# FAILURE ANALYSIS OF NICKEL-HYDROGEN CELL SUBJECTED TO SIMULATED LOW EARTH ORBIT CYCLING

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## ABSTRACT

A nickel-hydrogen cell completed 10,080 simulated low earth orbit charge/discharge cycles at depths-of-discharge ranging from 50 to 80 percent prior to failure. The cell is of the Air Force design, rated at 50 ampere-hours, 8.9 cm (3.5 inches) in diameter. Upon disassembly, the end of the polysulfone core supporting the electrode stack was found to have fractured. This allowed the electrode stack to expand. A massive short was found at the inner diameter of the electrodes centered roughly at plate set 34 to 37 from the positive end of the electrode stack. The damaged area extended through approximately one third of the electrode stack, with the effect becoming progressively less with distance from plate set 34 to 37. Measured thicknesses of the positive plates were significantly greater than the initial specification values. The postulated cause of failure is: (1) Positive plate growth caused fracture of the shoulder from the end of the polysulfone core on which the electrodes are mounted, (2) The electrode stack relieved and pressure points were created at the area near the inner diameter of the plates at the tab attachment, and (3) A short occurred at a pressure point between opposing plates and propagated to other electrode sets due to thermal and mechanical stresses caused by the short.

## INTRODUCTION

Nickel-hydrogen cell serial number 148 was provided to McDonnell Douglas Astronautics Company-St. Louis Division (MDAC-STL) by the Air Force Wright Aeronautical Laboratory (AFWAL) for parametric and simulated low earth orbit cyclic tests. The cell is rated at 50 ampere-hours and is 8.9 cm (3.5 inches) in diameter. Figure 1 shows the cell general arrangement. This cell was constructed with asbestos separators.

MDAC-STL mounted the cells horizontally during test in a fixture which gripped the cell about the cylindrical section and permitted heat to flow from the cell to the aluminum clamp and then to the supporting aluminum plate. Figure 2 shows three cells in the test fixture. The aluminum baseplate was cooled by a circulating liquid coolant bath to permit temperature control of the test cells. Insulation was applied around the cells such that all heat removed from them was by conduction through the mounting clamp to the temperature controlled baseplate.

The cell was cycled by discharging into a fixed resistor such that 25 ampere-hours were removed over a 35-minute period, followed by charging at approximately 50 amperes to a voltage limit, which was then held constant while the current tapered for the balance of the 55-minute charge interval. Nominal cell temperature was 23°C. Cycling was controlled automatically to permit unattended operation. In order to prevent cell damage due to equipment malfunction, alarms were provided to shut down the test (open-circuit the cell) for over/under voltage, excessive discharge current, overtemperature, overpressure, and loss of facility power. Approximately 5 minutes into the charge period of cycle 10,080, the cell exceeded the temperature limit, and on the next data-scan a few seconds later the voltage dropped below 0.5 volts. The system automatically shut down, open-circuiting the cell. Eighteen minutes later when the next data set was recorded, the highest temperature was 89.6°C, measured at the top of the cylindrical section furthest removed from the coolant bath. Intermediate data points were not recorded, and the peak temperature excursion is not known. After about an hour, the cell voltage dropped to zero. Later in the day, a charge current of 5 amperes was applied for one hour but the voltage did not exceed 8.3 millivolts. The cell was then disconnected electrically from the test system but physically left in the fixture for approximately 11 months before the failure analysis was done.

## FAILURE ANALYSIS RESULTS

The cell was cut open with a lathe just below the weld toward the negative terminal (See Figure 1). Before any cutting operations, something loose could be heard rattling within the pressure vessel. When the negative end of the pressure vessel was removed, exposing the electrode stack, the ceramic insulating washer at the negative terminal was found broken into four pieces which accounts for the rattling noise. Also, the end plate, belleville washer, and the end of the polysulfone core were loose. These parts were captured by the negative leads, however, and not free to move within the pressure vessel. Figure 3 is a sketch of the electrode stack assembly showing component parts in greater detail. The end of the polysulfone core had fractured at the shoulder completely around the intersection with the central part of the core. Also, a plastic washer with a square opening and 2.69 cm (1.06 inches) outside diameter which was not identified on the drawing available to us, was found broken inside the cell. Figure 4 is a photograph of the shoulder of the core, broken ceramic insulating washer, end plate, unidentified washer, and belleville washer shown clockwise from the upper left. The electrode stack had relieved with the first negative roughly flush with the broken end of the polysulfone core. The reservoir had melted completely across the annular section in the area of the negative tab. Also, the electrode stack was indented in the area of the negative tab extending across the annular section of the plate. This may have been caused by the negative tabs which applied forces to the plates when the electrode stack relieved. Figure 5 is a photograph of the electrode stack prior to further disassembly, showing these features.

Referring to Figure 3, for purposes of identification the electrodes are numbered consecutively from the positive end (weld ring end). Therefore, negative plate number 41 is the first electrode encountered when disassembly proceeds from the fractured end of the polysulfone core. It was discovered during disassembly that this particular cell had been constructed with an additional reservoir between each set of plates rather than one at each end of the stack as shown in the artist's sketch of Figure 3. Mr. Don Warnock of AFWAL confirmed that some early cells had been constructed in this manner. The sequence of stack components was positive electrode, separator, negative electrode, gas screen, and reservoir. This sequence was repeated throughout the electrode stack. Another observation of general interest was that many of the positive plates had irregularly shaped depressed areas randomly dispersed over the surface. There appeared to be two distinct levels of material similar to looking over a broad plain with mesas protruding from it. Finally, the positive electrodes had grown in thickness considerably due to extended cycling.

