Stress Corrosion Evaluation of Nitinol 60 for the International Space Station Water Recycling System

P.D. Torres
Marshall Space Flight Center, Huntsville, Alabama

November 2016
The NASA STI Program...in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and mission, often concerned with subjects having substantial public interest.

- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office’s diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results...even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to <help@sti.nasa.gov>
- Phone the NASA STI Help Desk at 757–864–9658
- Write to: NASA STI Information Desk Mail Stop 148 NASA Langley Research Center Hampton, VA 23681–2199, USA
Stress Corrosion Evaluation of Nitinol 60 for the International Space Station Water Recycling System

P.D. Torres
Marshall Space Flight Center, Huntsville, Alabama

November 2016
Acknowledgments

The author wishes to acknowledge the following supporters:

**Marshall Space Flight Center**

AS42 (Transportation & Logistics Engineering Office): A. Richardson  
EE04 (Flight Programs & Partnerships Chief Engineers Office): R. Mize and B. Mitchell  
EM01 (Materials and Processes Laboratory): S. Singhal and M. Prince  
EM02 (Resource Management Team): D. Mahieux, J. Smith, T. Bili, and C. Cunningham  
EM10 (Materials Test Branch): A. Girgis, L. Sharff, W. Tilson, and C. Harris  
EM30 (Metals Engineering Division): T. Vaughn and F. Lowery  
EM31 (Failure Analysis and Metallurgy Branch): B. Panda, G. Jerman, J. Hastings, and J. Honeycutt  
EM32 (Metal Joining & Processes Branch): C. Russell, R. Hickman, M. Thames, and R. Lee (ESSSA)  
EM60 (Materials Selection & Control and Small Projects Branch): L. Foreman  
ES62 (ECLSS Development Branch): D. Carter and D. Long  
FP10 (ISS Office): K. Presson and W. Spearman

**TRADEMARKS**

Trade names and trademarks are used in this report for identification only. This usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Available from:

NASA STI Information Desk  
Mail Stop 148  
NASA Langley Research Center  
Hampton, VA 23681–2199, USA  
757–864–9658

This report is also available in electronic form at  
<http://www.sti.nasa.gov>
# TABLE OF CONTENTS

1. INTRODUCTION ............................................................................................................. 1  

2. DEFINITION .................................................................................................................... 2  
   2.1 Stress Corrosion ............................................................................................................ 2  

3. EXPERIMENTAL PROCEDURE ...................................................................................... 3  
   3.1 Test Matrix .................................................................................................................. 3  
   3.2 Material ........................................................................................................................ 3  
   3.3 Specimen Configuration .............................................................................................. 4  
   3.4 Tensile Tests of Specimens As Received ...................................................................... 5  
   3.5 Stressing of the Specimens ....................................................................................... 7  
   3.6 Test Environments ....................................................................................................... 8  

4. RESULTS AND DISCUSSION .......................................................................................... 9  

5. CONCLUSIONS ................................................................................................................ 24  

REFERENCES ....................................................................................................................... 25
# LIST OF FIGURES

1. Nitinol 60 test material certification ................................................................. 4
2. Drawing of round tensile specimen ..................................................................... 5
3. Photograph of Nitinol 60 round tensile specimen ............................................... 5
4. Tensile tests curves for Nitinol 60 ...................................................................... 6
5. Device for stressing stress corrosion round tensile specimens ............................ 7
6. Schematic diagram of specimen and frame assembly ............................................. 7
7. Stress corrosion assembly .................................................................................. 7
8. Representative Nitinol 60 specimen being immersed .......................................... 8
9. Alternate immersion apparatus .......................................................................... 8
10. Nitinol 60 specimens after a year-long exposure to sulfuric acid-based pretreat ...... 10
11. Nitinol 60 specimens after a year-long exposure to sulfuric acid-based brine ........ 10
12. Nitinol 60 specimens after a year-long exposure to phosphoric acid-based pretreat ........................................................................................................ 11
13. Nitinol 60 specimens after a year-long exposure to phosphoric acid-based brine ..... 11
14. Nitinol 60 specimens after a year-long exposure to 3.5% NaCl alternate immersion per ASTM G44 .................................................................................. 12
15. Metallographic and overall views of Nitinol 60 stressed to 50 ksi after a year-long exposure to sulfuric acid-based pretreat ......................................................... 13
16. Metallographic and overall views of Nitinol 60 stressed to 50 ksi after a year-long exposure to sulfuric acid-based brine .......................................................... 14
17. Metallographic and overall views of Nitinol 60 stressed to 50 ksi after a year-long exposure to phosphoric acid-based pretreat ......................................................... 15
LIST OF FIGURES (Continued)

