Radiation Report

AFE11612-SEP Single-Event Latch-Up (SEL) Radiation Report

ABSTRACT

The purpose of this study is to characterize the effects of heavy-ion irradiation on the single-event latch-up (SEL) performance of the AFE11612-SEP highly integrated analog monitor and control device. The device includes 12 12-bit digital-to-analog converters (DACs) and a 16-channel, 12-bit, analog-to-digital converter (ADC). Heavy-ions with an LET_{EFF} of 43MeV×cm2/mg were used to irradiate the devices with a fluence of 1 × 107 ions/cm2. The results demonstrate that the AFE11612-SEP is SEL-free up to LET_{EFF} = 43MeV×cm2/mg at 125°C.

Table of Contents

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1 Overview

The AFE11612-SEP is a radiation-tolerant, full featured, general purpose, 12-bit digital-to-analog converter (DAC) that can operate from a single 2.7V to 5.5V supply and consumes just 177uA current at 3.6V. The on-chip output amplifier allows rail-to-rail output swing and the three-wire serial interface operates at clock rates up to 30MHz over the specified supply voltage range. The device uses CMOS7 technology and is compatible with standard SPI, QSPI, MICROWIRE, and DSP interfaces. The supply voltage (VA) for the AFE11612-SEP serves as the voltage reference, providing the widest possible output dynamic range. A power-on reset circuit maintains that the DAC output powers up to zero volts and remains there until there is a valid write to the device. A power-down feature reduces power consumption to less than one micro Watt (typ).

See the AFE11612-SEP product page on ti.com for more details.

Table 1-1. Overview Information (1)

Description	Device Information
TI part number	AFE11612-SEP
MLS number	AFE11612PAP-SEP
Device function	Radiation-tolerant, sixteen-channel, 500-kSPS, 12-bit ADC
Technology	HPA07
Exposure facility	Radiation Effects Facility, Cyclotron Institute, Texas A&M University
Heavy ion fluence per run	$1×10^6$ – $1×10^7$ ions/cm^2
Irradiation temperature	125°C (for SEL testing)

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2 SEE Mechanisms

The primary single-event effect (SEE) event of interest in the AFE11612-SEP is the destructive single-event latch-up (SEL). From a risk and impact point-of-view, the occurrence of an SEL is potentially the most destructive SEE event and the biggest concern for space applications. The HPA07 process node was used for the AFE11612-SEP. CMOS circuitry introduces a potential for SEL susceptibility. SEL can occur if excess current injection caused by the passage of an energetic ion is high enough to trigger the formation of a parasitic cross-coupled PNP and NPN bipolar structure (formed between the p-sub and n-well and n+ and p+ contacts). The parasitic bipolar structure initiated by a single-event creates a high-conductance path (inducing a steady-state current that is typically orders-of-magnitude higher than the normal operating current) between power and ground that persists (is latched) until power is removed or until the device is destroyed by the high-current state. The process modifications applied for SEL-mitigation were sufficient as the AFE11612-SEP exhibited no SEL with heavy-ions up to a of LET_{EFF} = 43MeV×cm2/mg at a fluence of 107 ions/cm2 and a chip temperature of 125°C.

This study was performed to evaluate the SEL effects with a bias voltage of 5.5V on AVDD, DVDD, VIODD, and AVCC, with internal 2.5V reference that sets the DAC output voltage to 5V. Heavy ions with LETEFF = 43MeV×cm2/mg were used to irradiate the devices. Flux of 105 ions/s-cm2 and fluence of 107 ions/cm2 were used during the exposure at 125°C temperature.

Figure 2-1 shows a functional block diagram for this device.