Shorting of adjacent positive and negative plates was found at the inner perimeter of the plates in the area of the negative tab. In many cases, active material from the positive plate was embedded in the adjacent negative. The gas screen and reservoir between negative and positive plates had melted and shrunk and were fused to the teflon coated side of the negative electrodes. Figures 6 and 7 illustrate these conditions. Figure 6 is a photograph of positive plate 36 viewed from the negative end of the electrode stack. Note the missing active material and the burned area at the core where the tab attachment to the adjacent negative was located. Figure 7 is a photograph of the adjacent negative plate 37 viewed from the positive side of the electrode stack after removal. Note the active material from positive plate 36 adhering in the tab area, and the melting and shrinking of the gas screen and reservoir which adhere to the plate. Such damage was found to extend from the negative end of the electrode stack to plate set 27. The most massive damage appeared to occur in plate sets 34 to 37 with the effect becoming less pronounced on either side. Also, the plates became more planar as disassembly progressed toward the positive end of the electrode stack.

The heat pulse generated when the shorting occurred appeared to discolor and swell the polysulfone core, such that a ribbed appearance was created and a black deposit was left where the positive plates restricted this swelling. Figure 8 is a photograph illustrating this phenomenon at the fractured end of the core (negative end of electrode stack). The dimension from the end of the core to the first indentation caused by a positive plate is less than the combined thickness of the end plate and belleville washer, which implies that the end of the core fractured prior to the occurrence of the short.

## CONCLUSIONS

The thicknesses of positive plates were measured during disassembly and are tabulated in Figure 9. As built positive electrodes have a thickness of of 0.762 mm (0.030 inches) to 0.813 mm (0.032 inches). Assuming that each positive electrode was fabricated at the maximum dimension, the electrode stack heighth increased by 1.00 cm (0.395 inches) due to positive plate growth during cycling. This growth is believed to have caused the fracture of the shoulder from the center of the polysulfone core. Examination of the failed area shows striations in the material which is typical of a fatigue failure in metals. Since the material properties of polysulfone are differe a similar conclusion can not be supported. Also, the angle that the tabs mal with the electrodes were acute angles in the case of negative electrodes and obtuse angles for positive electrodes. The effect is most pronounced at the negative end of the electrode stack where the greatest relative movement occurred. This is believed to have been caused when the electrode stack relieved, by the forces applied through the tab. The tabs are restricted in the center of the core and act as a column pushing on the attachment poin in the case of negative electrodes. In the case of positive electrodes, the tab pulls on the attachment point.

A chronological history of the failure can be postulated as follows:

- o Positive plate growth during cycling causes fracture of the shoulder from the polysulfone core.
- o Forces applied to the electrodes when the stack expands create pressure points between adjacent pairs of electrodes, most pronounced at the tab attachments.
- o A short occurs at a pressure point after some period of time.
- o The heat pulse and mechanical forces generated by the short cause the failure to propagate to adjacent plate sets.