18. Metallographic and overall views of Nitinol 60 stressed to 50 ksi after a year-long exposure to phosphoric acid-based brine .......................................................... 16

19. Metallographic and overall views of a Nitinol 60 specimen after exposure to 3.5% NaCl alternate immersion (365 days at 25 ksi and 32 days at 75 ksi) .......... 17

20. Graphic showing variation of ultimate tensile strength for Nitinol 60 exposed to various environments ................................................................. 20

21. Stress corrosion specimens exposed to various environments and tensile tested .... 22

22. Stress-strain curves for stress corrosion specimens exposed to various environments ................................................................. 23
LIST OF TABLES

1. Stress corrosion test matrix for Nitinol 60 ................................................................. 3
2. Tensile data for Nitinol 60 .............................................................................................. 6
3. Stress corrosion test results of Nitinol 60 ........................................................................ 9
4. Extended SCC evaluation in 3.5% NaCl alternate immersion ........................................ 12
5. Tensile strength data for exposed Nitinol 60 specimens following exposure to various environments ........................................................................................................ 19
6. Summarized tensile strength data for exposed Nitinol 60 specimens following exposure to various environments ................................................................. 20
7. Modulus of elasticity, fracture elongation, and reduction of area for Nitinol 60 after exposure .................................................................................................................................. 21
LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

√ surface finish (arithmetic average roughness value)
AI alternate immersion
AI aluminum
ASTM American Society for Testing and Materials
CP commercially pure
ECLSS Environmental Control and Life Support System
ELI extra-low interstitial
HCl hydrochloric acid
HNO₃ nitric acid
ksi kilopounds per square inch
NaCl sodium chloride
Ni nickel
Nitinol Nickel Titanium Naval Ordinance Laboratory
PABB phosphoric acid-based brine
PABP phosphoric acid-based pretreat
pretreat pretreatment
SABB sulfuric acid-based brine
SABP sulfuric acid-based pretreat
SCC stress corrosion cracking
Ti titanium
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNC</td>
<td>Unified National Course</td>
</tr>
<tr>
<td>UTS</td>
<td>ultimate tensile strength</td>
</tr>
<tr>
<td>$UTS_f$</td>
<td>final ultimate tensile strength (after exposure)</td>
</tr>
<tr>
<td>$UTS_i$</td>
<td>initial ultimate tensile strength (average for nonexposed specimens)</td>
</tr>
</tbody>
</table>
TECHNICAL MEMORANDUM

STRESS CORROSION EVALUATION OF NITINOL 60 FOR THE INTERNATIONAL SPACE STATION WATER RECYCLING SYSTEM

1. INTRODUCTION

A stress corrosion cracking (SCC) evaluation of Nitinol 60 was performed because this alloy is considered a candidate bearing material for the Environmental Control and Life Support System (ECLSS), specifically in the Urine Processing Assembly of the International Space Station. An SCC evaluation that preceded this one during the 2013–2014 timeframe included various alloys: Inconel 625, Hastelloy® C-276, titanium (Ti) commercially pure (CP), Ti 6Al-4V, extra-low interstitial (ELI) Ti 6Al-4V, and Cronidur 30. In that evaluation, most specimens were exposed for a year. The results of that evaluation were published in NASA/TM—2015–218206, entitled “Stress Corrosion Evaluation of Various Metallic Materials for the International Space Station Water Recycling System,”¹ available at the NASA Scientific and Technical Information program web page: http://www.sti.nasa.gov. Nitinol 60 was added to the test program in 2014.
2. DEFINITION

2.1 Stress Corrosion

Stress corrosion may be defined as the combined action of sustained tensile stress and corrosion to cause premature failure of a susceptible material. Certain metallic materials are more susceptible than others. If a susceptible material is placed in service in a corrosive environment under tension of sufficient magnitude, and the duration of service is sufficient to permit the initiation and growth of cracks, failures can occur at a stress lower than the material would normally be expected to withstand.
3. EXPERIMENTAL PROCEDURE