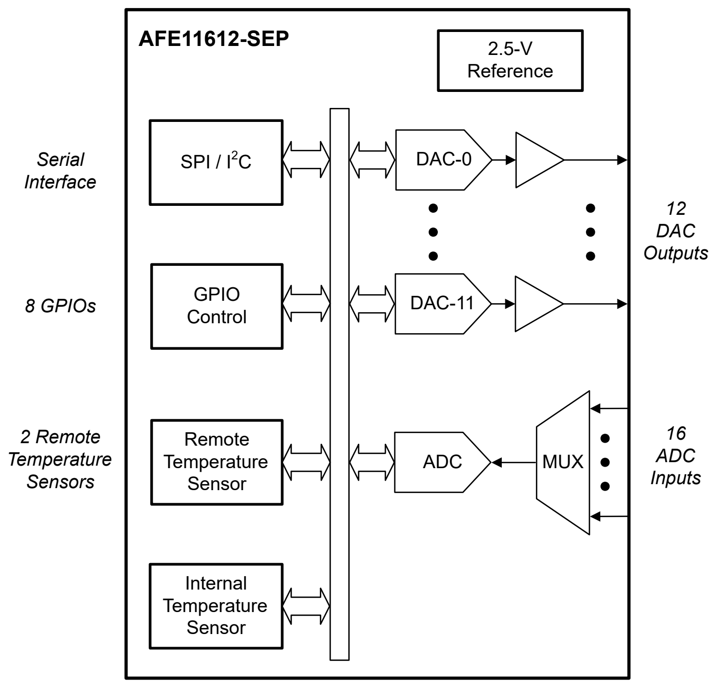

Figure 2-1. Functional Block Diagram of the DAC121S101-SEP

3 Test Device and Test Board Information

The AFE11612-SEP is packaged in a 64-pin HTQFP shown with the pinout in Figure 3-1. Figure 3-2 shows the biasing configuration used for both the SEL and SET tests.

The package was decapped to reveal the die face for all heavy ion testing.

