Il décrit en outre l'installation d'essai, les normes applicables, ainsi que le protocole d'essai.

Les essais de rupture par fluage ont été réalisés dans des conditions de charge (effort de traction) constante. On chauffait une éprouvette jusqu'à une température prescrite, puis on appliquait la charge. On notait alors le temps avant défaillance. Le but de ces essais était de combler le manque de données sur la rupture par fluage des aciers pour wagons-citernes portés à haute température. De telles données sont nécessaires pour prévoir la défaillance de la citerne dans le cas où des wagons-citernes sont exposés au feu. Les éprouvettes avaient été prélevées sur des citernes impliquées récemment dans un déraillement et elles étaient constituées autant d'aciers neufs que d'aciers âgés. Les prélèvements ont été effectués dans les deux axes, transversal et longitudinal, afin de vérifier si l'acier était isotrope.

Les données obtenues pour chaque éprouvette sont d'excellente qualité, avec une très faible dispersion. Les résultats révèlent que les caractéristiques de rupture par fluage varient d'une éprouvette à l'autre. Certains aciers âgés se sont montrés aussi performants que les nouveaux, mais pas tous. Cela étant, toutes les éprouvettes étaient isotropes au moment de la rupture par fluage à haute température.

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EXECUTIVE SUMMARY

This report contains tension and stress-rupture test data on various railway tank-car steels at room temperature and temperatures between 500ºC and 720ºC. It also describes the test facility, applicable standards, and procedures that were followed during the tests. The stress-rupture tests were part of an overall program to study thermal protection system defects in rail tank-cars.

Certain dangerous goods tank-cars must be thermally protected so they can survive accidental fire impingement. The requirement for thermal protection systems for pressure tank-cars is specified in CAN/CGSB-43.147-2002, section 15.8, which states:

> *If a thermal protection system is specified by this standard, the system must be capable of preventing the release of any dangerous goods from the tank car, except release through the pressure relief device, when subjected to the following conditions:*
>
> *(1) A pool fire for 100 min, and*
> *(2) A torch fire for 30 min.*

It is known from field surveys that some operating dangerous goods tank-cars have defective thermal protection systems. With the size of the North American fleet of tank-cars, it is not feasible to fix all of these defects immediately, for both cost and logistical reasons. For this reason, work has been under way to try to determine which level of defect is acceptable from a safety standpoint. This has involved both fire testing and computer modelling of defects in tank-car thermal protection systems.

Detailed stress-rupture data is needed to improve our ability to predict tank-car rupture when exposed to accidental fire impingement. Current models (such as AFFTAC) assume tank failure when the nominal hoop stress exceeds the tank wall material's ultimate tensile strength at the peak wall temperature. This method predicts tank failure times well when the fire is severe and widespread. However, when the fire heating is less intense (as in the case of thermal protection system defects), this method is not conservative. For modelling tank-cars in fires, detailed stress-rupture data is needed in the range of 500ºC to 720ºC wall temperature and 150 to 250 MPa nominal hoop stress. Failure times of less than 100 minutes are of most interest because these cover the time range for thermal protection systems (i.e., thermal protection systems must stop a tank from rupture for 100 minutes in an engulfing fire).

The stress-rupture testing was conducted using a tensile testing machine with a furnace mounted on it so the test sample could be maintained at a constant high temperature. The tests were conducted under constant load (tensile force) conditions. The sample was heated to a specified temperature and the load was applied. The time to failure was then recorded.

The steel samples were obtained from a recent train derailment and included both new and older steels. Samples were cut in both hoop and longitudinal directions to determine whether the steel was isotropic in terms of high-temperature stress rupture.

Excellent data was obtained with very little data scatter in each sample. The data covers the range of temperatures and pressures of most interest in this study. The results show that stress-rupture properties vary between steel samples. Some older steels were as good as new steels, and some were not. However, all samples appeared isotropic when it came to high temperature stress rupture.

The data has since been used in the tank thermal model for tank failure prediction, which is covered in a separate report (TP 14368E).

SOMMAIRE

Ce rapport rend compte d'essais de traction et de rupture par fluage réalisés sur divers aciers pour wagons-citernes, à température ambiante et à haute température (de 500º C à 720º C). Il décrit en outre l'installation d'essai, les normes applicables, ainsi que le protocole d'essai. Les essais de rupture par fluage ont été menés dans le cadre d'un vaste programme d'inventaire des défauts des systèmes de protection thermique des wagons-citernes.

Certains wagons-citernes utilisés pour le transport de marchandises dangereuses doivent être dotés d'une protection thermique pour pouvoir survivre en cas d'incendie. L'exigence de systèmes de protection thermique pour les wagons-citernes est énoncée au paragraphe 15.8 de la norme CAN/CGSB-43.147-2002, qui se lit comme suit :

> *Si un système de protection thermique est exigé par la présente norme, il doit être capable d'empêcher tout rejet des marchandises dangereuses hors du wagon-citerne, à l'exception de tout rejet par le dispositif de décharge de pression, lorsque soumis à :*
>
> *(1) un feu en nappe pendant 100 min; et*
> *(2) une flamme de chalumeau pendant 30 min.*

Des études sur le terrain ont révélé des défectuosités du système de protection thermique de certains wagons-citernes en exploitation. Étant donné la taille du parc nord-américain de wagons-citernes, il n'est pas possible de réparer tous ces défauts immédiatement, autant pour des raisons financières que logistiques. C'est pourquoi des travaux ont été entrepris pour déterminer jusqu'à quel point une défectuosité est acceptable du point de vue de la sécurité. Deux démarches ont été utilisées, soit des essais au feu et une modélisation informatique de défectuosités dans des systèmes de protection thermique de wagon-citerne.

Des données détaillées sur la rupture par fluage d'un wagon-citerne sont nécessaires pour mieux prévoir le moment de rupture de la citerne dans le cas où elle serait exposée accidentellement au feu. Les modèles actuels (l'AFFTAC, par exemple) posent comme hypothèse une défaillance de la citerne lorsque la contrainte périphérique nominale dépasse la résistance à la traction de la paroi de la citerne, à la température de pointe de la paroi. Cette méthode permet de prédire avec justesse le temps avant défaillance dans les cas d'incendie de grande envergure. Mais lorsque la chaleur est moins intense (comme dans le cas d'une défectuosité du système de protection thermique), cette méthode pèche par manque de prudence. Pour modéliser des wagons-citernes exposés au feu, il faut disposer de données détaillées sur la rupture par fluage de la citerne alors que ses parois atteignent des températures de 500º C à 720º C et qu'elle est soumise à une contrainte périphérique nominale de 150 à 250 MPa. Les temps avant défaillance inférieurs à 100 minutes sont ceux auxquels il faut s'attarder, car il s'agit du délai de sécurité offert par les systèmes de protection thermique (ces systèmes doivent empêcher la rupture d'une citerne soumise à un feu enveloppant pendant 100 minutes).

Les essais de rupture par fluage ont été menés à l'aide d'une machine d'essai de traction équipée d'un générateur de chaleur qui maintenait l'éprouvette à haute température. Les essais ont été réalisés dans des conditions de charge (effort de traction) constante. On chauffait une éprouvette jusqu'à une température prescrite, puis on appliquait la charge. On notait alors le temps avant défaillance.

Les éprouvettes avaient été prélevées sur des citernes impliquées récemment dans un déraillement et elles étaient constituées autant d'aciers neufs que d'aciers âgés. Les prélèvements ont été effectués dans les deux axes, transversal et longitudinal, afin de vérifier si l'acier était isotrope au moment de la rupture par fluage à haute température.

Les données obtenues pour chaque éprouvette sont d'excellente qualité, avec une très faible dispersion. Elles correspondent à la gamme des températures et des pressions qui présentent le plus d'intérêt dans la présente étude. Les résultats révèlent que les caractéristiques de rupture par fluage varient d'un acier à l'autre. Certains aciers âgés se sont montrés aussi performants que les nouveaux, mais pas tous. Cela étant, toutes les éprouvettes étaient isotropes au moment de la rupture par fluage à haute température.

Les données ont servi à l'élaboration du modèle thermique utilisé pour prédire la défaillance des citernes, lequel est l'objet d'un rapport distinct (TP 14368E).

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1. INTRODUCTION

This report contains tension and stress-rupture test data on various railroad tank car steels at room temperature and specific temperatures, respectively. It also describes the test facility, applicable standards, and procedures that were followed during the tests of tension and stress-rupture.

This work has been done as part of the overall study of defects in thermal protection systems of rail tank-cars for the Transportation Development Centre of Transport Canada. This stress-rupture data is needed for the purposes of modeling tank failure in fires when the tanks have defects in their thermal protection systems.

1.1 Background

These stress-rupture tests are part of an overall program to study thermal protection system defects in rail tank-cars.

Certain dangerous goods tank-cars must be thermally protected so they can survive accidental fire impingement. The requirement for thermal protection systems for pressure tank-cars is specified in CAN/CGSB-43.147-2002, section 15.8, which states:

If a thermal protection system is specified by this standard, the system must be capable of preventing the release of any dangerous goods from the tank car, except release through the pressure relief device, when subjected to the following conditions:

> *(1) A pool fire for 100 min, and*
> *(2) A torch fire for 30 min.*

It is known from field surveys that some operating dangerous goods tank-cars have defective thermal protection systems. With the size of the North American fleet of tank-cars, it is not feasible to fix all of these defects immediately, due to both cost and logistical reasons. This research program was intended to help identify which tanks need immediate attention.

Several published reports have been prepared by A.M.Birk and his team in connection with this issue [1-5].

The work has led us to the point where a computer model has been developed to predict critical thermal protection defect sizes on tank-cars. This thermal model requires some additional data and final validation before it can be used to assess defects in the field.

The following data is needed to further support the theoretical work.

i. Obtain high temperature stress-rupture data (by test) of tank steels, including both old steels and new (to cover the true condition of the tank-car fleet).

ii. Conduct a CFD (computational fluid dynamics) study to obtain predictions for the pressurization of tanks with fire heating of localized thermal protection defects.
iii. Obtain medium-scale fire test data of tanks with defective thermal protection for final validation of failure times.

This report presents the results of the stress-rupture testing. Reports on the CFD work and the fire testing of medium-scale propane tanks with thermal protection defects will be published separately.

1.2 Objectives and Scope

The objective of this work was to obtain detailed stress-rupture data for the steel samples collected. This data should be in the range of direct interest to modeling thermally protected tanks in fires. This means the test data should apply over steel sample temperatures from about 550°C to 720°C and for stress levels from about 100 to 300 MPa. Tables 1.1 and 1.2 provide conversions for temperature and stress to ^{o}F and ksi, respectively.