3.1 Test Matrix

A stress corrosion test matrix showing the number of specimens and how they were allocated to various types of tests is presented in table 1. As seen in table 1, different types of ECLSS solutions were used in this evaluation. The 3.5% NaCl alternate immersion tests per ASTM G44\textsuperscript{2} are for comparison. Five specimens were used for tensile tests.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Stress Level (ksi)</th>
<th>Number of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete immersion in phosphoric acid-based pretreat</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td>Complete immersion in phosphoric acid-based brine</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td>Complete immersion in baseline sulfuric acid-based pretreat</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>Complete immersion in baseline sulfuric acid-based brine</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td>Alternate immersion in 3.5% NaCl per ASTM G44</td>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td>Tensile tests</td>
<td>N/A</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>40</td>
</tr>
</tbody>
</table>

3.2 Material

Nitinol 60 is an isostatically pressed (at 1,800 °F (982 °C)) bearing material containing approximately 60% nickel and approximately 40% titanium. This material is a shape memory alloy discovered in the late 1950s by the U.S. Naval Ordnance Laboratory. Because of difficulties in producing this material, it was abandoned; however, the composition and processing parameters were recently revived by Summit Materials, LLC under the trademarked name SM-100. Additional information on this alloy is presented in reference 3. MSFC-SPEC-3706\textsuperscript{4} establishes the chemical composition, heat treatment, hardness, and tensile requirements of this alloy.
For traceability purposes, the material certification—obtained from NASA Glenn Research Center—is shown in figure 1. Information included in figure 1 includes specific lot, chemical composition, and form of material.

![Material Certification](image)

Figure 1. Nitinol 60 test material certification.

Nitinol 60 is a high-strength, low-modulus material, and in this program, it was tested in the hard condition with a Rockwell C hardness of at least 58.

### 3.3 Specimen Configuration

The drawing for the stress corrosion sample is shown in figure 2. Forty specimens were fabricated per this drawing. A representative machined Nitinol 60 specimen is shown in figure 3.
Notes:
(1) Tolerances: ±0.005 in, except otherwise specified.
(2) Surface finish (arithmetic average roughness value): 16 μin for the reduced section.
(3) Thread dimensions must be as specified. Measurement by fabricator is mandatory.
(4) No undercutting of radii permitted.
(5) Gauge section to be concentric with axis within 0.002 in total indicator reading (gauge section of the tensile specimen cannot have more than 0.002 in total run-out) and parallel.
(6) No file marks or nicks permitted within gauge section.
(7) Drawing not to scale.

Figure 2. Drawing of round tensile specimen.

Figure 3. Photograph of Nitinol 60 round tensile specimen.

3.4 Tensile Tests of Specimens As Received

Five Nitinol 60 specimens were tensile tested per ASTM E8\textsuperscript{5} as received to obtain the mechanical properties and the results are presented in table 2. All the five specimens that were tensile tested failed before yielding, therefore, no yield strength values were obtained. The ultimate tensile strength (UTS) values are shown in increasing order in table 2. These values varied significantly, ranging from 146.1 ksi to 199.6 ksi, with an average value of 172.4 ksi. It is common for
high hardness materials like this to behave in this manner. Tensile tests curves (load versus displacement) are presented in figure 4. It can be observed from these curves the very low ductility of this material when heat treated as for bearings. The modulus of elasticity (Young’s modulus) was very consistent and the average value was 12.9 Msi.

Table 2. Tensile data for Nitinol 60.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Ultimate Tensile Strength (ksi)</th>
<th>Modulus of Elasticity (Msi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiTi60-10</td>
<td>146.1 (minimum value)</td>
<td>12.8</td>
</tr>
<tr>
<td>NiTi60-21</td>
<td>148.6</td>
<td>13.2</td>
</tr>
<tr>
<td>NiTi60-1</td>
<td>175.6 (median)</td>
<td>12.9</td>
</tr>
<tr>
<td>NiTi60-41</td>
<td>192.3</td>
<td>–</td>
</tr>
<tr>
<td>NiTi60-31</td>
<td>199.6 (maximum value)</td>
<td>12.7</td>
</tr>
<tr>
<td>Average Values</td>
<td>172.4</td>
<td>12.9</td>
</tr>
</tbody>
</table>

UTS standard deviation: 24.52
UTS coefficient of variation: 14.22%

Figure 4. Tensile tests curves for Nitinol 60.
3.5 Stressing of the Specimens

The strain corresponding to the desired stress levels was obtained by using the averaged modulus of elasticity of 12.9 Msi (strain equals stress divided by modulus of elasticity). The specimens were stressed per ASTM G496 by using the stressing device shown in figure 5.