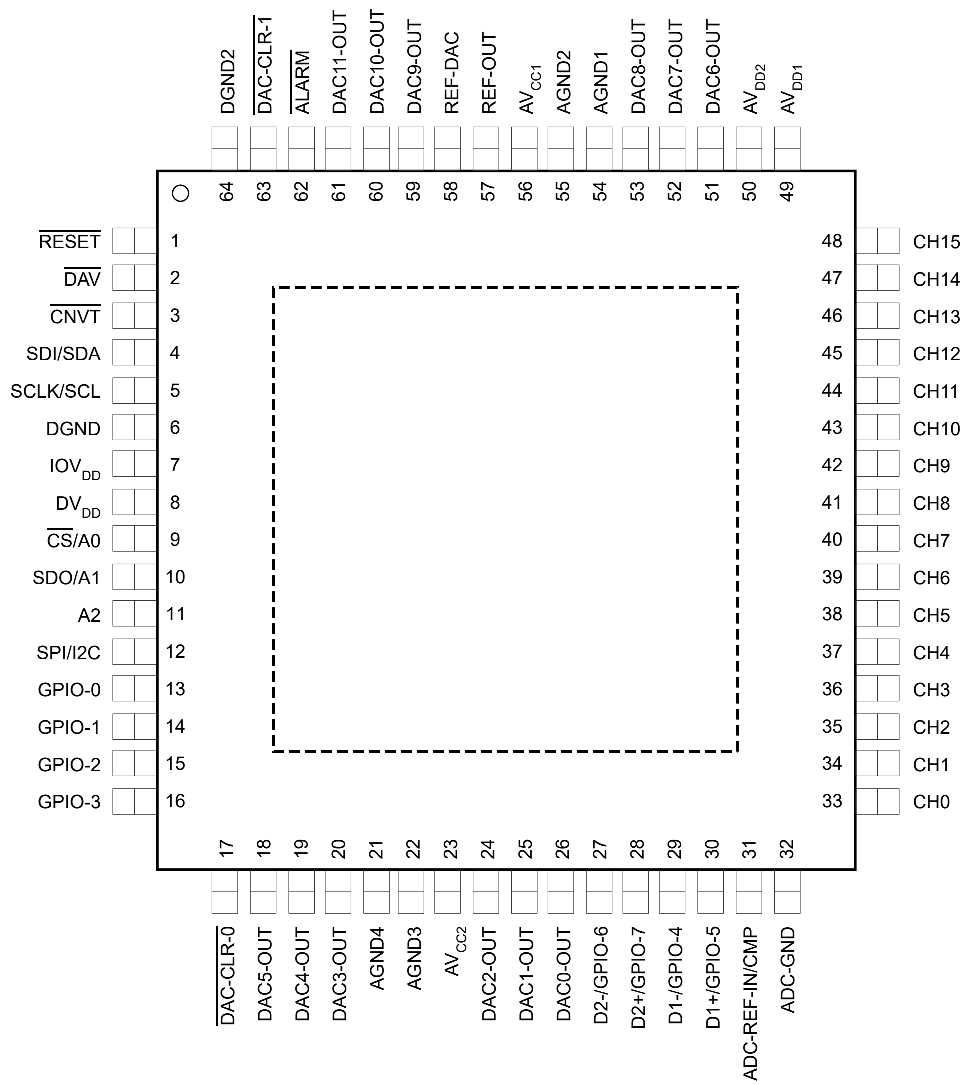

Figure 3-1. AFE11612-SEP Pinout Diagram

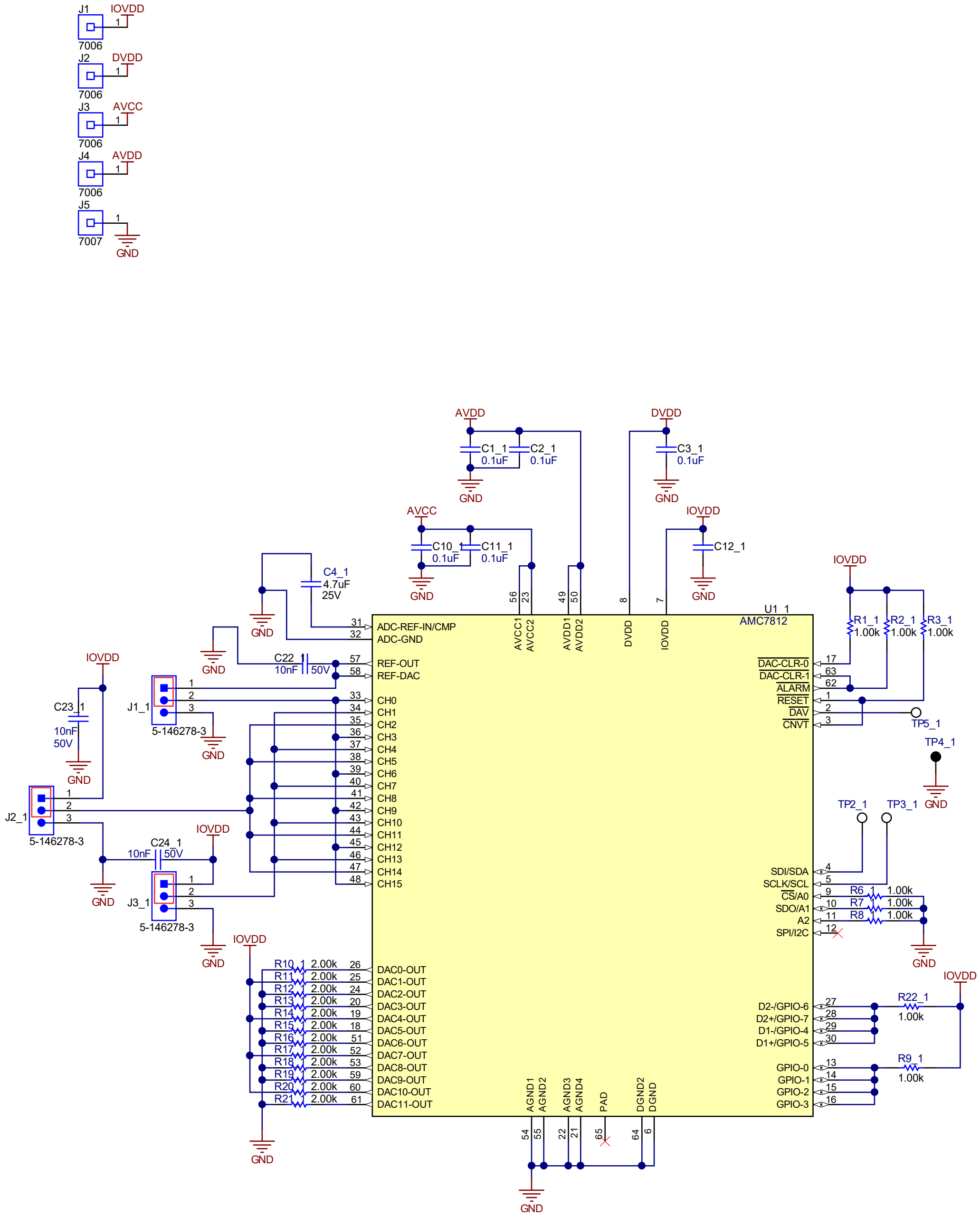

Figure 3-2. AFE11612-SEP Bias Configuration

4 Irradiation Facility and Setup

The heavy ion species used for the SEE studies on this product were provided and delivered by the TAMU Cyclotron Radiation Effects Facility [3] using a superconducting cyclotron and advanced electron cyclotron resonance (ECR) ion source. Ion beams are delivered with high uniformity over a 1-inch diameter circular cross-sectional area for the in-air station. Uniformity is achieved by means of magnetic defocusing. The intensity of the beam is regulated over a broad range spanning several orders of magnitude. For the bulk of these studies, ion fluxes between 10^4 and 10^5 ions/s-cm^2 were used to provide heavy ion fluences between 10^6 and 10^7 ions/cm^2. For these experiments Silver (Ag) ions were used. Ion beam uniformity for all tests was in the range of 91% to 98%.

5 Results

5.1 Single-Event Latch-Up Results

During SEL characterization, the device was heated using forced hot air, maintaining the device temperature at 125°C. The temperature was monitored by means of a K-type thermocouple attached as close to the device as possible. The species used for SEL testing was a silver (^{47}Ag) ion with an angle-of-incidence of 0° for an LETEFF = 43MeV×cm^2/mg. The