Ni-H₂ Cell Characterization for INTELSAT Programs

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ABSTRACT

Various Ni/H₂ cell designs manufactured for INTELSAT Programs during the past decade have been characterized electrically as a function of temperature. The resulting data for these INTELSAT V, VI, VII and VIIA cells are assembled in a manner which allows ready comparison of performance. Also included is a detailed description of each design.

INTRODUCTION

As part of a coordinated program to extend the operational lives of its spacecraft, INTELSAT characterizes the performance of each type of battery cell flown.

INTELSAT is operating batteries using 30 Ah cells made by Eagle-Picher, Industries, 48 Ah cells from Hughes Aircraft Company, and 85 Ah cells made by Gates Aerospace Batteries. In the near future we will be operating 120 Ah Gates cells also.

Life testing, performance characterization, and associated analytical work is done at COMSAT Corporation Laboratory, Clarksburg, Md.

This paper reports on the results of the performance characterization, with temperature, of the four types of Ni/H₂ cells in or about to be in operation with the INTELSAT fleet of geostationary communications satellites.
BACKGROUND

One reason why INTELSAT is successful in achieving long life for its operational fleet of spacecraft is the care taken in the operation of the spacecraft batteries. In support of the orbital operation, batteries of each type flown are placed into real time life test. These tests, performed at COMSAT Laboratories, simulate the operation in orbit as closely as possible. A test is normally started three seasons before the first use of the batteries in orbit. Individual cells are operated in the same test with the battery and are periodically removed from the test for destructive physical analysis (DPA). These tests are not intended to validate the design of the batteries; rather they are to address problems on the ground before they are encountered in orbit. Solutions can be devised and tested to ensure continued operation in orbit.

In addition to the life testing, COMSAT also performed a series of parametric performance tests, at the cell level, to characterize the response of the batteries under a variety of thermal and charge conditions.

Since 1983 INTELSAT spacecraft have all had Ni/H₂ batteries. These batteries have used cells from the three main Ni/H₂ cell manufacturers in the USA. Sixteen batteries using 30 Ah Eagle-Picher Industries (EPI) cells are in operation on the later INTELSAT V spacecraft, ten batteries using 44 Ah Hughes Aircraft Company cells are in operation on the INTELSAT VI spacecraft, and two batteries using 85 Ah Gates Aerospace Batteries have recently been launched on the first INTELSAT VII. This is the first of at least six similar spacecraft which will be joined by three INTELSAT VIIA spacecraft equipped with batteries using 120 Ah Gates cells. These are the four types of cell reported upon.

Details of the cells are given in Table 1. Figures 1 to 4 show cross-sectional drawings of each cell. While Table 2 gives details of each battery, INTELSAT has always flown two batteries per spacecraft. Figures 5 to 7 are pictures of each type of battery. As yet no pictures are available of an INTELSAT VIIA battery.
PARAMETRIC TESTING

In each of the four cases, a minimum of four cells of each type were subjected to charge/discharge cycles at 10°C intervals from +30 to -20°C except for the I-5 cells which, because of their design, operate successfully down to -30°C. In addition, self discharge performance data was generated at 10, 20, and 30°C for durations of 144 hours. The testing sequence is presented in Table 3. Pressure, temperature, cell voltage, charge, and discharge current are carefully monitored.

Figure 8 displays a typical series of charge/discharge voltage and temperature profiles. From this type of data, cell end-of-charge voltage, mid-discharge voltage and capacity are determined as a function of cell temperature. This is a modification to the data which was previously presented using chamber set point temperature for the abscissa [1]. Two cells of each group were instrumented with strain-gauges. A typical series of charge/discharge pressure profiles are displayed in Figure 9. When this data is normalized to 0°C using the gas law and cell temperature data, the resulting profiles indicate the degree to which the gauges are temperature compensated. The charging pressure profiles can be used to generate plots of instantaneous charge efficiency by taking their derivative with respect to time. Finally, pressure profiles for 144 hours of self-discharge were determined at 10, 20, and 30°C. These pressure profiles were converted to capacity remaining profiles by considering the pressure range for capacity measurements. The results for each case are displayed in Figures 10 to 13. Plotted are capacity, end-of-charge voltage and mid-discharge voltage as a function of cell temperature; charge efficiency versus charge in and percent capacity remaining as a function of open-circuit time at temperature.