The various components of the stressing fixtures are identified in the schematic diagram shown in figure 6.

![Figure 5. Device for stressing stress corrosion round tensile specimens.](image)

![Figure 6. Schematic diagram of specimen and frame assembly.](image)

Figure 5. Device for stressing stress corrosion round tensile specimens.

Figure 6. Schematic diagram of specimen and frame assembly.

In this method, the specimen is assembled into the stressing fixtures and an extensometer component is attached on the reduced section of the specimen. Two sidebars are then pushed toward the center by means of the device. The strain is measured by obtaining the difference between the initial and final readings. A representative assembly is shown in figure 7.

![Figure 7. Stress corrosion assembly.](image)

Figure 7. Stress corrosion assembly.
3.6 Test Environments

The majority of the specimens in this test program were exposed by total immersion in the four ECLSS solutions used: (1) Sulfuric acid-based pretreat, (2) sulfuric acid-based brine, (3) phosphoric acid-based pretreat, and (4) phosphoric acid-based brine.

These solutions also contain small amounts of chromic acid. The brine for each ECLSS solution was obtained by distillation of the pretreat, removing part of the water, and leaving a more concentrated solution. The pretreat and brine solutions had a pH of approximately 2. Exposure was carried out by completely immersing the specimens in the liquids, which were contained in plastic containers. The specimens were exposed for 1 year. A representative specimen being immersed is presented in figure 8.

![Figure 8. Representative Nitinol 60 specimen being immersed.](image)

Several samples were also tested in alternate immersion in 3.5% NaCl per ASTM G44 for comparison. Tests in alternate immersion are performed in a neutral pH. In the alternate immersion method the specimens are exposed to 1-hour cycles. Each cycle includes a 10-minute immersion period in a 3.5% NaCl solution followed by a 50-minute drying period. The cycles continued 24 hours per day for the duration of the test. The alternate immersion apparatus is presented in figure 9.

![Figure 9. Alternate immersion apparatus.](image)
4. RESULTS AND DISCUSSION

The stress corrosion results presented in table 3 show that no failures occurred in any environment after a year of exposure, which is a significant positive result. Appearance of the specimens after this year-long exposure can be observed in figures 10 through 14.

Table 3. Stress corrosion test results of Nitinol 60.

<table>
<thead>
<tr>
<th>Test Environment</th>
<th>Stress Level (ksi)</th>
<th>Failure Ratio</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfuric acid-based pretreat</td>
<td>15</td>
<td>0/2</td>
<td>No failures in a year-long exposure</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0/3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>0/3</td>
<td></td>
</tr>
<tr>
<td>Sulfuric acid-based brine</td>
<td>15</td>
<td>0/2</td>
<td>No failures in a year-long exposure</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0/3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>0/3</td>
<td></td>
</tr>
<tr>
<td>Phosphoric acid-based pretreat</td>
<td>15</td>
<td>0/2</td>
<td>No failures in a year-long exposure</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0/3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>0/3</td>
<td></td>
</tr>
<tr>
<td>Phosphoric acid-based brine</td>
<td>15</td>
<td>0/2</td>
<td>No failures in a year-long exposure</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0/3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>0/3</td>
<td></td>
</tr>
<tr>
<td>3.5% NaCl alternate immersion per ASTM G44</td>
<td>25</td>
<td>0/3</td>
<td>No failures in a year-long exposure</td>
</tr>
</tbody>
</table>

Notes:
- Forty specimens were received for this evaluation. Five of them were used for tensile data and the rest were used for the SCC evaluation as shown above.
- Failure ratio is the number of failures over number of specimens tested at the same condition.
Figure 10. Nitinol 60 specimens after a year-long exposure to sulfuric acid-based pretreat.

Figure 11. Nitinol 60 specimens after a year-long exposure to sulfuric acid-based brine.
Figure 12. Nitinol 60 specimens after a year-long exposure to phosphoric acid-based pretreat.