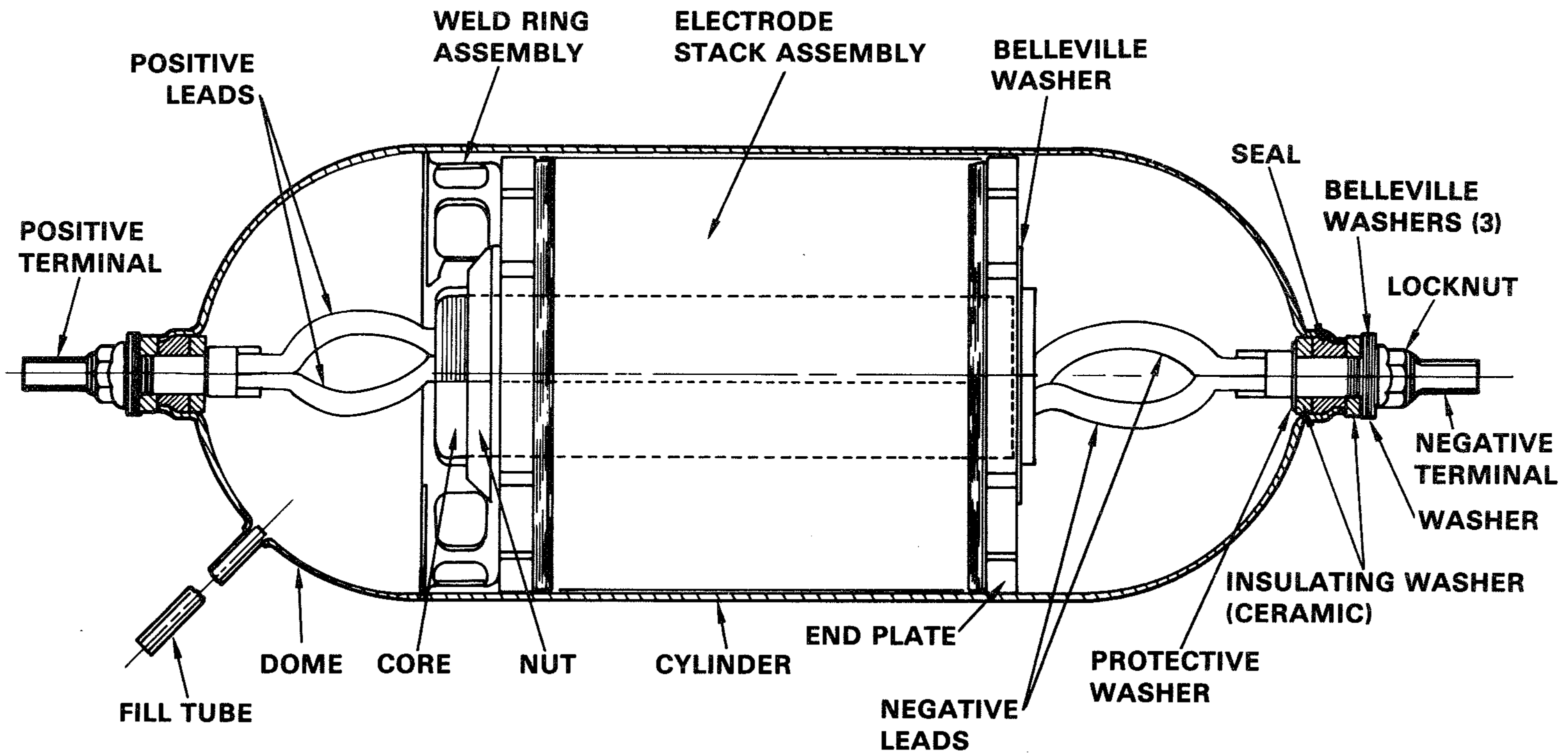


Figure 1. 50 ampere-hour nickel-hydrogen cell.

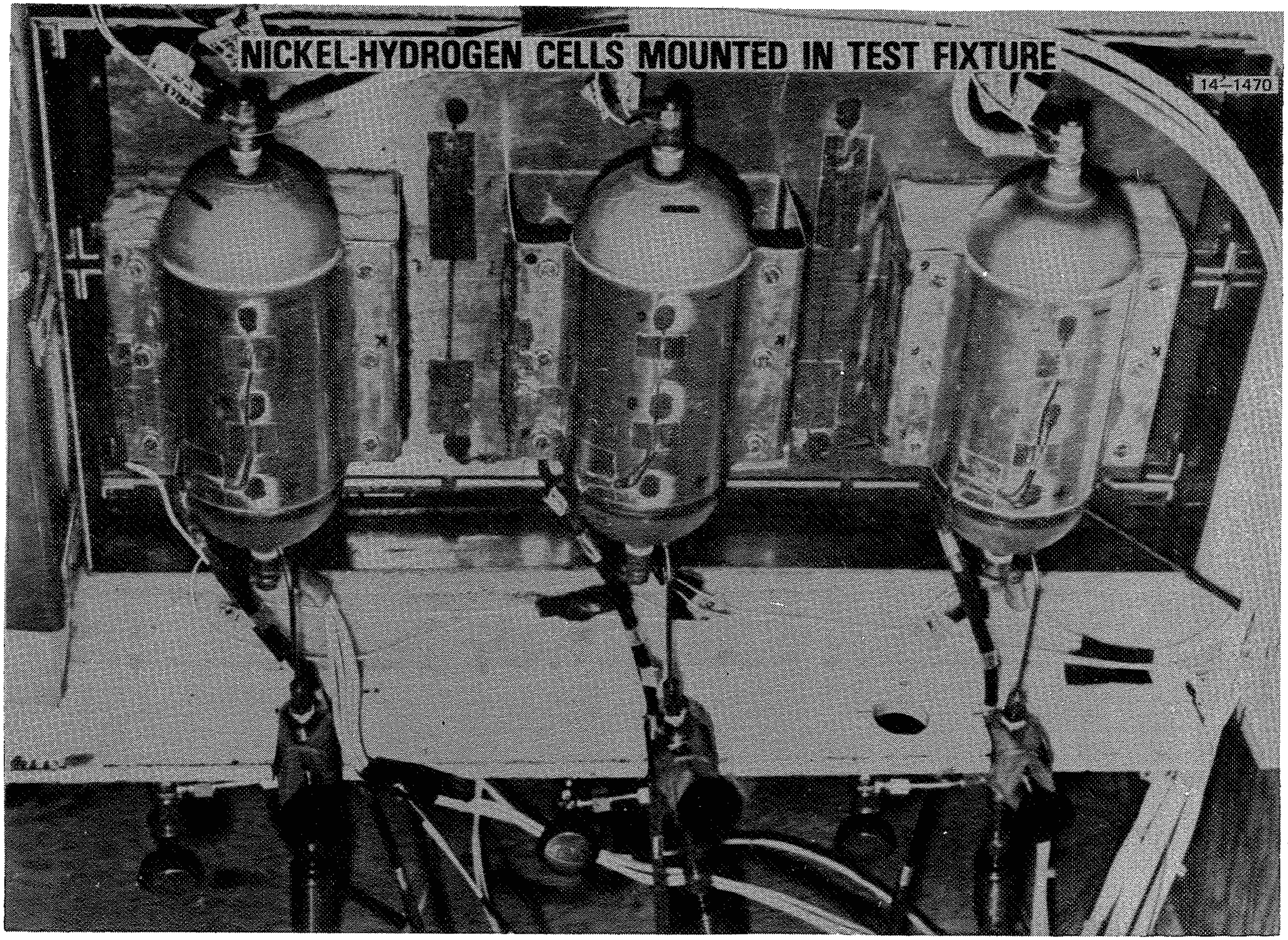


Figure 2. Nickel-hydrogen cells mounted in test figure.