The self-discharge data can be further developed assuming first order kinetics and Arrhenius behavior [2]. The resulting self-discharge characteristics and Arrhenius plots are displayed in Figure 14. The activation energy associated with the rate constant for each case is included in Table 4.

<table>
<thead>
<tr>
<th>TABLE 1. SUMMARY OF INTELSAT Ni-H$_2$ CELL DESIGNS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
</tr>
<tr>
<td>Cell Dimensions (cm)</td>
</tr>
<tr>
<td>Diameter</td>
</tr>
<tr>
<td>Total Length</td>
</tr>
<tr>
<td>Cell Mass (g)</td>
</tr>
<tr>
<td>Capacity @ 10°C to 1.0V (Ah)</td>
</tr>
<tr>
<td>Stack Design</td>
</tr>
<tr>
<td>Component Shape</td>
</tr>
<tr>
<td>Configuration</td>
</tr>
<tr>
<td>Arrangement</td>
</tr>
<tr>
<td>Terminal Design</td>
</tr>
<tr>
<td>Positive Electrode</td>
</tr>
<tr>
<td>Plaque Type</td>
</tr>
<tr>
<td>Impregnation Type</td>
</tr>
<tr>
<td>Ni(OH)$_2$ Loading (g/cc)</td>
</tr>
<tr>
<td>Co(OH)$_2$ Loading (g/cc)</td>
</tr>
<tr>
<td>Plate Thickness (mm)</td>
</tr>
<tr>
<td>No. of Plates</td>
</tr>
<tr>
<td>Mass Fraction (%)</td>
</tr>
<tr>
<td>Separator Type</td>
</tr>
<tr>
<td>Thickness (mm)</td>
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<tr>
<td>Mass Fraction</td>
</tr>
<tr>
<td>Electrolyte</td>
</tr>
<tr>
<td>Discharged State (w/o)</td>
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<tr>
<td>Mass Fraction (%)</td>
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<tr>
<td>Negative Electrode</td>
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<tr>
<td>No. of Plates</td>
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<tr>
<td>Thickness (mm)</td>
</tr>
<tr>
<td>Pt Loading (g/cm$^2$)</td>
</tr>
<tr>
<td>Mass Fraction (%)</td>
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</table>
Figure 1. Cross-sectional view of an INTELSAT V NiH2 Cell

Figure 2. Cross-sectional view of an INTELSAT VI NiH2 Cell
Figure 3. Cross-sectional view of an INTELSAT VII NiH2 Cell

Figure 4. Cross-sectional view of an INTELSAT VI/IA NiH2 Cell
# Table 2. Summary of Intelsat Battery Designs

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>I-V</th>
<th>I-VI</th>
<th>I-VII</th>
<th>I-VII-A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ford Aerospace</td>
<td>HAC</td>
<td>SS/Loral</td>
<td>SS/Loral</td>
<td></td>
</tr>
<tr>
<td>No. Batteries/SC</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<tr>
<td>No. Packs/Battery</td>
<td>1</td>
<td>2</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>No. Cells/Battery</td>
<td>27</td>
<td>32</td>
<td>27</td>
<td>27</td>
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<tr>
<td>Battery Dimensions (cm)</td>
<td></td>
<td>2 Quadrants</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>51.8</td>
<td></td>
<td>51.0</td>
<td>50.8</td>
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<tr>
<td>Width</td>
<td>52.1</td>
<td></td>
<td>51.0</td>
<td>50.8</td>
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<tr>
<td>Height</td>
<td>22.2</td>
<td>28</td>
<td>30.4</td>
<td>30.4</td>
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<tr>
<td>Radius</td>
<td>80</td>
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<td>80</td>
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<tr>
<td>Battery Mass (Kg)</td>
<td>30.12</td>
<td>63.9</td>
<td>66.8</td>
<td>81.45</td>
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<tr>
<td>Rated Capacity (Ah)</td>
<td>30</td>
<td>44</td>
<td>85.5</td>
<td>120</td>
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<tr>
<td>Reconditioning (Ω)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load A</td>
<td>50</td>
<td>43.2</td>
<td>23.5</td>
<td>16.2</td>
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<tr>
<td>Load B</td>
<td>86.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diode Bypass</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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Figure 5. INTELSAT V NiH2 Battery