Figure 13. Nitinol 60 specimens after a year-long exposure to phosphoric acid-based brine.
The three specimens that were exposed for a year in alternate immersion were unloaded, then, one was reloaded to 75 ksi, one was reloaded to 100 ksi, and one was reloaded to 125 ksi. Afterwards all three samples were exposed for 32 additional days in alternate immersion. No failures occurred, as shown in table 4. Though this result is good, only one sample was tested at each stress level. More samples would be needed to better assess the stress corrosion resistance at these higher stress.

Table 4. Extended SCC evaluation in 3.5% NaCl alternate immersion.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Stress Level (ksi)</th>
<th>Failure Ratio</th>
<th>Days to Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>38</td>
<td>75</td>
<td>0/1</td>
<td>No failures after the</td>
</tr>
<tr>
<td>39</td>
<td>100</td>
<td>0/1</td>
<td>32 additional days</td>
</tr>
<tr>
<td>40</td>
<td>125</td>
<td>0/1</td>
<td></td>
</tr>
</tbody>
</table>

At the end of all the final exposures, the specimens were cleaned and unloaded. Representative specimens were subjected to metallography and the results are presented in figures 15 through 19. Metallography did not reveal corrosion or stress corrosion attack on any of the specimens.
Figure 15. Metallographic and overall views of Nitinol 60 stressed to 50 ksi after a year-long exposure to sulfuric acid-based pretreat.
Figure 16. Metallographic and overall views of Nitinol 60 stressed to 50 ksi after a year-long exposure to sulfuric acid-based brine.
Figure 17. Metallographic and overall views of Nitinol 60 stressed to 50 ksi after a year-long exposure to phosphoric acid-based pretreat.
Figure 18. Metallographic and overall views of Nitinol 60 stressed to 50 ksi after a year-long exposure to phosphoric acid-based brine.
Figure 19. Metallographic and overall views of a Nitinol 60 specimen after exposure to 3.5% NaCl alternate immersion (365 days at 25 ksi and 32 days at 75 ksi).
The remaining stress corrosion specimens were tensile tested to determine final ultimate tensile strength values. The results are presented in table 5 and plotted in figure 20. In addition to post-test ultimate tensile strength values, table 5 contains the ratio of each one of those values to the average tensile strength of nonexposed specimens (which was 172.4 ksi). The final ultimate tensile strength (UTSf) values ranged from 126.1 ksi (for a specimen exposed to sulfuric acid-based brine) to 184.7 ksi (for a specimen exposed to sulfuric acid-based pretreat). Summarized values for each environment, shown in increasing order of average final ultimate tensile strength, are presented in table 6. The lower the ratio of final to initial tensile strength, the more the corrosive effect of the environment. Therefore, based on the average ratios shown in table 6 obtained after 365 days for the ECLSS environments, they can be listed from most corrosive to least corrosive as follows (the average ultimate tensile strength ratio is shown in parenthesis): (1) Sulfuric acid-based brine (0.85 average ratio), (2) phosphoric acid-based brine (0.87 ratio), (3) sulfuric acid-based pretreat (0.92 ratio), and (4) phosphoric acid-based pretreat (0.98 ratio).
Table 5. Tensile strength data for exposed Nitinol 60 specimens following exposure to various environments.