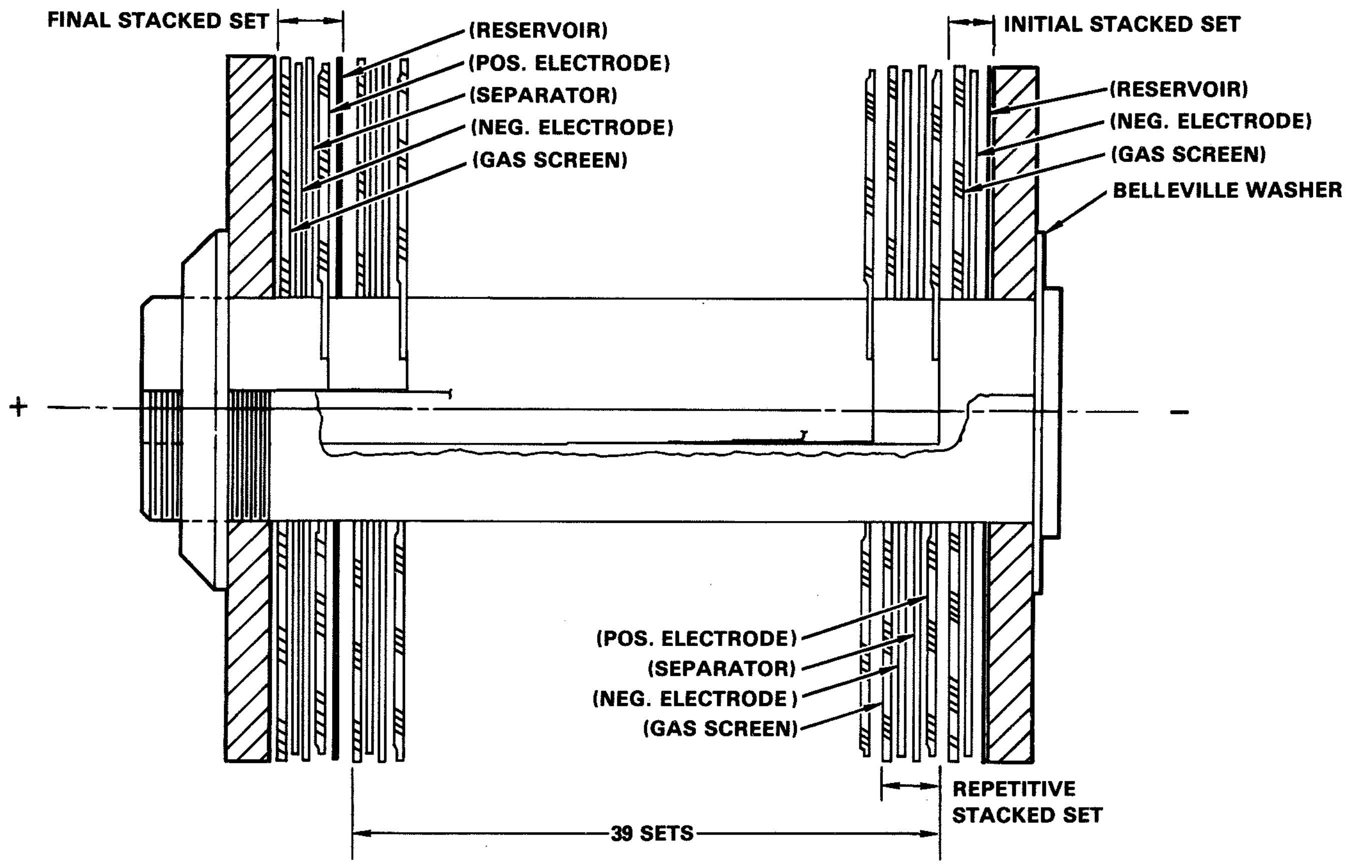


Figure 3. Electrode stack sketch.