Figure 6. Two INTELSAT VI NiH2 Batteries on the Flt. 1 S/C
Figure 7. INTELSAT VII NiH2 Battery
<table>
<thead>
<tr>
<th>Sequences</th>
<th>Temp.</th>
<th>Measurements</th>
<th>Charge/Discharge</th>
<th>I-V</th>
<th>I-VI</th>
<th>I-VII</th>
<th>I-VII A</th>
<th>Remarks</th>
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<tr>
<td>1</td>
<td>10°C</td>
<td>Reconditioning</td>
<td>C/20  , C/2</td>
<td>x</td>
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<td>x</td>
<td>x</td>
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<tr>
<td>2</td>
<td>10°C</td>
<td>Capacity</td>
<td>C/10  , C/2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>10°C</td>
<td>Capacity</td>
<td>C/10  , C/2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
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<tr>
<td>4</td>
<td>0°C</td>
<td>Capacity</td>
<td>C/10  , C/2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>5</td>
<td>0°C</td>
<td>Capacity</td>
<td>C/10  , C/2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>-10°C</td>
<td>Capacity</td>
<td>C/10  , C/2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
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<tr>
<td>7</td>
<td>-10°C</td>
<td>Capacity</td>
<td>C/10  , C/2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>8</td>
<td>-20°C</td>
<td>Capacity</td>
<td>C/10  , C/2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>9</td>
<td>-20°C</td>
<td>Capacity</td>
<td>C/10  , C/2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
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<tr>
<td>10</td>
<td>-30°C</td>
<td>Capacity</td>
<td>C/10  , C/2</td>
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<td></td>
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<td>-30°C</td>
<td>Capacity</td>
<td>C/10  , C/2</td>
<td>x</td>
<td></td>
<td></td>
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<tr>
<td>12</td>
<td>10°C</td>
<td>Capacity</td>
<td>C/10  , C/2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>13</td>
<td>10°C</td>
<td>Capacity</td>
<td>C/10  , C/2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>20°C</td>
<td>Capacity</td>
<td>C/10  , C/2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>15</td>
<td>20°C</td>
<td>Capacity</td>
<td>C/10  , C/2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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</tr>
<tr>
<td>16</td>
<td>30°C</td>
<td>Capacity</td>
<td>C/10  , C/2</td>
<td>x</td>
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<td></td>
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<tr>
<td>17</td>
<td>30°C</td>
<td>Capacity</td>
<td>C/10  , C/2</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>10°C</td>
<td>Capacity</td>
<td>C/10  , C/2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>10°C</td>
<td>Charge Stand</td>
<td>C/10  , C/2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>20°C</td>
<td>Charge Stand</td>
<td>C/10  , C/2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>2</td>
</tr>
<tr>
<td>21</td>
<td>30°C</td>
<td>Charge Stand</td>
<td>C/10  , C/2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>3</td>
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C = 30Ah  C = 48Ah  C = 86Ah  C = 120Ah

<table>
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<tr>
<th>CELLS</th>
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</thead>
<tbody>
<tr>
<td>L4-04</td>
<td>L003*</td>
<td>L1-001*</td>
<td>L1-002*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L4-84</td>
<td>L012*</td>
<td>L1-022*</td>
<td>L1-004*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L4-90</td>
<td>L013</td>
<td>L2-023</td>
<td>L1-016</td>
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<td></td>
</tr>
<tr>
<td>L4-107*</td>
<td>L014</td>
<td>L2-060</td>
<td>L1-018</td>
<td>L1-022</td>
<td>L1-032</td>
<td></td>
</tr>
</tbody>
</table>