The scope of this work was limited to testing only.

1.3 Summary

The samples used for tension and stress-rupture tests originated from four destroyed railroad tank-cars from the Melrose derailment in Ontario on February 21, 2003. Their reporting marks are TILX 302277, ACFX 18833, ACFX 17080, and ACFX 17026 and were constructed with TC128B steel in 2002, 1968, and 1964 and with A212B steel in 1964, respectively. The tank car steel was machined into a round specimen with a gauge diameter of 8 mm in the reduced gauge section.

For the tension and stress-rupture tests, an Instron model 8500 universal servo-hydraulic testing instrument was used with the dynamic capacity of 100 kN. This machine is located in the Department of Mechanical and Materials Engineering at Queen’s University in Kingston, Ontario. Series IX software was applied as the control software for the Instron machine.

The specimens were uniformly heated using a radiant type ceramic fiber heater that has the maximum operating temperature of 980°C. A temperature controller was used to maintain constant temperature of the sample during the test. Temperature variation along the length of the test sample was limited to under 3°C.

The samples were tested using ASTM standard E139. Yield and tensile strengths, elongation, and reduction of area were measured on tension tests at room temperature. Rupture times were recorded at various combinations of stress and temperature in the stress-rupture tests. The tests were conducted under constant loading of the specimens. The stress ranged from 60 MPa to 350 MPa and the temperatures ranged from 550°C to 720°C. The failure times varied from a few minutes to a maximum of about 100 minutes.

Table 1.1 Temperature conversion

Temperature in ^{o}C	Temperature in ^{o}F
450	842
500	932
550	1022
600	1112
650	1202
700	1292
750	1382
816	1500

Table 1.2 Stress conversion

Stress in MPa	Stress in ksi
100	14.5
125	18.1
150	21.8
175	25.4
200	29.0
225	32.6
250	36.3
300	43.5

2. TEST SPECIMENS

Several samples of steels were removed from the destroyed tank-cars of TILX30277, ACFX18833, ACFX17080, and ACFX17026. The samples were cut on a band saw in hoop and longitudinal directions. The samples were machined with a round cross section and with the dimensions shown in Figure 2.1 in accordance with ASTM standard E8M-98 for tensile and stress-rupture tests. The curved hoop samples were not straightened and the round test samples machined from these pieces were as large as possible so that flats did not appear.

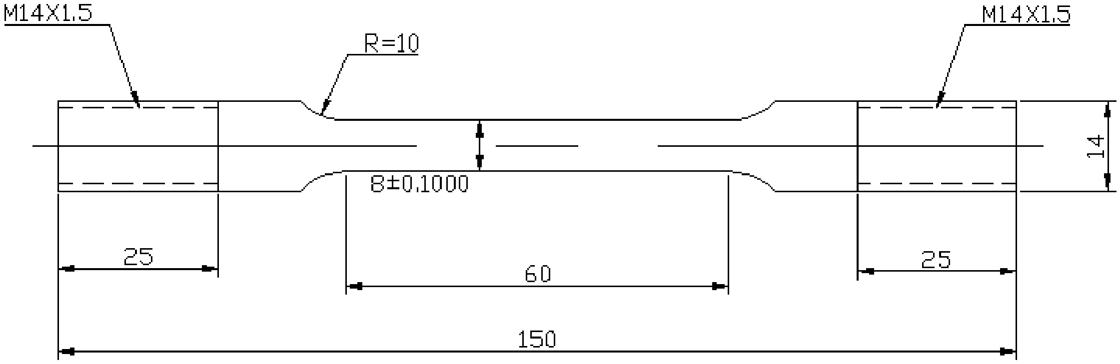

Figure 2.1 Dimensions (in millimetres) of round test specimen

2.1 Dimensions

The dimensions of the round test specimens are shown in Figure 2.1 and Table 2.1. The basic proportions are based on ASTM destination E8M-98.

Table 2.1 Dimensions of round test specimens

Diameter	Gauge length	Radius of fillet	Length of reduced section
8 mm	40 mm	10 mm	60 mm

On the round specimen, the gauge length for measurement of elongation is equal to five times the nominal diameter (40 mm). It is common practice to use a gauge length of 50 mm. We were not able to do this in our tests because the original steel samples were curved (from the tank-car plate) and, as a result, when the samples were machined the largest gauge length diameter possible was 8 mm. The gauge length should be five times this and hence we have a 40 mm gauge length. The specimens had threaded ends to fit the holders of the testing machine so that the forces could be applied axially.

For brittle materials, large radius fillets at the ends of the gauge length should be used. The radius of the fillet of 10 mm for our ductile specimens was large enough compared to the minimum specified radius of fillet of 8 mm for a standard 9 mm diameter specimen.

The length of the grip section of 25 mm was long enough to allow the specimen to extend well into the grips, and was longer than the specified minimum length of grip section of 10 mm specified for the standard 12.5 mm specimens. Particular attention was given to the uniformity and quality of the surface finish. This has been reported as a factor in the variability of test results for high strength and very low ductility materials.

Table 2.2 lists the source of the steel samples.

Table 2.2 Summary of samples

Tank Reporting Mark	TILX30277	ACFX18833	ACFX17080	ACFX17026
Year of Construction	2002	Oct 1968	Oct 1964	May 1964
Material (Steel)	TC128B	TC128B	TC128B	A212B

3. TEST FACILITY

The tests were done using an Instron model 8500 universal servo-hydraulic test instrument. The gripping devices were made from alloy A286. A ceramic fiber electric heater was used to achieve the maximum test temperature of 720°C. A pulse width modulated type digital temperature controller was used to maintain constant sample temperature during the test.

3.1 Servo-hydraulic Test Instrument

For the tension and stress-rupture tests, an Instron model 8500 universal servo-hydraulic testing instrument was used. It consists of a control console, load frames, actuators, and load cells. Combined with the instruments, the Series IX software was used for data acquisition and remote control of the tester.

The Instron model 8500 is a multiprocessor-based control console, which provides full digital control of the testing system. The Instron 3390 series actuator has a dynamic capacity of 100 kN and a static capacity of 200 kN. The actuator is capable of speeds ranging from 1 micron per hour ($6.5\text{x}10^{-7}$ in/min) up to 20 m/sec (50,000 in/min).

Figure 3.1 Stress-rupture test instruments

Figure 3.2 Gripping devices and furnace

An Instron 2518 series load cell was used and is designed specifically for fatigue testing applications. The load cell features an annular shear stressed element that provides axial load transfer, high resistance to side loads and bending moments, and high stiffness.

3.2 Gripping Devices

To hold and pull the specimen inside the furnace it was necessary to machine high-temperature gripping devices, consisting of upper and lower pull rods and couplers. The gripping devices were made of super alloy A-286, solution treated (982°C) and aged, with superior characteristics of high strength and good corrosion resistance at high temperature. This material is also easier to machine than Inconel. The couplers and pull rods were designed to have shoulder ends, which prevent the application of bending forces on the specimens. The dimensions of the couplers and pull rods are shown in Appendix A.

3.3 Furnace

The samples were heated during the testing by a custom-made furnace mounted on the Instron testing machine. The furnace was a radiant-type electric clamshell heater. The heater elements were vacuum-formed ceramic fiber blocks with embedded resistance heating coils (purchased from Omega Scientific). The heater's maximum operating temperature was 980°C and its power output was 1130 W at 120 VAC.

3.4 Temperature Controller

An Omega CN2100-R20 temperature controller was used to control the heating. The controller has a 20 A current rating using a mechanical relay. It has control modes of on/off and PI with sensor inputs of J, K thermocouples and RTD. For control purposes, each sample was instrumented with two K type thermocouples to measure the sample temperature and temperature uniformity.

4. ROOM TEMPERATURE TENSION TESTS

Twenty-three specimens from four different tank-cars underwent tension tests at room temperature to obtain the ultimate tensile strengths, yield strengths and elongations of the tank-car steels. Of the samples tested at room temperature, 13 specimens were from the tank-car hoop orientation, and 10 specimens were from the tank-car longitudinal orientation. During or after each test, any test process or its data that was not acceptable according to test standard ASTM E8M [6] was rejected.

4.1 Test Standard

Tension tests were conducted based on ASTM E8M-98 standard test methods for tension testing of metallic materials.

4.2 Test Procedure

Samples were prepared as follows:

1) The cross-section area of a test specimen was determined by measuring the diameter at the centre of the reduced section.
2) The gauge length on the test specimen was marked with a permanent marker to measure the elongation of the specimen after the test.

For the tension tests, the allowable limits for the rate of strain are between 0.05 and 0.5 m/m of the length of the reduced section per minute. During the current tension tests 0.1 m/m/min rate of strain was set.

The operation procedure of the Instron 8500 servo-hydraulic machine for tension and stress-rupture tests is detailed in Appendix C.

The following are reasons samples or tests would be rejected:

- sample surface was poorly machined,
- wrong dimensions,
- steel property changed because of poor machining,
- test was incorrect, or
- fracture was outside the gauge length.

4.3 Test Results

The results of the tension tests at room temperature show that all four tank steels met the tension strength, yield strength, and percent elongation requirements specified in the AAR Manual of Standards and Recommended Practices, Specifications for Tank Cars, M-1002, Appendix M, Paragraph 7.4 (former reference M128) [7].

4.3.1 Tensile Strength

According to the AAR specification for tank-cars, M-1002, issued in December 2000 [7], the tensile strength requirement for TC128 grade B is over 560 MPa. From ASTM A515/A515M-92 [8] and ASME boiler and pressure vessel code, section VIII rules for construction of pressure vessels, the minimum requirement of tensile strength for A515 grade 70 is 485 MPa. Figure 4.1 shows that the tensile strengths of all the test specimens passed the minimum requirements of the AAR, ASTM, and ASME specifications for tank-cars.