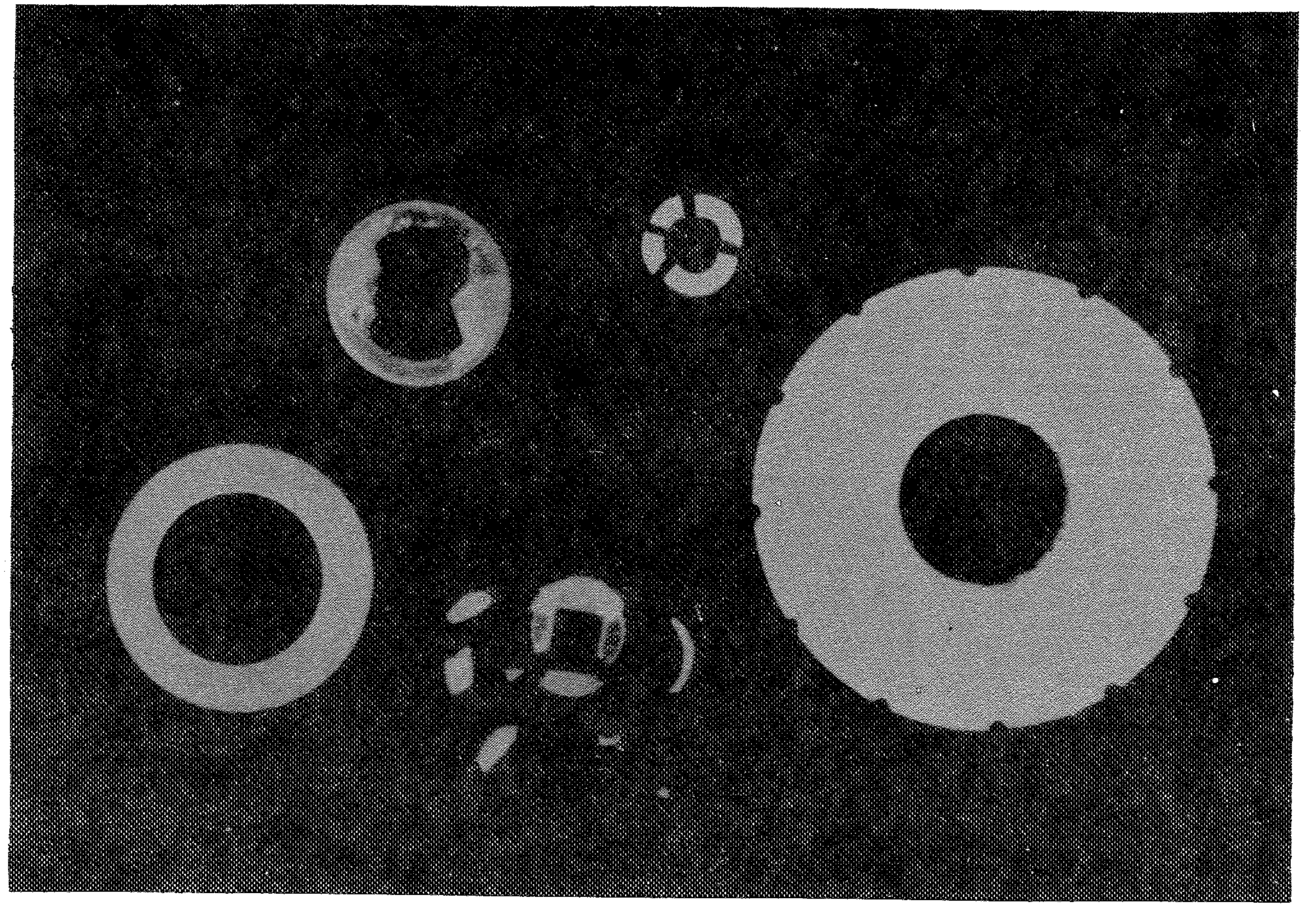

Figure 4. Loose parts/materials found within failed cell.

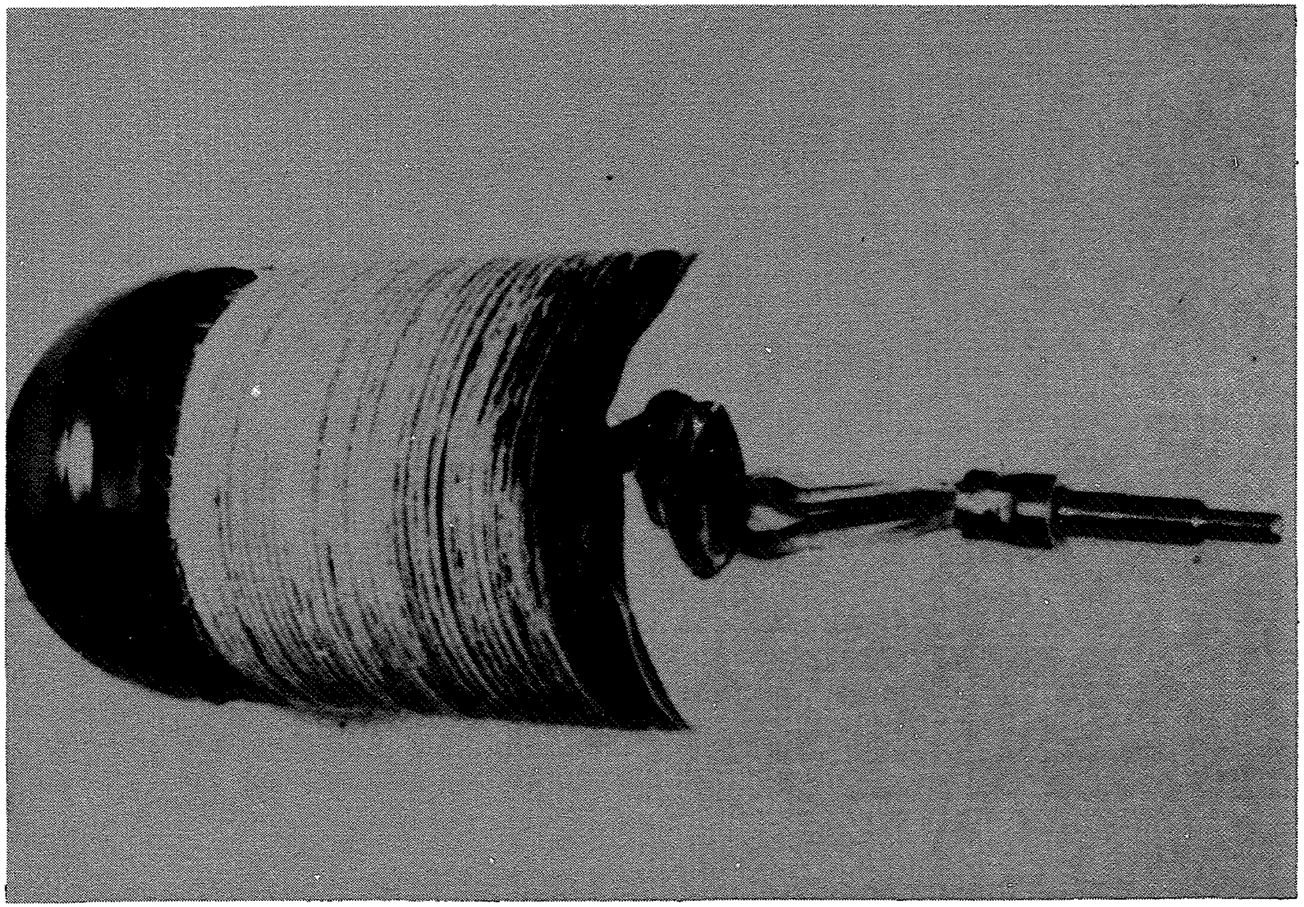

Figure 5. Electrode stack prior to disassembly.