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Test Environment</th>
<th>Stress Level (ksi)</th>
<th>UTSt (ksi)</th>
<th>UTSw/UTSt</th>
<th>Evaluation Performed</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>Sulfuric acid-based pretreat (365 days)</td>
<td>15</td>
<td>158.4</td>
<td>0.92</td>
<td>Tensile test</td>
<td>Broke at end of gauge length</td>
</tr>
<tr>
<td>19</td>
<td></td>
<td>15</td>
<td>–</td>
<td>–</td>
<td>Metallography</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Sulfuric acid-based brine (365 days)</td>
<td>25</td>
<td>127.1</td>
<td>0.74</td>
<td>Tensile test</td>
<td>Broke at end of gauge length</td>
</tr>
<tr>
<td>24</td>
<td></td>
<td>25</td>
<td>166.5</td>
<td>0.97</td>
<td>Tensile test</td>
<td>Broke at end of gauge length</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td>25</td>
<td>–</td>
<td>–</td>
<td>Metallography</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Phosphoric acid-based pretreat (365 days)</td>
<td>50</td>
<td>184.7</td>
<td>1.07</td>
<td>Tensile test</td>
<td>Broke in two places</td>
</tr>
<tr>
<td>27</td>
<td></td>
<td>50</td>
<td>153.2</td>
<td>0.89</td>
<td>Tensile test</td>
<td>Broke at end of gauge length</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>50</td>
<td>–</td>
<td>–</td>
<td>Metallography</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Sulfuric acid-based brine (365 days)</td>
<td>15</td>
<td>143.2</td>
<td>0.83</td>
<td>Tensile test</td>
<td>Broke at end of gauge length</td>
</tr>
<tr>
<td>28</td>
<td></td>
<td>15</td>
<td>–</td>
<td>–</td>
<td>Metallography</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td></td>
<td>25</td>
<td>150.1</td>
<td>0.87</td>
<td>Tensile test</td>
<td>Broke at end of gauge length</td>
</tr>
<tr>
<td>33</td>
<td></td>
<td>25</td>
<td>126.1</td>
<td>0.73</td>
<td>Tensile test</td>
<td>Broke at end of gauge length</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>25</td>
<td>–</td>
<td>–</td>
<td>Metallography</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td></td>
<td>50</td>
<td>152.0</td>
<td>0.88</td>
<td>Tensile test</td>
<td>Broke at end of gauge length</td>
</tr>
<tr>
<td>37</td>
<td></td>
<td>50</td>
<td>159.1</td>
<td>0.92</td>
<td>Tensile test</td>
<td>Broke in two places</td>
</tr>
<tr>
<td>34</td>
<td></td>
<td>50</td>
<td>–</td>
<td>–</td>
<td>Metallography</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Sulfuric acid-based brine (365 days)</td>
<td>15</td>
<td>148.4</td>
<td>0.86</td>
<td>Tensile test</td>
<td>Broke in two places</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>15</td>
<td>–</td>
<td>–</td>
<td>Metallography</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>25</td>
<td>158.0</td>
<td>0.92</td>
<td>Tensile test</td>
<td>Broke in two places</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>25</td>
<td>177.2</td>
<td>1.03</td>
<td>Tensile test</td>
<td>Broke at gauge length</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>25</td>
<td>–</td>
<td>–</td>
<td>Metallography</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>50</td>
<td>176.1</td>
<td>1.02</td>
<td>Tensile test</td>
<td>Broke at gauge length</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>50</td>
<td>181.1</td>
<td>1.05</td>
<td>Tensile test</td>
<td>Broke at end of gauge length</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>50</td>
<td>–</td>
<td>–</td>
<td>Metallography</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Phosphoric acid-based brine (365 days)</td>
<td>15</td>
<td>166.3</td>
<td>0.96</td>
<td>Tensile test</td>
<td>Broke at end of gauge length</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>15</td>
<td>–</td>
<td>–</td>
<td>Metallography</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>25</td>
<td>133.7</td>
<td>0.78</td>
<td>Tensile test</td>
<td>Broke at end of gauge length</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>25</td>
<td>130.8</td>
<td>0.76</td>
<td>Tensile test</td>
<td>Broke in two places</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>25</td>
<td>–</td>
<td>–</td>
<td>Metallography</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td></td>
<td>50</td>
<td>152.4</td>
<td>0.88</td>
<td>Tensile test</td>
<td>Broke at end of gauge length</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>50</td>
<td>168.9</td>
<td>0.98</td>
<td>Tensile test</td>
<td>Broke at end of gauge length</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>50</td>
<td>–</td>
<td>–</td>
<td>Metallography</td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>3.5% NaCl alternate immersion per ASTM G44 (397 days)</td>
<td>1 yr at 25 ksi + 32 days at 100 ksi</td>
<td>145.2</td>
<td>0.84</td>
<td>Tensile test</td>
<td>Broke at gauge length</td>
</tr>
<tr>
<td>40</td>
<td></td>
<td>1 yr at 25 ksi + 32 days at 125 ksi</td>
<td>150.0</td>
<td>0.87</td>
<td>Tensile test</td>
<td>Broke near end of gauge length</td>
</tr>
<tr>
<td>38</td>
<td></td>
<td>1 yr at 25 ksi + 32 days at 75 ksi</td>
<td>–</td>
<td>–</td>
<td>Metallography</td>
<td></td>
</tr>
<tr>
<td>Averages</td>
<td></td>
<td>147.6</td>
<td>0.86</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
• UTSt = Initial average ultimate tensile strength of nonexposed specimens = 172.4 ksi. Values range from 146.1 to 199.6 ksi.
• UTSw = Final ultimate tensile strength of exposed specimens.
Figure 20. Graphic showing variation of ultimate tensile strength for Nitinol 60 exposed to various environments.