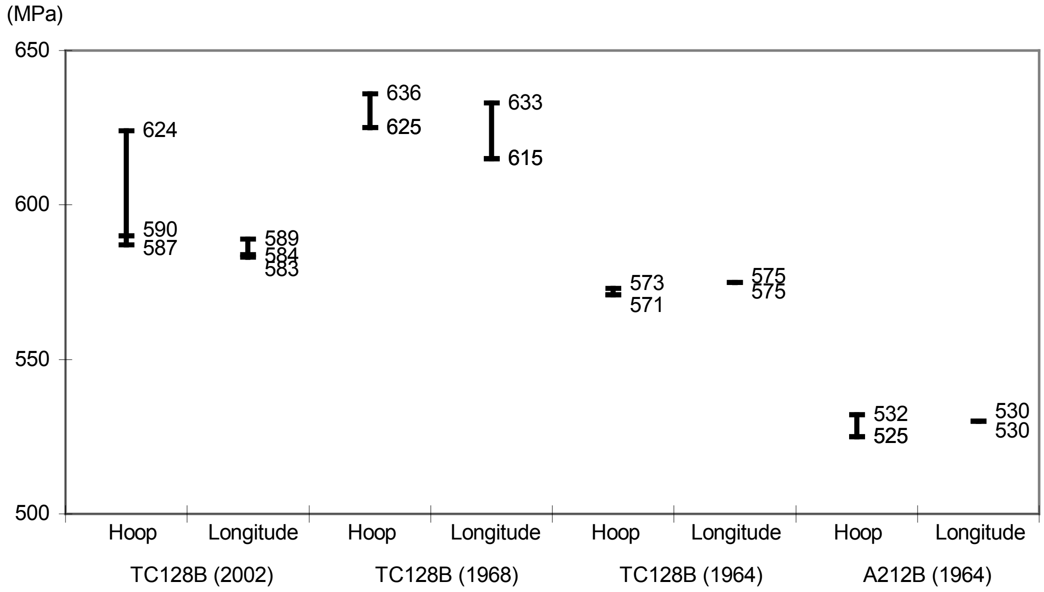

Figure 4.1 Tensile strengths at room temperature for various construction years of tank steels and their sample orientation

4.3.2 Yield Strength

The minimum yield strength requirement for TC128 grade B is 345 MPa, according to AAR specifications for tank-cars, and 260MPa for A515 grade 70 from ASTM A515/A515M-92 and ASME boiler and pressure vessel code, section VIII rules for construction of pressure vessels, respectively. We have determined yield strengths by an autographic diagram method that determines the upper and lower yield strengths. As shown in Figure 4.2, the upper and lower yield strengths for TC128B and A212B steels satisfy the minimum requirements.

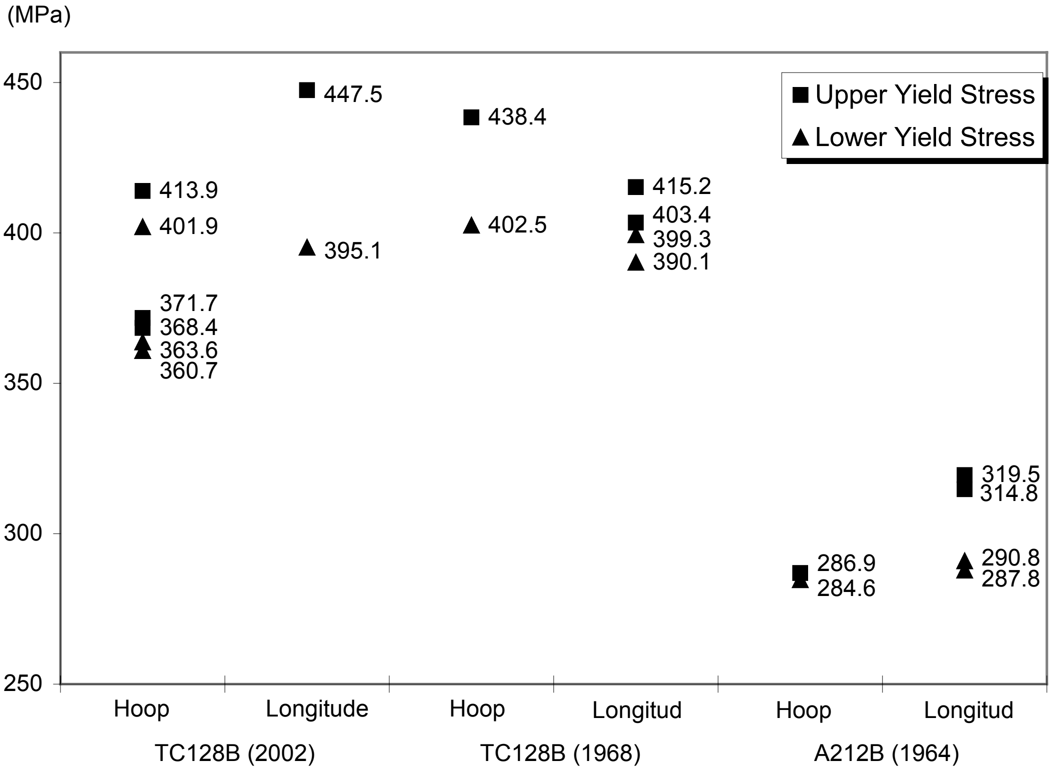

Figure 4.2 Upper and lower yield strengths at room temperature for various construction years of tank steels and their sample orientation

4.3.3 Elongation

All of the specimens had an original gauge length of 40 mm (i.e. 5 x 8 mm diameter). Figure 4.3 shows the percentage increases of the gauge length during the tension tests. The required elongation for 2 in. (51 mm) of welded metal (longitudinal) is at least 19% for TC128 grade B and 21% for A515 grade 70 according to AAR M-1002 and ASTM A515/A515M-92, respectively. The elongations of the tested specimens exceeded the minimum requirements in all cases.

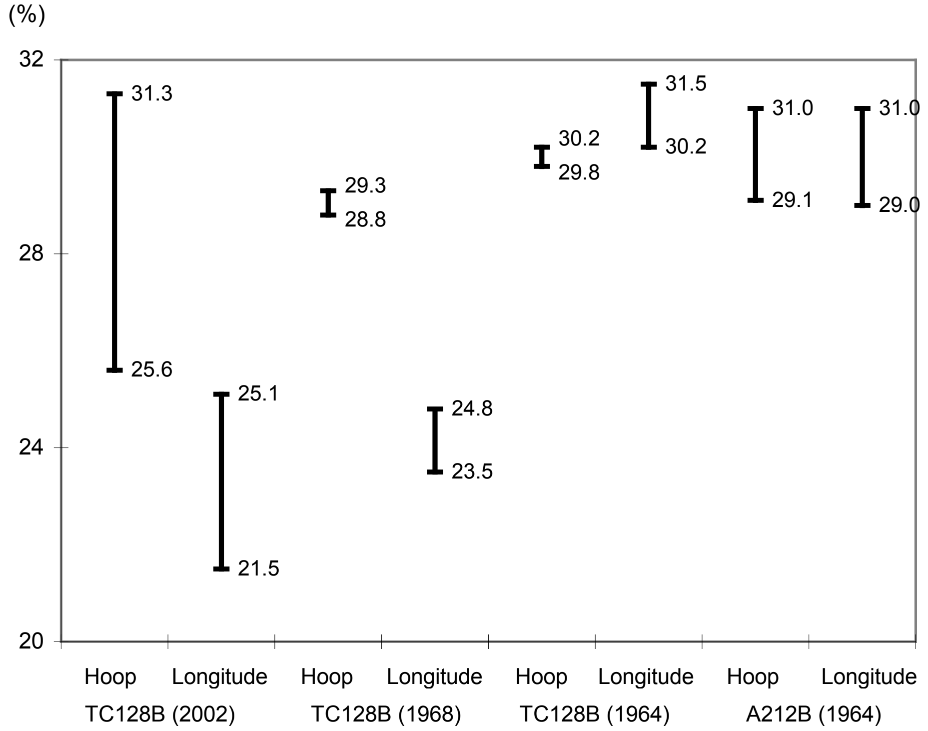

Figure 4.3 Elongations at room temperature for various construction years of tank steels and their sample orientation

5. STRESS-RUPTURE TESTS

Understanding the high temperature stress-rupture properties of tank-car steels at a specific stresses and temperatures is essential to understanding the rupture of tank-cars when subjected to fire environments. The objective of the stress-rupture tests was to determine the time to failure as a function of sample temperature and nominal stress under conditions of constant loading.

These tests involved taking tension test samples and heating them to high temperature in an electrical furnace. The samples were then loaded under conditions of constant tensile force until the samples failed in tension. It is the time to failure (rupture) that we are interested in. Note that the load force is constant. This means the actual sample stress increases with time as the sample stretches. This simulates the condition in a tank-car wall at constant pressure as the wall thins due to the stress and high temperature. The furnace was mounted on the tension test machine so that the samples could be loaded while they were held at constant high temperature.

Over 100 specimens of four different tank-car steels were tested for stress-rupture to obtain the relation of stress versus rupture time at a specific temperature. Among them, 80 specimens were from the tank-car hoop orientation, and 22 specimens were from the tank-car longitudinal orientation. Stress-rupture tests were conducted mainly at 550°C, 600°C, 620°C, 650°C, 680°C, and 720°C.

5.1 Test Standard

Stress-rupture tests were conducted based on ASTM E139-96 standard test methods for conducting creep, creep-rupture, and stress-rupture tests of metallic materials [9].

5.2 Test Procedure

The specimens were prepared as follows:

1) Satisfactory axial alignment was obtained with precisely machined threaded ends.
2) The cross-section area of a test specimen was determined by measuring the diameter at the position where the specimen was expected to break (at the midpoint of the reduced section).
3) The gauge length on the test specimen was marked with a permanent marker in order to attach thermocouples and measure temperature differences on the gauge length.
4) Anti-seize, high temperature lubricant was applied onto the specimen threads.
5) The required load was calculated based on the area of the minimum section and the desired nominal stress level.

Sample temperatures were monitored using two thermocouples attached to the gauge length. Thermocouple preparation included the following:

1) The thermocouple junction was kept in intimate contact with the specimen using a spring-like connection and shielded from radiation.
2) The thermocouple bead was as small as possible with no shorting of the circuit (such as could occur from twisting the thermocouple wires behind the bead or from a bare attachment wire touching both bare thermocouple wires).
3) Ceramic insulators were used on the thermocouples in the hot zone. The remaining portions of the wires were thermally shielded and electrically insulated with a ceramic or teflon covering.
4) Two thermocouples were located at the centre and upper limit (20 mm from the centre) of the gauge length. The thermocouple attached on the upper part of the specimen was controlled by the temperature controller.

In stress-rupture tests, the rate of loading was employed as the speed of testing. The load was applied in a manner to avoid shock loads or overloading due to inertia. The time applying the load was as short as possible within these limitations. We set 1% of a target load per second for the rate of loading.

The temperature rise of the furnace was carefully monitored as was the extension of the specimen due to the heating. The heating time depended on the target temperature and took between about 30 and 60 minutes. After reaching the target temperature, the holding time at the temperature prior to the start of the test was governed by the time necessary to ensure that the specimen had reached equilibrium and that the temperature could be maintained within the specified range. In our tests, about 20 minutes of holding time was applied.