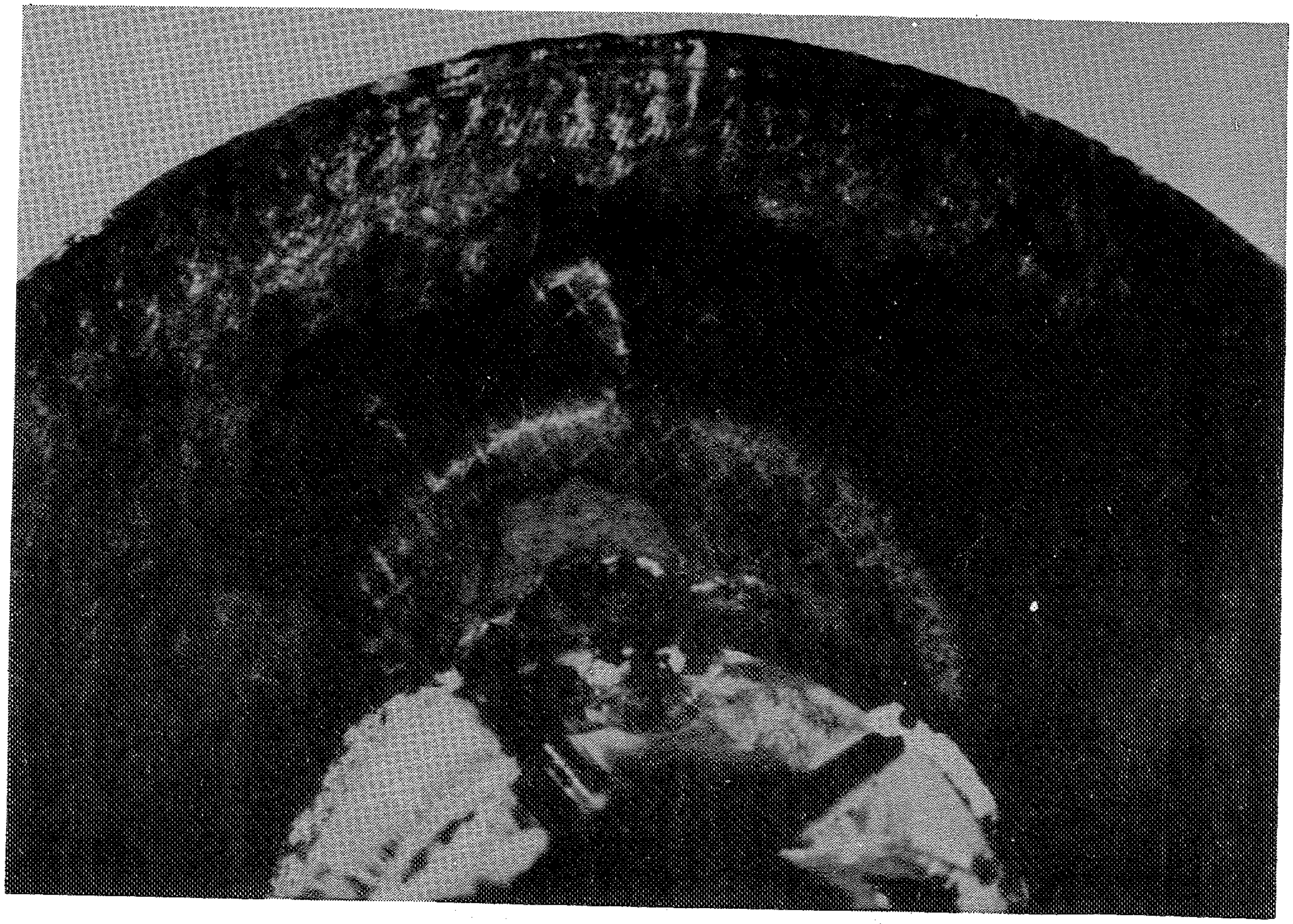

Figure 6. Typical positive plate showing active material loss.