Table 6. Summarized tensile strength data for exposed Nitinol 60 specimens following exposure to various environments.

<table>
<thead>
<tr>
<th>Test Environment</th>
<th>Average ( \text{UTS}_f ) (ksi)</th>
<th>Range of ( \text{UTS}_f ) (Maximum minus minimum in parentheses)</th>
<th>Median ( \text{UTS}_f ) (ksi)</th>
<th>Average ( \text{UTS}_f/\text{UTS}_i )</th>
<th>Median ( \text{UTS}_f/\text{UTS}_i )</th>
<th>Range of ( \text{UTS}_f/\text{UTS}_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfuric acid-based brine (365 days)</td>
<td>146.1</td>
<td>126.1–159.1 (33 ksi)</td>
<td>150.1</td>
<td>0.85</td>
<td>0.87</td>
<td>0.73–0.92</td>
</tr>
<tr>
<td>3.5% NaCl AI (397 days)</td>
<td>147.6</td>
<td>145.2–150 (4.8 ksi)</td>
<td>147.6</td>
<td>0.86</td>
<td>0.86</td>
<td>0.84–0.87</td>
</tr>
<tr>
<td>Phosphoric acid-based brine (365 days)</td>
<td>150.4</td>
<td>130.8–168.9 (38.1 ksi)</td>
<td>152.4</td>
<td>0.87</td>
<td>0.88</td>
<td>0.76–0.98</td>
</tr>
<tr>
<td>Sulfuric acid-based pretreat (365 days)</td>
<td>158</td>
<td>127.1–184.7 (57.6 ksi)</td>
<td>158.4</td>
<td>0.92</td>
<td>0.92</td>
<td>0.74–1.07</td>
</tr>
<tr>
<td>Phosphoric acid-based pretreat (365 days)</td>
<td>168.2</td>
<td>148.4–181.1 (32.7 ksi)</td>
<td>176.1</td>
<td>0.98</td>
<td>1.02</td>
<td>0.86–1.05</td>
</tr>
</tbody>
</table>

Notes:
- \( \text{UTS}_i = \) Initial average ultimate tensile strength of nonexposed specimens = 172.4 ksi. Values range from 146.1 to 199.6 ksi.
- \( \text{UTS}_f = \) Final ultimate tensile strength of exposed specimens.

The average ratio of final to initial tensile strength for the specimens exposed for 397 days in 3.5% NaCl alternate immersion was 0.86.
The ultimate tensile strength ratios shown provide an indication of the effect each environment had on Nitinol 60 in particular, and that effect may not necessarily be the same for other materials. Also, because of the scatter in the data, these values should be considered approximations. Though these results suggest some reduction in tensile properties took place, they are in contrast with the metallography results, which did not show any corrosion. Table 7 shows modulus of elasticity, fracture elongation, and reduction of area values after exposure. The modulus of elasticity values, in particular, were very consistent with an average value of 13 Msi. Average fracture elongation and reduction of area were 1.29% and 1.30%, respectively.

Table 7. Modulus of elasticity, fracture elongation, and reduction of area for Nitinol 60 after exposure.

<table>
<thead>
<tr>
<th>Test Result</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Median</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Coefficient of Variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of Elasticity (Msi)</td>
<td>13.6</td>
<td>12.3</td>
<td>13</td>
<td>13</td>
<td>0.39</td>
<td>2.97</td>
</tr>
<tr>
<td>Fracture Elongation (%)</td>
<td>1.59</td>
<td>1.04</td>
<td>1.26</td>
<td>1.29</td>
<td>0.15</td>
<td>11.46</td>
</tr>
<tr>
<td>Reduction of Area (%)</td>
<td>3.18</td>
<td>–</td>
<td>1.60</td>
<td>1.30</td>
<td>1.12</td>
<td>86.45</td>
</tr>
</tbody>
</table>