The operation procedure of the Instron 8500 servo-hydraulic machine for tension and stress-rupture tests is detailed in Appendix C.

As in the tension tests, the following are reasons a test would be rejected:

- sample surface was poorly machined,
- wrong dimensions,
- property changed because of poor machining,
- test was incorrect, or
- the fracture was outside the gauge length.

5.3 Test Results

The nominal stress versus rupture time was plotted at several different temperatures. In this case the nominal stress means the load force divided by the original sample cross-sectional area in the gauge length. The relation of stress, rupture time, and temperature for specimens of a tank-car can be condensed into a single curve by the method of Larson and Miller [10]. A picture of the specimen before and after the rupture test is shown in Figure 5.1.

Figure 5.1 Sample before and after stress-rupture test

5.3.1 Stress vs. Rupture Time and Sample Temperature

The curves of nominal rupture stress versus rupture time at several sample temperatures are shown in Figures 5.2 through 5.5 for various steel types from the hoop direction, and in Figures 5.6 through 5.9 for those from the longitudinal direction.

The graphs should be interpreted as follows:

i. Select the line that applies to the sample temperature of interest.
ii. On the horizontal axis locate the rupture time of interest.
iii. Move vertically up from the time axis until you intersect the temperature line. At this point, move to the left horizontally to the stress axis to read off the nominal rupture stress.

For stress rupture, the steel that lasts the longest before failure, at a given stress and temperature, is the best. For a given sample temperature, we expect the rupture time to increase as we reduce the nominal stress. If we reduce the stress far enough it may take thousands of hours for failure. This failure is usually referred to as creep failure. Here we are interested in failures in times less than 100 minutes.

For the tests of specimens from the hoop orientation, the stress-rupture properties of TC128B (2002) are not as good as those of TC128B (1968), shown in Figure 5.3. However, Figures 5.4 and 5.5 show that the strengths of both TC128B (2002) and TC128B (1968) are clearly superior to those of TC128B (1964) and A212B (1964).

Comparing the rupture strengths of TC128B (2002) with other reported results [11, 12], the rupture strength values of TC128B (2002) are about 35% lower than those of TC128B (RAX 201) [11] and about 15% higher than those of TC128B (RAX 202) [12]. The stress-rupture tests of TC128B (RAX 201) were performed at temperatures of 482°C, 566°C, and 649°C, and those of TC128B (RAX 202) at temperatures of 593°C, 621°C, 649°C, and 677°C.

In Figures 5.6 and 5.7, the rupture strengths of TC128B (2002) and TC128B (1968) do not show any dependence on the specimen direction to the tank axis. However, the specimens of TC128B (1964) and A212B (1964) reveal a small dependence on the direction, and show that the rupture strengths in the longitudinal direction are a little greater than those in the hoop direction.

1) Tests of samples from hoop direction

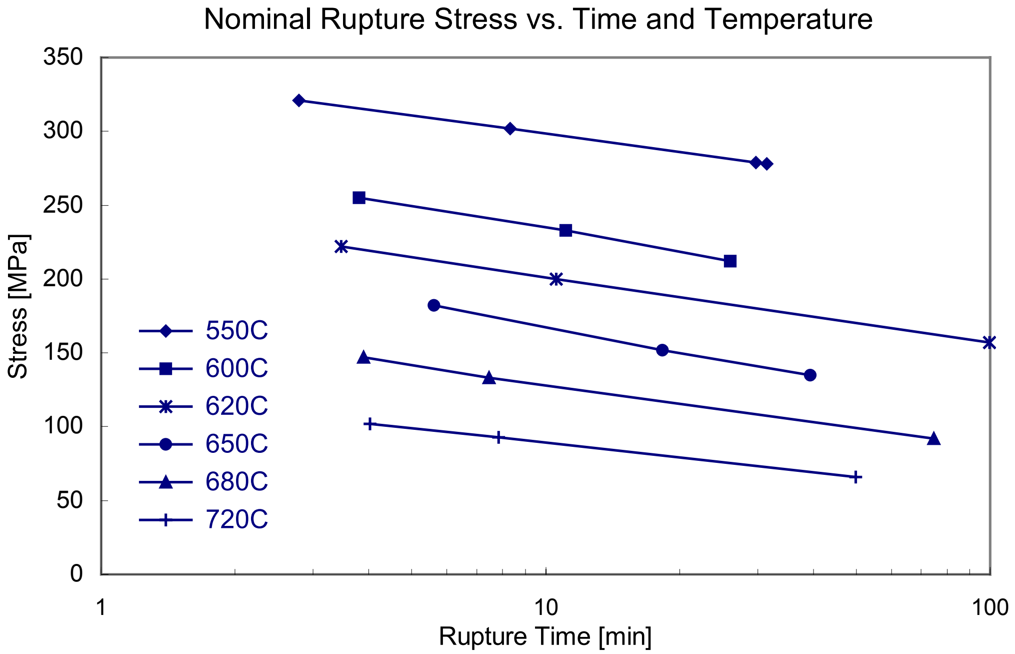

Figure 5.2 Stress versus rupture time at various heating temperatures for specimens of TC128B (2002) from hoop direction

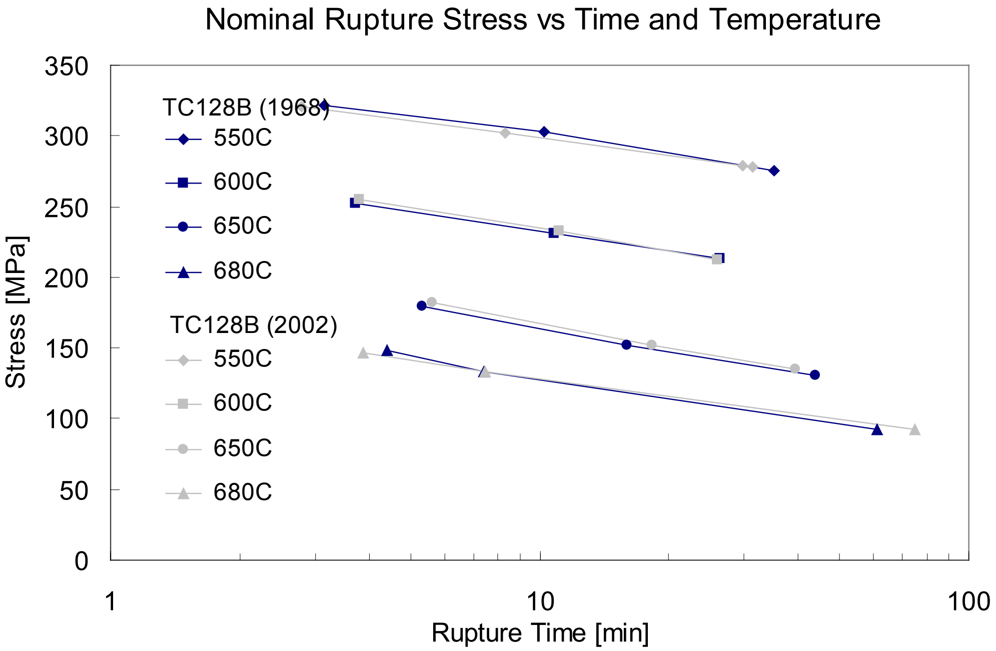

Figure 5.3 Stress versus rupture time at various heating temperatures for specimens of TC128B (1968 and 2002) from hoop direction

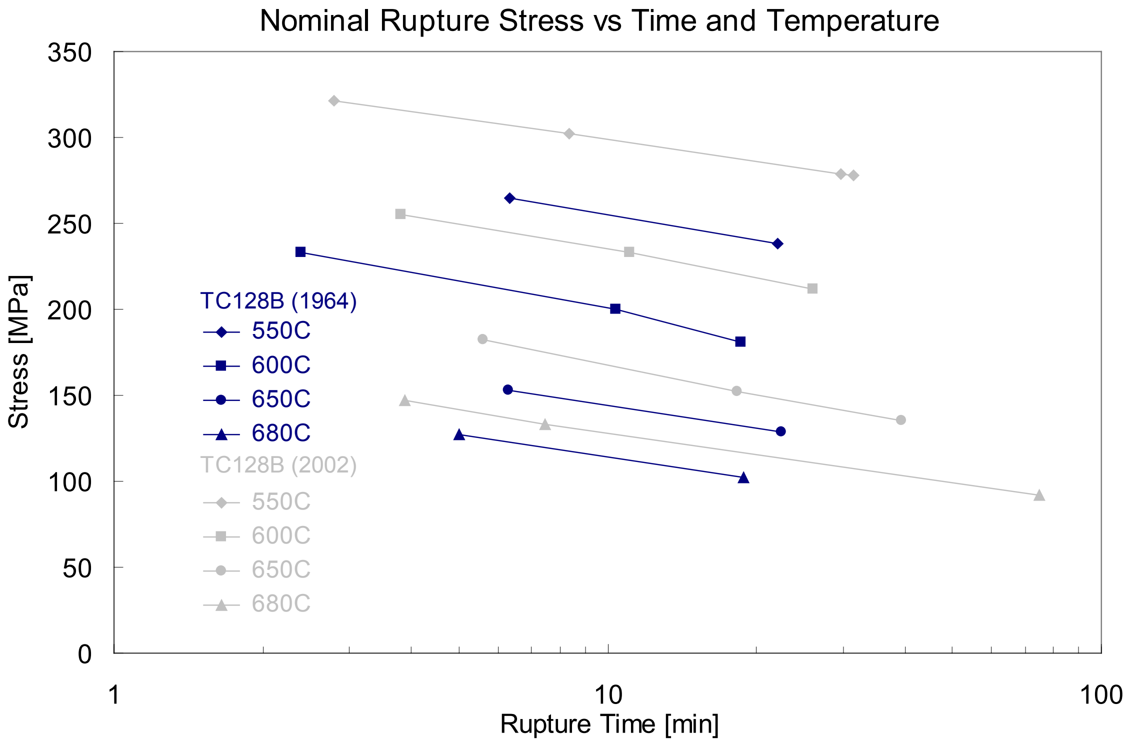

Figure 5.4 Stress versus rupture time at various heating temperatures for specimens of TC128B (1964 and 2002) from hoop direction