(1) Charge for 16 hours @ 10°C. Open circuit for 144 hours @ 10°C. Discharge to 0.1V @ 10°C
(2) Charge for 16 hours @ 10°C. Open circuit for 144 hours @ 20°C. Discharge to 0.1V @ 20°C
(3) Charge for 16 hours @ 10°C. Open circuit for 144 hours @ 30°C. Discharge to 0.1V @ 30°C

* Cells with Strain Gauge
### Table

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Cell Voltage (0.1V)</th>
<th>Cell Voltage (0.8V)</th>
<th>Cell Voltage (1.0V)</th>
<th>Cell Voltage (1.8V)</th>
<th>Cell Voltage (10.1V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80°C</td>
<td>1.241</td>
<td>138.60</td>
<td>171.13</td>
<td>1.242</td>
<td>137.10</td>
</tr>
<tr>
<td>-10°C</td>
<td>1.230</td>
<td>149.30</td>
<td>182.60</td>
<td>1.232</td>
<td>147.00</td>
</tr>
<tr>
<td>-20°C</td>
<td>1.211</td>
<td>154.15</td>
<td>185.25</td>
<td>1.214</td>
<td>149.32</td>
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<tr>
<td>-30°C</td>
<td>1.248</td>
<td>123.22</td>
<td>151.96</td>
<td>1.249</td>
<td>126.33</td>
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<tr>
<td>-40°C</td>
<td>1.261</td>
<td>109.34</td>
<td>135.54</td>
<td>1.262</td>
<td>106.51</td>
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<tr>
<td>-50°C</td>
<td>1.263</td>
<td>87.40</td>
<td>108.13</td>
<td>1.265</td>
<td>84.30</td>
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</tbody>
</table>

### Diagrams

1. **INTELSAT VI A - CHARGE/DISCHARGE VOLTAGE PROFILE**

2. **INTELSAT VI A - CHARGE/DISCHARGE TEMPERATURE PROFILE**

**FIGURE 8**

1993 NASA Aerospace Battery Workshop
<table>
<thead>
<tr>
<th>Temp.</th>
<th>Charge Slope</th>
<th>Charge Intercept</th>
<th>Discharge Slope</th>
<th>Discharge Intercept</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°C</td>
<td>64.05</td>
<td>19</td>
<td>-5.716</td>
<td>815</td>
</tr>
<tr>
<td>-10°C</td>
<td>61.12</td>
<td>20</td>
<td>-5.48</td>
<td>641</td>
</tr>
<tr>
<td>-20°C</td>
<td>58.77</td>
<td>19</td>
<td>-5.251</td>
<td>633</td>
</tr>
<tr>
<td>10°C</td>
<td>65.79</td>
<td>31</td>
<td>-6.161</td>
<td>734</td>
</tr>
<tr>
<td>20°C</td>
<td>68.95</td>
<td>27</td>
<td>-6.458</td>
<td>734</td>
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<tr>
<td>30°C</td>
<td>69.93</td>
<td>26</td>
<td>-6.656</td>
<td>608</td>
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</tbody>
</table>

**FIGURE 9**

1993 NASA Aerospace Battery Workshop -253- Nickel-Hydrogen Technologies Session
Figure 10

Nickel-Hydrogen Technologies Session

1993 NASA Aerospace Battery Workshop

-254-
**INTELSAT VI**

### Capacitance vs Temperature

\[ y = 78.45 - 0.322x - 6.221 \times 10^{-3}x^2 + 7.846 \times 10^{-5}x^3 \]

**End of Charge Voltage vs Temperature**

\[ y = 1.548 - 2.216 \times 10^{-3}x \]

### Mid Discharge Voltage vs Temperature

\[ y = 1.252 + 7.402 \times 10^{-6}x \]