kinetic energy in the vacuum for this ion is 1.634GeV (15MeV/amu line). A flux of approximately 10^5 ions/s-cm^2 and a fluence of approximately 10^7 ions/cm were used for two runs. The bias voltage of 5.5V on AVDD, DVDD, VIODD, and AVCC, with internal 2.5V reference that sets the DAC output voltage to 5V. The run duration to achieve this fluence was approximately 2 minutes. As shown in Table 5-1, no SEL events were observed during the two runs. Table 5-1, Figure 5-2, and Figure 5-3 shows the current plots during beam exposure. Current fluctuations are upset during the beam exposure due to transients and noticeably the AFE11612 current supplies recovers to an original state post exposure.

Table 5-1. DAC121S101-SEP SEL Conditions Using ^{47}Ag at an Angle-of-Incidence of 0°

Run #	Distance (mm)	Temperature (°C)	Ion	Angle	Flux (ions×cm^2/mg)	Fluence (# ions)	LET_{EFF} (MeV×cm^2/mg)
25	40	125	Ag	0°	1.09E+05	1.00E+07	43
26	40	125	Ag	0°	1.09E+05	1.00E+07	43

No SEL events were observed, indicating that the AFE11612-SEP is SEL-immune at LET_{EFF} = 43MeV×cm^2/mg and T = 125°C. Using the MFTF method described in Appendix A and combining (or summing) the fluences of the two runs at 125°C (1 × 107), the upper-bound cross section (using a 95% confidence level) is calculated in Equation 1:

$$\sigma SEL \leq 1.84 \times 10^{-7}\ cm^2 \quad (1)$$

where:

- LET_{EFF} = 43MeV×cm^2/mg
- T = 125°C

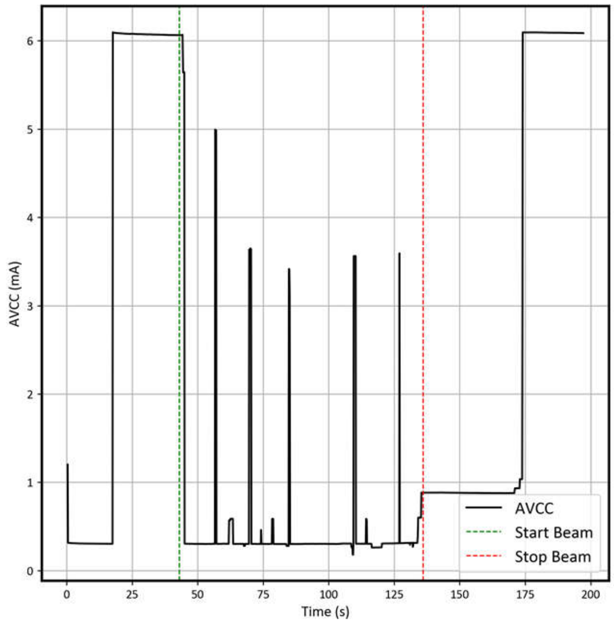

Figure 5-1. Current versus Time (I versus t) Data for VA Current During SEL Run

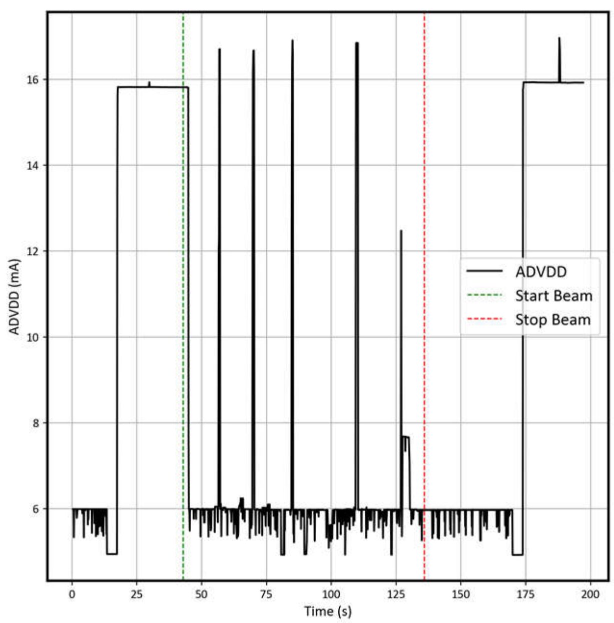

Figure 5-2. AVDD Transients During Run

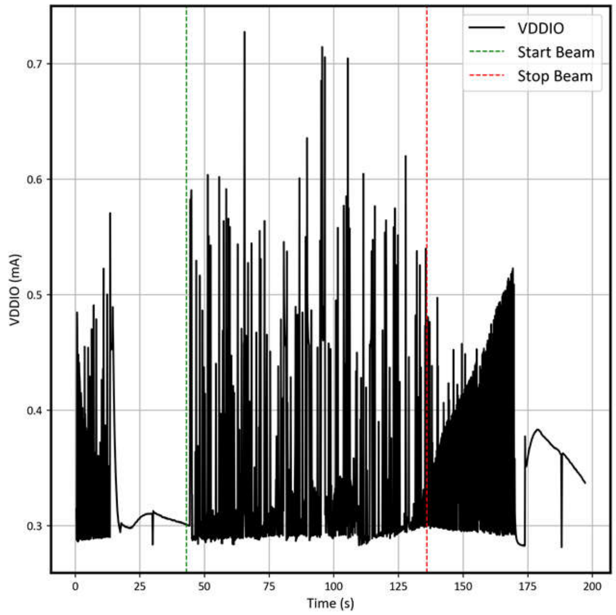

Figure 5-3. VDDIO Transients During Run

6 Summary

Radiation effects of the radiation-tolerant, sixteen-channel, 500-kSPS, 12-bit analog-to-digital converter. AFE11612-SEP, was studied. This device passed a total dose rate of up to 20krad(Si) and is latch-up immune up to LET_{EFF} = 43MeV×cm^2/mg and T = 125°C.

7 Confidence Interval Calculations

For conventional products where hundreds of failures can occur during a single exposure, the average failure rate of devices can be determined by being tested in a heavy-ion beam as a function of fluence with a high degree of certainty and reasonably tight standard deviation, and thus obtain a good deal of confidence that the calculated cross section is accurate.

With radiation-hardened parts however, determining the cross section is difficult because often few or no failures are observed during an entire exposure. Determining the cross section using an average failure rate with standard deviation is no longer a viable option, and the common practice of assuming a single error occurred at the conclusion of a null-result can end up in a greatly underestimated cross section.