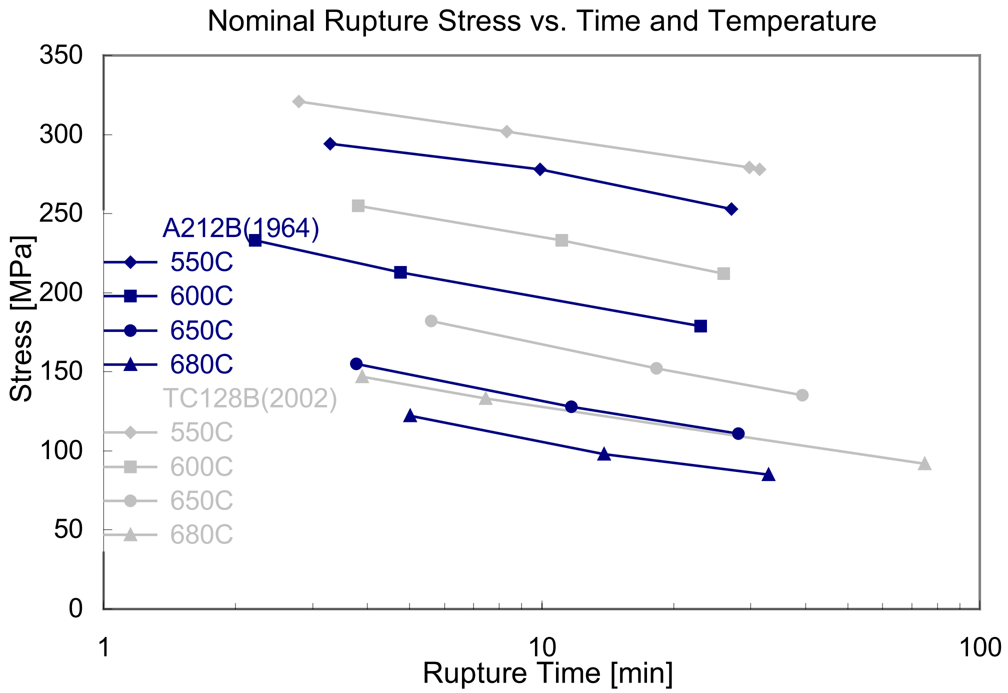

Figure 5.5 Stress versus rupture time at various heating temperatures for specimens of A212B (1964 and 2002) from hoop direction

2) Tests of Samples in Longitudinal Direction

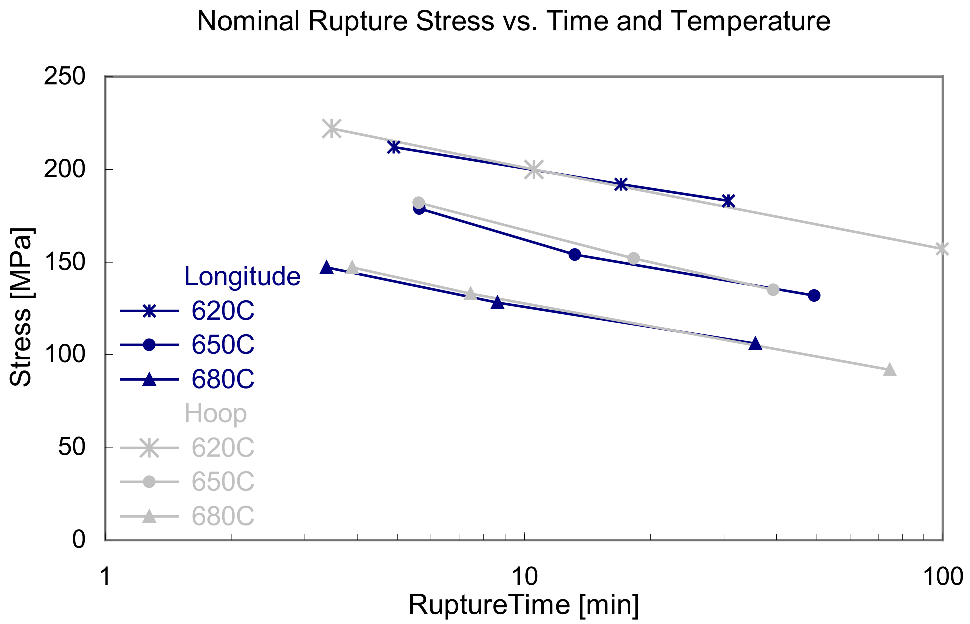

Figure 5.6 Stress versus rupture time at various heating temperatures for specimens of TC128B (2002) from hoop and longitudinal direction

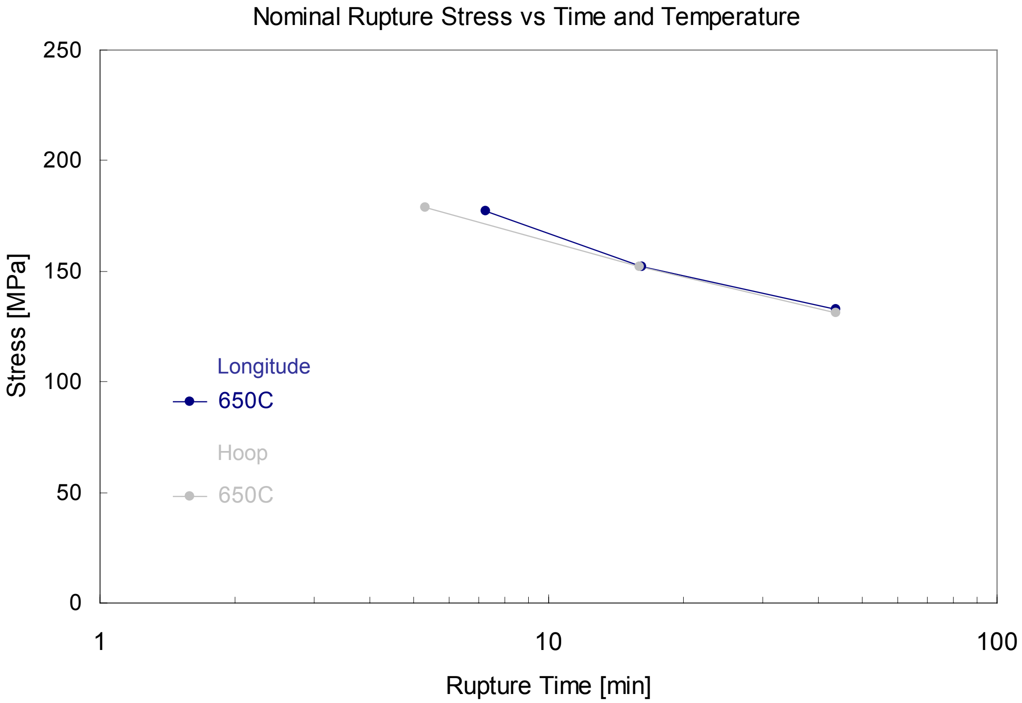

Figure 5.7 Stress versus rupture time at various heating temperatures for specimens of TC128B (1968) from hoop and longitudinal direction

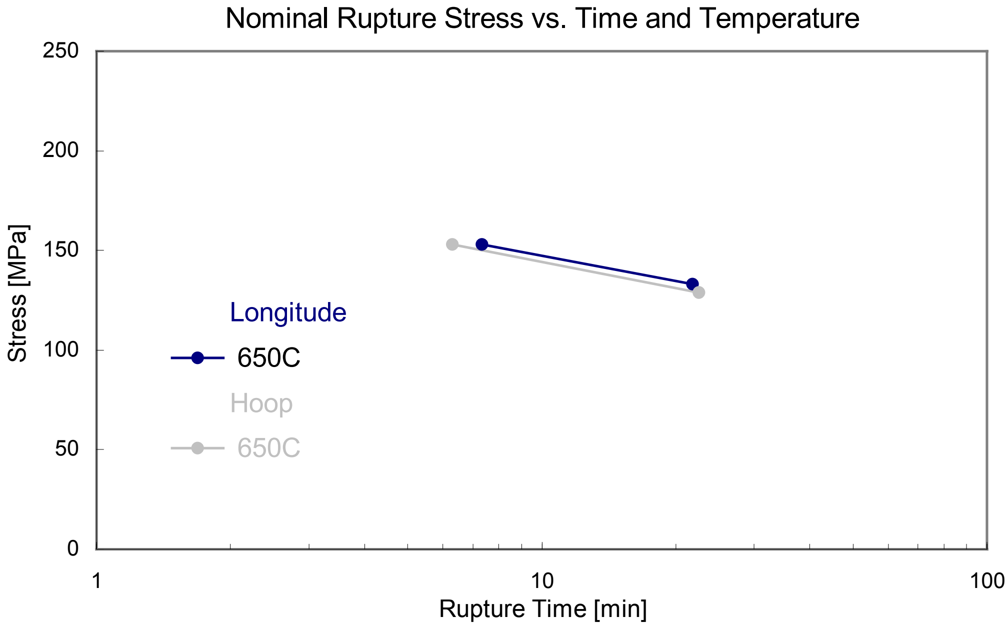

Figure 5.8 Stress versus rupture time at various heating temperatures for specimens of TC128B (1964) from hoop and longitudinal direction

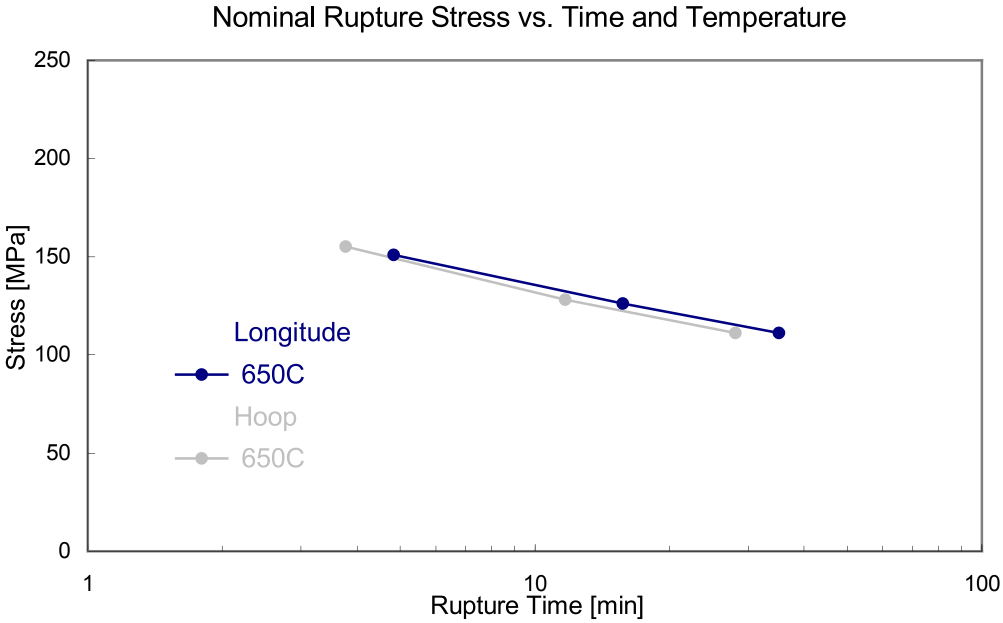

Figure 5.9 Stress versus rupture time at various heating temperatures for specimens of A212B (1964) from hoop and longitudinal direction