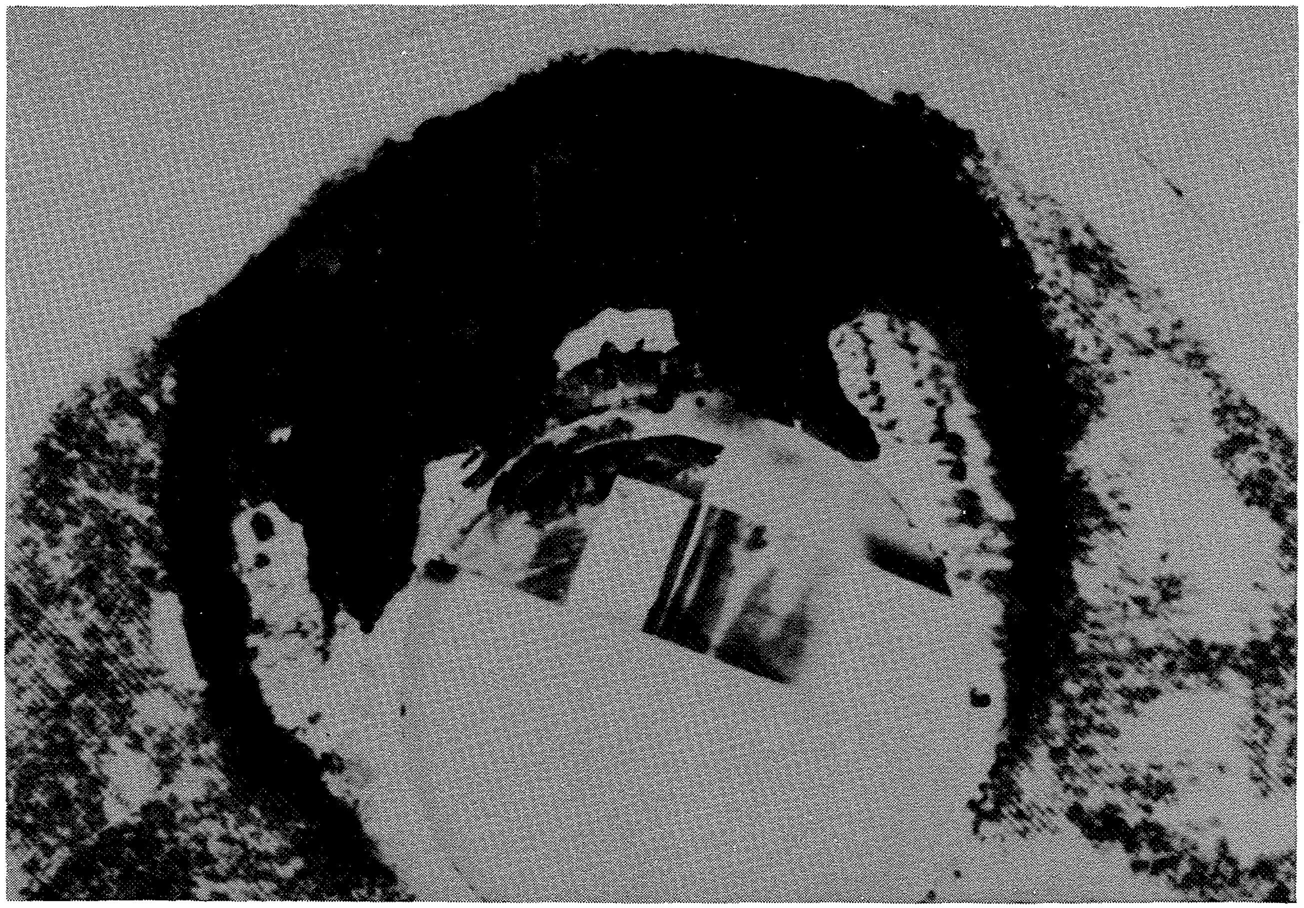

Figure 7. Typical negative plate showing adhesion of reservoir and gas screen.