Representative samples that were tensile tested are shown in figure 21. The samples did not experience any necking-down effect (localized area reduction of the specimen during plastic deformation) because of the low ductility of this material when it is in the hard condition. Also notice the tendency of these samples to break close to the end of the reduced section. Of the 22 specimens that were tensile tested after exposure, 14 broke at or near the end of the reduced section, 5 broke in two places, and only 3 broke within the gauge length. Stress-strain curves for these samples are shown in figure 22.
Sample N60-27-SABP-50: Stressed to 50 ksi, exposed for 1 year in sulfuric acid-based pretreat, and tensile tested to failure (153.2 ksi UTS)

Sample N60-36-SABB-50: Stressed to 50 ksi, exposed for 1 year in sulfuric acid-based brine, and tensile tested to failure (152 ksi UTS)

Sample N60-8-PABP-50: Stressed to 50 ksi, exposed for 1 year in phosphoric acid-based pretreat, and tensile tested to failure (176.1 ksi UTS)

Sample N60-17-PABB-50: Stressed to 50 ksi, exposed for 1 year in phosphoric acid-based brine, and tensile tested to failure (152.4 ksi UTS)

Sample N60-39-Al-25: Stressed to 25 ksi, exposed for 1 year in NaCl alternate immersion, reloaded to 100 ksi and exposed for 32 additional days, and then tensile tested to failure (145.2 ksi UTS)

Figure 21. Stress corrosion specimens exposed to various environments and tensile tested.
Figure 22. Stress-strain curves for stress corrosion specimens exposed to various environments
5. CONCLUSIONS

All the stress corrosion specimens exposed to the ECLSS solutions (sulfuric acid-based pre-treat, sulfuric acid-based brine, phosphoric acid-based pretreat, and phosphoric acid-based brine) survived the year-long stress corrosion test at stress levels up to 50 ksi. The complementary specimens exposed to 3.5% NaCl alternate immersion per ASTM G44 also survived the year-long stress corrosion test at a stress level of 25 ksi, as well as the 32-day extended test at stress levels of up to 125 ksi. Metallographic examinations of representative specimens did not detect stress corrosion cracks on the specimens. However, the average ultimate tensile strength of exposed specimens were lower than the average for the initially tested specimens in air with no exposure. From the stress corrosion standpoint, that reduction is not expected to be a deterrent for the proposed use of this alloy as a bearing material, since for that type of applications, the stresses are in compression.
REFERENCES


Stress Corrosion Evaluation of Nitinol 60 for the International Space Station Water Recycling System

P.D. Torres

George C. Marshall Space Flight Center
Huntsville, AL 35812

National Aeronautics and Space Administration
Washington, DC 20546–0001

Unclassified-Unlimited
Subject Category 26
Availability: NASA STI Information Desk (757–864–9658)

Prepared by the Materials and Processes Laboratory, Engineering Directorate

A stress corrosion evaluation was performed on Nitinol 60 because this alloy was proposed to be used as a bearing material for the Urine Processing Assembly of the Environmental Control and Life Support System (ECLSS) of the International Space Station. The specimens exposed to the ECLSS solutions (sulfuric acid-based pretreat, sulfuric acid-based brine, phosphoric acid-based pretreat, and phosphoric acid-based brine) survived the year-long stress corrosion test at stress levels up to 50 ksi. Metallography did not detect stress corrosion cracks, however, reduction in tensile strength took place. That is not expected to be a deterrent for the use of this material for bearings as stresses will be in compression.

International Space Station, Environmental Control and Life Support System, Urine Processing Assembly, stress corrosion cracking, corrosion, Nitinol 60, urine pretreatment, urine brine, water recycling in the Space Station, water recovery in the Space Station
The NASA STI Program...in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and mission, often concerned with subjects having substantial public interest.

- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results...even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI program home page at [http://www.sti.nasa.gov](http://www.sti.nasa.gov)

- E-mail your question via the Internet to help@sti.nasa.gov

- Phone the NASA STI Help Desk at 757–864–9658

- Write to: NASA STI Information Desk Mail Stop 148 NASA Langley Research Center Hampton, VA 23681–2199, USA
Stress Corrosion Evaluation of Nitinol 60 for the International Space Station Water Recycling System

P.D. Torres
Marshall Space Flight Center, Huntsville, Alabama