5.3.2 Stress vs. Larson-Miller Parameter

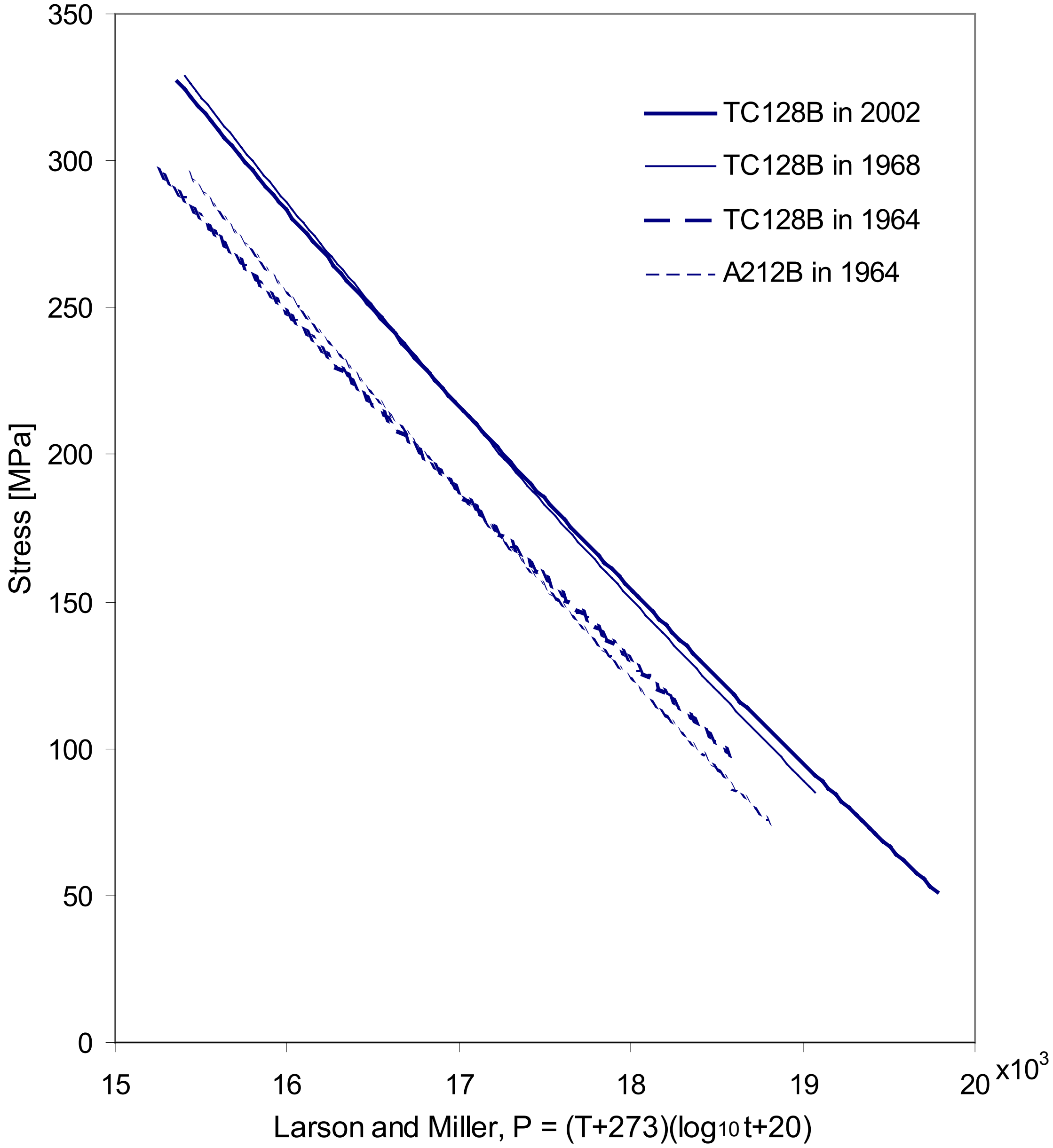

Figure 5.10 Stress versus Larson-Miller parameter for various railroad tank steels

The data plotted in the stress versus rupture time at specific temperatures in section 5.3.1 can be compressed into a single curve by plotting the strength as a function of the Larson-Miller parameter [11], $P=(T+273)(\log_{10} t+20)$, in which T is the test temperature in degrees Celsius, and t is the rupture time in hours. Each stress versus Larson-Miller parameter plot for the tank steels is depicted with its original data in Appendix E.

6. CONCLUSIONS

We have obtained by test, the mechanical properties of ultimate tensile and yield strengths and elongations of a selected number of tank-car steels. All of the test results satisfy AAR, ASTM, and ASME requirements.

The high temperature stress-rupture properties for the various tank-car steels were also obtained by test. The data is very consistent and shows very little scatter, suggesting the results are of high quality. The results show that the stress-rupture properties of TC128B (2002) are not greater than those of TC128B (1968), although these are both superior to the samples of TC128B (1964) and A212B (1964).

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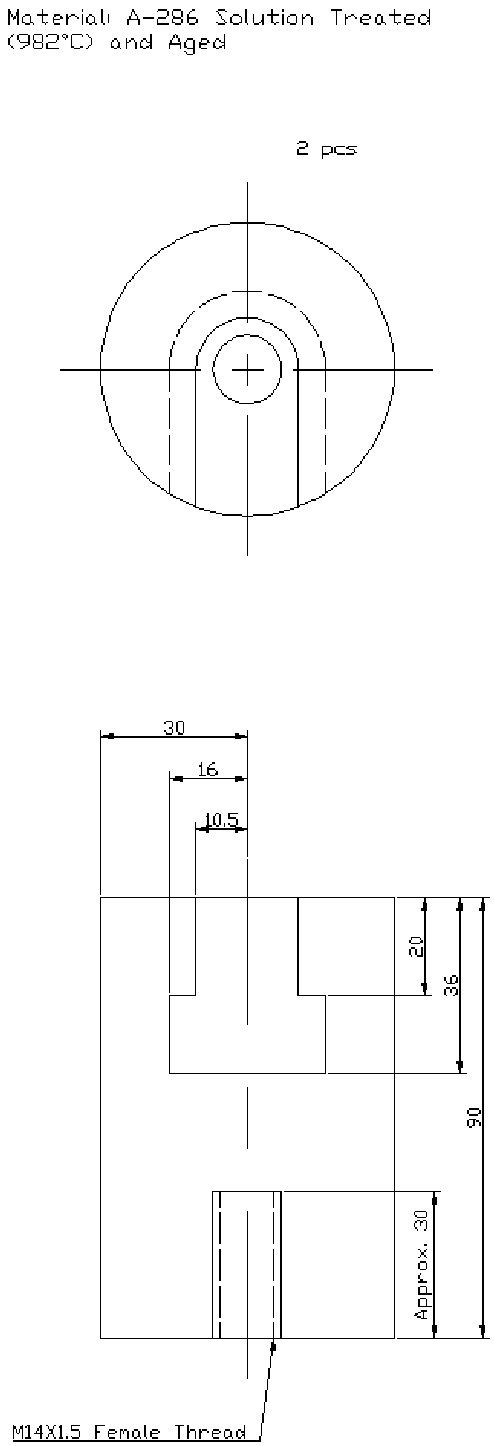
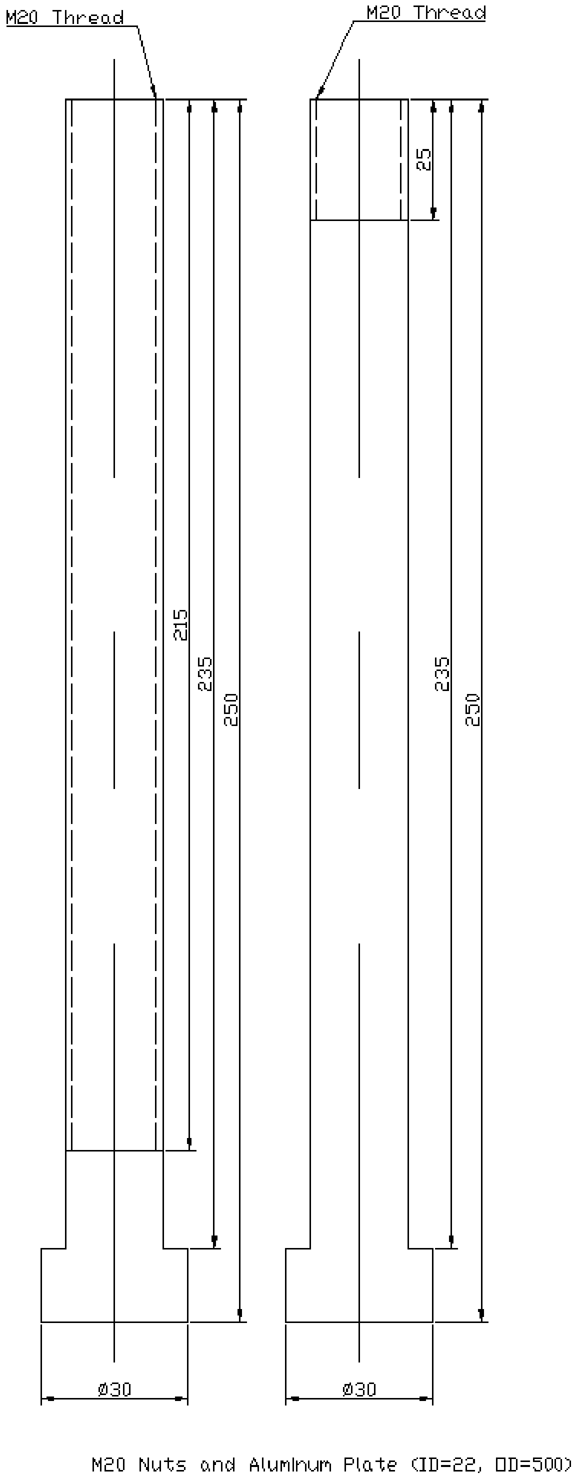
Appendix A. Gripping Devices





Appendix B. Instron 8500 Series Control Console Setup

B.1 Load Protect

- Load Protect only works in position control.
- It is not intended for dynamic control, but to protect the specimen during specimen loading.
- The minimum value that can be set for Load Protect is 0.2% of the full-scale rating for the load cell.