In cases where observed failures are rare or non-existent, using confidence intervals and the chi-squared distribution is indicated. The chi-squared distribution is particularly well-suited for the determination of a reliability level when the failures occur at a constant rate. In the case of SEE testing where the ion events are random in time and position within the irradiation area, a failure rate is expected that is independent of time (presuming that parametric shifts induced by the total ionizing dose do not affect the failure rate), and thus the use of chi-squared statistical techniques is valid (because events are rare, an exponential or Poisson distribution is usually used).

In a typical SEE experiment, the device-under-test (DUT) is exposed to a known, fixed fluence (ions/cm^2) and the DUT is monitored for failures. This process is analogous to fixed-time reliability testing and, more specifically, time-terminated testing where the reliability test is terminated after a fixed amount of time whether or not a failure has occurred (in the case of SEE tests fluence is substituted for time and is therefore a fixed fluence test [5]). Calculating a confidence interval specifically provides a range of values that is likely to contain the parameter of interest (the actual number of failures per fluence). Confidence intervals are constructed at a specific confidence level. For example, a 95% confidence level implies that if a given number of units were sampled numerous times and a confidence interval estimated for each test, the resulting set of confidence intervals brackets the true population parameter in approximately 95% of the cases.

To estimate the cross section from a null-result (no fails observed for a given fluence) with a confidence interval, start with the standard reliability determination of the lower-bound (minimum) mean-time-to-failure for fixed-time testing (an exponential distribution is assumed) in Equation 2:

$$MTTF = \frac{2nT}{\chi^2_{2(d+1);100\left(1-\frac{\alpha}{2}\right)}} \tag{2}$$

where:

- *MTTF* is the minimum (lower-bound) mean-time-to-failure
- *n* is the number of units tested (presuming each unit is tested under identical conditions)
- *T* is the test time
- χ^2 is the chi-square distribution evaluated at 100(1 – α / 2) confidence level
- *d* is the degrees-of-freedom (the number of failures observed)

With slight modification to this equation for the purposes of this test, invert the inequality and substitute *F* (fluence) in the place of *T*, as shown in Equation 3:

$$MFTF = \frac{2nF}{\chi^2_{2(d+1);100\left(1-\frac{\alpha}{2}\right)}} \tag{3}$$

where:

- *MFTF* is mean-fluence-to-failure
- *F* is the test fluence
- X^2 is the chi-square distribution evaluated at 100(1 – α / 2) confidence
- *d* is the degrees-of-freedom (the number of failures observed)

The inverse relation between *MTTF* and failure rate is mirrored with the *MFTF*. Thus, the upper-bound cross section is obtained by inverting the *MFTF* as shown in Equation 4:

$$\sigma = \frac{\chi^2_2(d+1);100\left(1-\frac{\alpha}{2}\right)}{2nF} \quad (4)$$

Assume that all tests are terminated at a total fluence of 10^6 ions/cm^2. Also assume there are a number of devices with very different performances that are tested under identical conditions. Assume a 95% confidence level (σ = 0.05). When *d* increases from 0 events to 100 events, the actual confidence interval becomes smaller, indicating that the range of values of the true value of the population parameter (in this case the cross section) is approaching the mean value + 1 standard deviation. This difference makes sense when considering that as more events are observed the statistics are improved such that uncertainty in the actual device performance is reduced.

Table 7-1. Experimental Example Calculation of MFTF and σ Using a 95% Confidence Interval

Degrees-of-Freedom (d)	2(d + 1)	χ^2 at 95%	Calculated Cross Section (cm^2)		
			Upper-Bound at 95% Confidence	Mean	Average + Standard Deviation
0	2	7.38	3.69E–06	0.00E+00	0.00E+00
1	4	11.14	5.57E–06	1.00E–06	2.00E–06
2	6	14.45	7.22E–06	2.00E–06	3.41E–06
3	8	17.53	8.77E–06	3.00E–06	4.73E–06
4	10	20.48	1.02E–05	4.00E–06	6.00E–06
5	12	23.34	1.17E–05	5.00E–06	7.24E–06
10	22	36.78	1.84E–05	1.00E–05	1.32E–05
50	102	131.84	6.59E–05	5.00E–05	5.71E–05
100	202	243.25	1.22E–04	1.00E–04	1.10E–04

8 References

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9 Revision History