### Charge Efficiency vs Charge In

### Capacity Remaining (%) vs Time

---

**FIGURE 11**
FIGURE 13
FIGURE 14

1993 NASA Aerospace Battery Workshop -258- Nickel-Hydrogen Technologies Session
### TABLE 4. SELF-DISCHARGE ANALYSIS

<table>
<thead>
<tr>
<th></th>
<th>Intercept</th>
<th>Slope</th>
<th>Rate x 10^-3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10°C</td>
<td>20°C</td>
<td>30°C</td>
</tr>
<tr>
<td><strong>INTELSAT V</strong></td>
<td>98.31</td>
<td>92.05</td>
<td>90.16</td>
</tr>
<tr>
<td><strong>INTELSAT VI</strong></td>
<td>88.11</td>
<td>90.09</td>
<td>93.64</td>
</tr>
<tr>
<td><strong>INTELSAT VII</strong></td>
<td>88.32</td>
<td>91.44</td>
<td>93.36</td>
</tr>
<tr>
<td><strong>INTELSAT VIIA</strong></td>
<td>85.93</td>
<td>90.36</td>
<td>89.79</td>
</tr>
</tbody>
</table>

#### THE SELF-DISCHARGE CHARACTERISTICS (Self-Discharge Time, t>10 hours)

<table>
<thead>
<tr>
<th></th>
<th>10°C</th>
<th>20°C</th>
<th>30°C</th>
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<tbody>
<tr>
<td><strong>INTELSAT V</strong></td>
<td>ln(PR)-ln(90.51)-0.0132xt</td>
<td>ln(PR)-ln(93.05)-0.0203xt</td>
<td>ln(PR)-ln(90.16)-0.0032xt</td>
</tr>
<tr>
<td><strong>INTELSAT VI</strong></td>
<td>ln(PR)-ln(89.11)-0.0194xt</td>
<td>ln(PR)-ln(90.09)-0.0034xt</td>
<td>ln(PR)-ln(90.64)-0.0067xt</td>
</tr>
<tr>
<td><strong>INTELSAT VII</strong></td>
<td>ln(PR)-ln(88.52)-0.0009xt</td>
<td>ln(PR)-ln(91.44)-0.0020xt</td>
<td>ln(PR)-ln(93.36)-0.0043xt</td>
</tr>
<tr>
<td><strong>INTELSAT VIIA</strong></td>
<td>ln(PR)-ln(85.93)-0.0005xt</td>
<td>ln(PR)-ln(90.36)-0.0028xt</td>
<td>ln(PR)-ln(89.70)-0.0031xt</td>
</tr>
</tbody>
</table>

#### THE EQUATIONS THAT BEST FIT THE ARRHENIUS PLOT

- **INTELSAT V**: \( \ln(\text{Rate}) = \ln(1.1100 \times 10^2) - 3864.3 / \text{Temperature (K)} \)
- **INTELSAT VI**: \( \ln(\text{Rate}) = \ln(57.462 \times 10^4) - 5538.4 / \text{Temperature (K)} \)
- **INTELSAT VII**: \( \ln(\text{Rate}) = \ln(38.192 \times 10^3) - 4912.9 / \text{Temperature (K)} \)
- **INTELSAT VIIA**: \( \ln(\text{Rate}) = \ln(38.958 \times 10^3) - 4911.5 / \text{Temperature (K)} \)

#### PERCENT CAPACITY REMAINING FOR ANY OPEN-CIRCUIT TIME AND AT ANY TEMPERATURE

- **INTELSAT V**: \( PR=98.91/e^y_t \) (where \( y=11.100 \times 10^2 / e^{3864.3/\text{Temp. (K)}} \), time>10 hrs)
- **INTELSAT VI**: \( PR=98.95/e^y_t \) (where \( y=57.462 \times 10^4 / e^{5538.4/\text{Temp. (K)}} \), time>10 hrs)
- **INTELSAT VII**: \( PR=91.11/e^y_t \) (where \( y=38.126 \times 10^3 / e^{4912.9/\text{Temp. (K)}} \), time>10 hrs)
- **INTELSAT VIIA**: \( PR=88.02/e^y_t \) (where \( y=36.958 \times 10^3 / e^{4911.5/\text{Temp. (K)}} \), time>10 hrs)

#### ACTIVATION ENERGY (kcal/mole)

<table>
<thead>
<tr>
<th></th>
<th>INTELSAT V</th>
<th>INTELSAT VI</th>
<th>INTELSAT VII</th>
<th>INTELSAT VIIA</th>
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<td>7.729</td>
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1993 NASA Aerospace Battery Workshop, Nickel-Hydrogen Technologies Session