B.2 Event Detection

- XFR&HLD: Do not choose this menu for event detection of tension tests and tensile stress-rupture tests. This setup makes the actuator compress after breaking the specimen.
- SY.STOP: Hold the position of the actuator where the event detects. Need to turn on DAS (Series IX software) in order to hold the event time.
- UNLOAD: Same as XFR&HLD.
- HOLD: Going down the actuator after detecting the event.
- FINISH: Same as HOLD.
- RESET: Same as HOLD.

Appendix C. Instron 8500 Operation Procedure for Tension and Stress-Rupture Tests

1. Turn on the Main Electrical Power Switch on FIB.
   - Self check of each module in the system.
   - Wait until the following message on the lower display:

     INSTRON 8500
     Press any key to continue

   Control is in the position as a default.

2. Press the HYDRAULICS-ON button on the Hydraulic Control Panel.

3. Calibrate the Load Cell:
   - Press SETUP button of the Load channel.
   - Press CALibration → cal → AUTO and GO

   Wait until calibration light lit.

4. Move the load frame in order to make a space for placing the grips, and specimen:
   1) Open the CLAMP slightly and listen for a "hiss" sound.
   2) Turn either the RAISE or LOWER hand valves WITH CLAMP OPEN.
   3) After a suitable position is reached, tighten the RAISE/LOWER valve, then the CLAMP valve.

5. Place the *upper grip* (pulling rods, coupling) and specimen into the Instron machine.
   - Do not place the specimen into the lower grip (pulling rod, coupling).

6. Balance the load created by the upper grip and specimen:
   - Press SETUP button of the Load channel.
   - Press CALibration → cal → BALANCE

   Now, the balanced load (almost zero load) is shown on the upper right screen.

7. Set up Load Protect for protecting the specimen during specimen loading.
   - Press the LOAD PROTECT button.
   - Press a key under the current Load Protect value. → Enter a value (-0.3kN for protecting a compression) & ENTER. → Press ON/OFF button to activate.

8. Move the actuator in order to be set so as to leave appropriate room for tension and grip the specimen.
   The good position of the actuator may be about 0mm of its range from +66mm to – 61mm.

1) Press the ACTUATOR-HIGH button.
2) Press the white buttons for moving the actuator and gripping the specimen so that the specimen is *just touching (you can get this condition when the load reaches the balanced load)* the fixture attached to the load cell.
   Actuator's position and the load are shown on the left and right side of the upper screen, respectively.

Tighten the fixture (Yellow collar) after all the adjustments are made.

9. Switch to Load control:
   - Press LOAD button of the Load channel.
   - Press IMMED.

It is now not possible to adjust the position of the actuator at load control. If an adjustment is needed*, switch the system back to position control (press POSITION button → IMMED)*

10. Set the LIMITS (MAX. and MIN.) of Load:
   - Press MAX of the load channel.
     For example, a screen shows the following:

MAX	75	action	digital	
limit	kN	SY.STOP	lines	ON/OFF

This means "The Maximum Limit of load is 75kN and SY.STOP occurs when the load is reached."

   - Press the key under 'kN' → Enter the max limit of load using the numeric keypad → Press 'ENTER' when it is finished.
   - Press the key under 'action' → Choose 'SY.STOP'.
   - Press ON/OFF button to activate MAX.

The LED of MAX is lit indicating it is in effect.

Set the MIN. limit of load the same as the MAX limit of load.
(the MIN limit of load = - value for preventing compression load on the specimen 'SY.STOP' for 'action')

11. Set the LIMITS (MAX. and MIN.) of Position with 'SY.STOP'

12. Set the WAVEFORM:
Press WAVEFORM button of Load for stress-rupture tests and of Position for tensile tests.

i) Constant Load for stress-rupture tests

LOAD			Enough Time Set
TRAPEZ	kN	kN/s	secs

- kN/s - Load smoothly and make the time for applying the load as short as possible without shock loads or overloading due to inertia.
  (The total loading time should not take more than 5 to 10% of the total time of rupture.)

Press the key under 'more' for 2nd ramp set up.
Set the 2nd ramp load and slope with the same as 1st ramp values.
Set the 2nd hold time of 0.

ii) Increasing Position for tension tests

Pos'n	shape	30	0.1 (or 0.2)
Ramps	S RAMP	mm	mm/s

13. Set and activate the 1st event detector:
    - Press the EVENT DETECTION button on the control panel.

Select event detector number				
1	2	3	4	5

- Press the key under 1.
- Set the 1st event detection as follows:

Event	type	action	digital	
Load	BREAK	SY.STOP	lines	ON/OFF

14. Ensure the Time/Counter is at TIME status.
    If not at TIME status, press Time/Counter → choose Time.

15. Check the setup carefully before the test takes place.
    Ensure the actuator is at ACTUATOR-HIGH status.

16. Start the test :
    The default control of channel is in Position.
    - Press 'LOAD' key of the Load channel (for only stress-rupture tests).
    - Press 'IMME' key (for only stress-rupture tests).
    - Press 'START' key on the control panel.

Test can be terminated any time by pressing FINISH button on the panel.

When one of the event detector is triggered, the system will respond to the mode preset.
(The rupture time would be the constant loading time only.
ASTM E139-96 Chapter5.6 Measure the elapsed time between complete application of the load and the time at which fracture of the specimen occurs.)

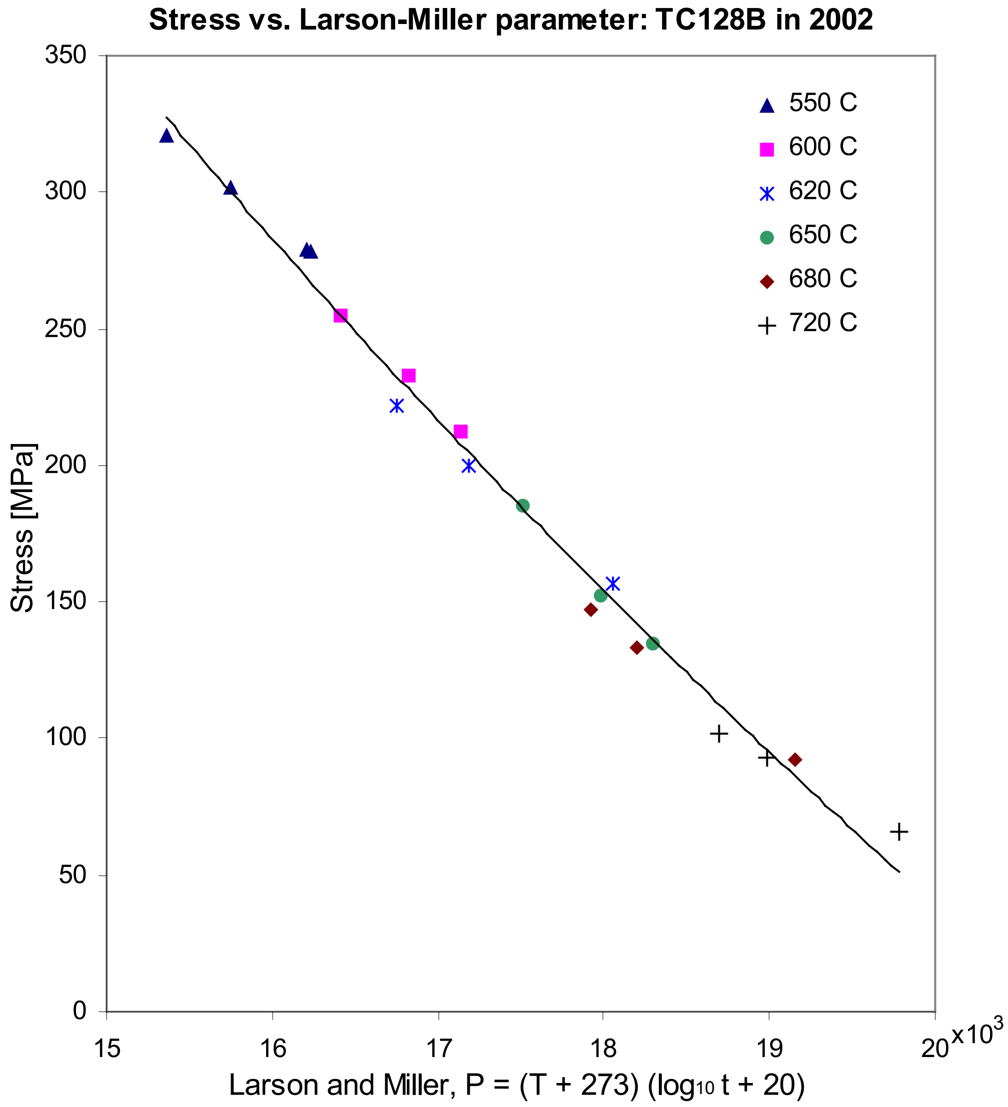
When the event detector or the limit is triggered, press 'FUNCTION' key and 'RESET' key under the Stop. This will make the operation normal.

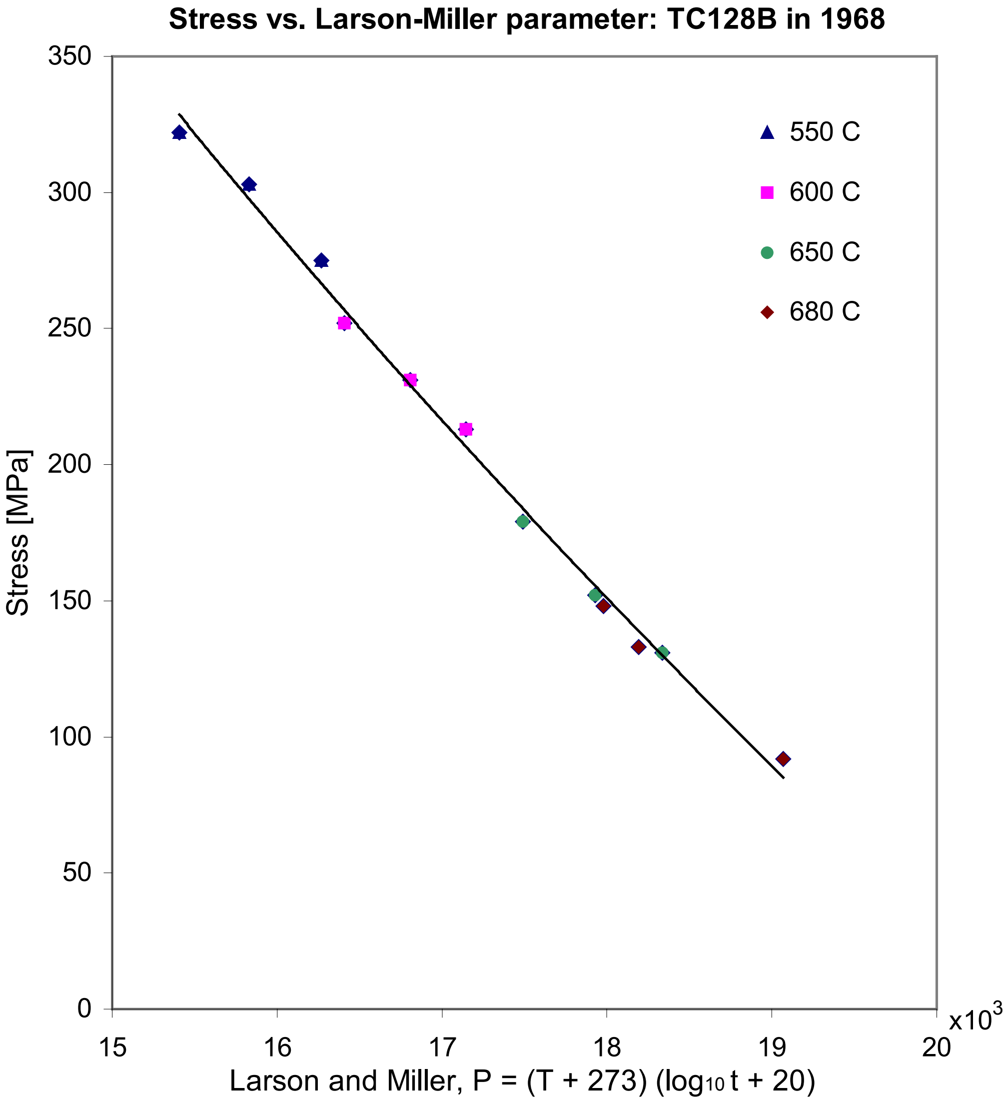
17. Switch to Position control:
    - Press POSITION button of the Position channel.
    - Press IMMED.

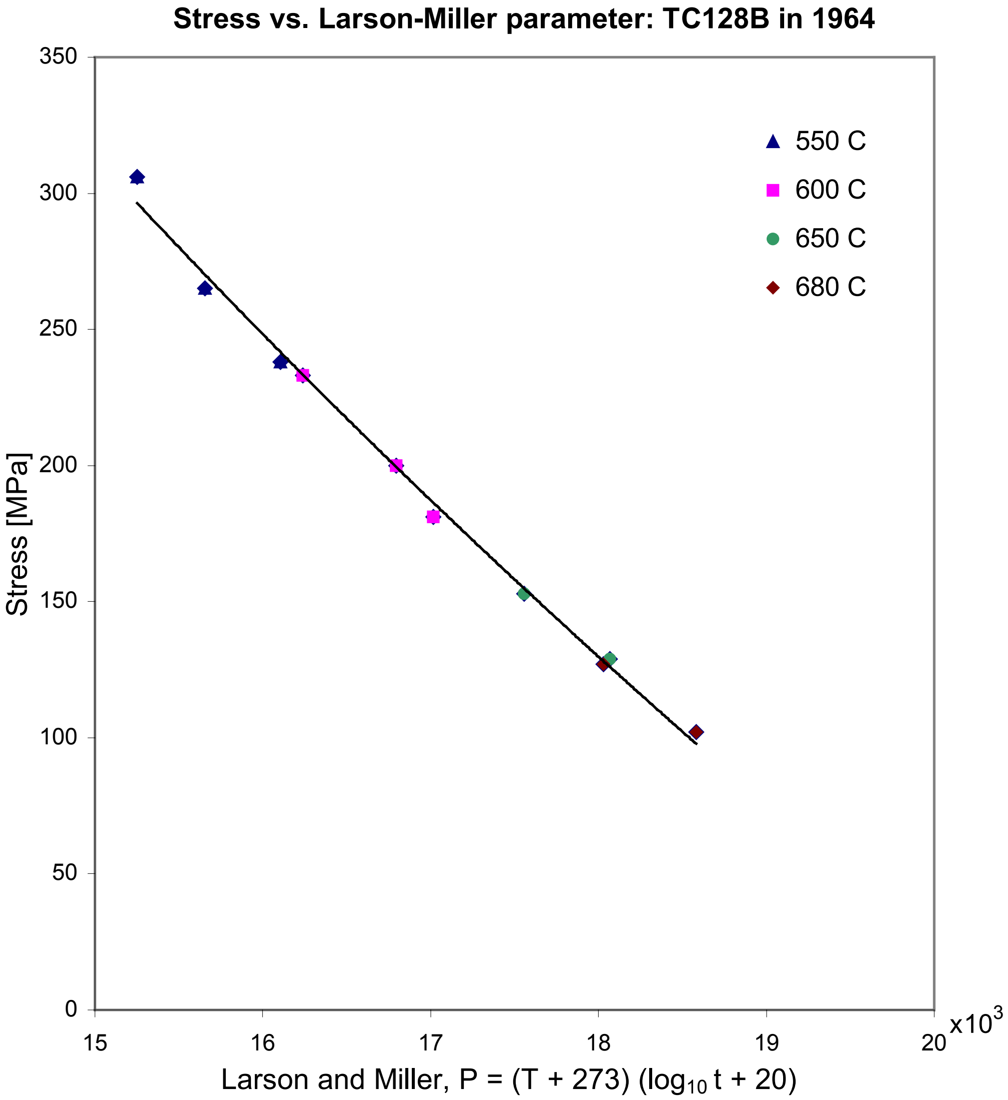
    The position of the actuator can be now adjusted.

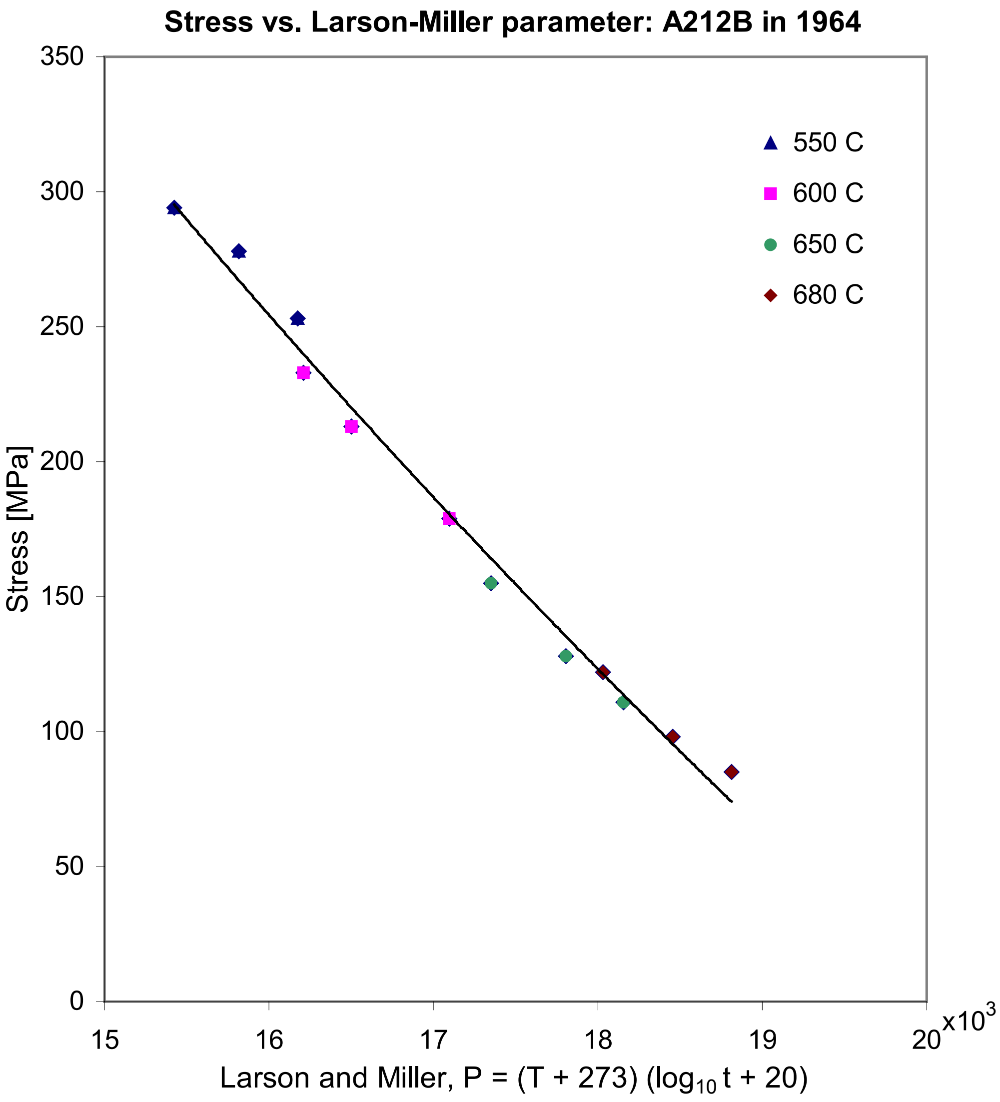
18. Turn the actuator off by pressing the ACTUATOR-OFF button.
    Shut the hydraulics off by pressing the HYDRAULICS-OFF button.
    Wait for a few minutes before turning off the Main Electrical Power Switch on FIB.

Appendix D. Stress vs. Larson-Miller Parameter




Stress vs. Larson-Miller parameter: TC128B in 1968
350
300
250
200
150
100
50
0
Stress [MPa]
▲ 550 C
■ 600 C
● 650 C
◆ 680 C
15
16
17
18
19
20
x10^3
Larson and Miller, P = (T + 273) (log10 t + 20)


Stress vs. Larson-Miller parameter: TC128B in 1964
Stress [MPa]
350
300
250
200
150
100
50
0
15
16
17
18
19
20
x10^3
Larson and Miller, P = (T + 273) (log$_{10}$ t + 20)
▲ 550 C
■ 600 C
● 650 C
◆ 680 C


Stress vs. Larson-Miller parameter: A212B in 1964
350
300
250
200
150
100
50
0
Stress [MPa]
15
16
17
18
19
20
x10^3
Larson and Miller, P = (T + 273) ($\log_{10}$ t + 20)
▲ 550 C
■ 600 C
● 650 C
◆ 680 C