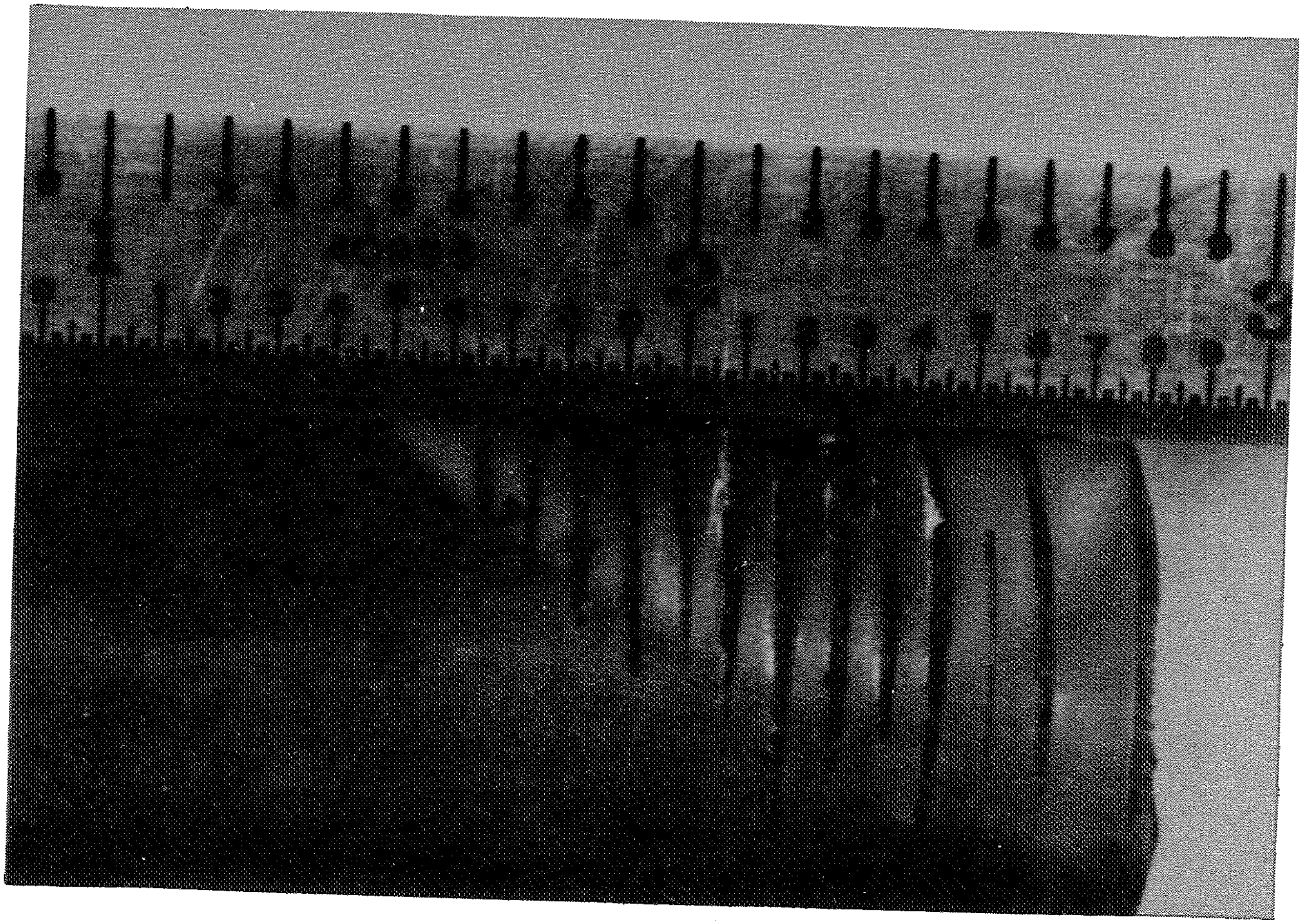

Figure 8. Fractured end of polysulfone core.

| PLATE IDENTIFICATION | THICKNESS CENTIMETERS | (INCHES) | PLATE IDENTIFICATION | THICKNESS CENTIMETERS | (INCHES) |
|---|---|---|---|---|---|
| P1 | 0.097 | 0.038 | P21 | 0.097 | 0.038 |
| P2 | 0.102 | 0.040 | P22 | 0.104 | 0.041 |
| P3 | 0.107 | 0.042 | P23 | 0.104 | 0.041 |
| P4 | 0.109 | 0.043 | P24 | 0.112 | 0.044 |
| P5 | 0.104 | 0.041 | P25 | 0.104 | 0.041 |
| P6 | 0.109 | 0.043 | P26 | 0.109 | 0.043 |
| P7 | 0.094 | 0.037 | P27 | 0.107 | 0.042 |
| P8 | 0.107 | 0.042 | P28 | 0.099 | 0.039 |
| P9 | 0.109 | 0.043 | P29 | 0.112 | 0.044 |
| P10 | 0.117 | 0.046 | P30 | 0.109 | 0.043 |
| P11 | 0.112 | 0.044 | P31 | 0.109 | 0.043 |
| P12 | 0.102 | 0.040 | P32 | 0.099 | 0.039 |
| P13 | 0.117 | 0.046 | P33 | 0.109 | 0.043 |
| P14 | 0.117 | 0.046 | P34 | 0.107 | 0.042 |
| P15 | 0.122 | 0.048 | P35 | 0.102 | 0.040 |
| P16 | 0.102 | 0.040 | P36 | 0.109 | 0.043 |
| P17 | 0.104 | 0.041 | P37 | 0.097 | 0.038 |
| P18 | 0.114 | 0.045 | P38 | 0.104 | 0.041 |
| P19 | 0.107 | 0.042 | P39 | 0.104 | 0.041 |
| P20 | 0.112 | 0.044 | P40 | 0.097 | 0.038 |

TOTAL THICKNESS OF ALL POSITIVES 4.255 CM (1.675 IN.)

Figure 9. Measured positive plate thicknesses-Cell S/N 148.

Q. Pickett, Hughes Aircraft: Could you tell me what year the cells were made?

A. Mueller, McDonnell Douglas Astronautics Company: No I can't. The serial number is 148 if that helps. I think we got them in about 1980.

COMMENT

Pickett, Hughes Aircraft: I just wanted to comment that these don't have the plates that we are currently making now.

Mueller, McDonnell Douglas Astronautics Company: No these have the old plates. I don't know. I talked to different people about this plate expansion problem or the plate expansion I saw they have told me that there is some test data available. I think they cited some at Lewis and one other location that shows that the plates that you have now expansion rates of less than 10% of what we see here.

Q. Lim, Hughes Research Lab: Do you have the plate loading data for this?

A. Mueller, McDonnell Douglas Astronautics Company: No I have not.

Q. Unidentified: You didn't mention much about the broken ceramic washer which is something that would concern me because it's going to be representative of ceil failure. Did you find anything to tell you why that broke? Whether it broke earlier or at the same time as the core?

A. Mueller, McDonnell Douglas Astronautics Company: No. I theorized that broke at the same time and my theory is that it broke due to the mechanical shock which created the timely shorting. We had no indication we were leaking hydrogen and I do think that's a good indication that the end of the core broke before the cell shortage. I might mention also that the cell continued to work relatively well up until the cycle before the failure occurred.

Q. Green, RCA-Astro: Could you tell us anything about the history of the cells, what was done before you yourself put them on test.

A. Mueller, McDonnell Douglas Astronautics Company: Yes we got them from the Air Force and I assume that all that was done to them was normal exceptance testing. We did some characterization test where we tried different charge schemes and different charge rates probably about a month in duration. Then we went on to cycling and we did 10,000 cycles on this particular cell - 90 minute cycles.

COMMENT

Rogers, Hughes Aircraft: Just a comment on the ceramic washer. Had that failed prior to your main failure you would undoubtedly lost the hydrogen.

Mueller, McDonnell Douglas Astronautics Company: I would think so.

Rogers, Hughes Aircraft: It's clear that was associated with the other failure in the cell.

Mueller, McDonnell Douglas Astronautics Company: As I was saying before there was no indication of performance degradation other than normal graceful degradation before the failure occurred.

Q. Ritterman, Comsat: You had no pressure indicator on the cells as I saw.

A. Mueller, McDonnell Douglas Astronautics Company: Yes we did.

Q. Ritterman, Comsat: You did have pressure?

A. Mueller, McDonnell Douglas Astronautics Company: And we saw no loss of pressure.

COMMENT

Milden, Aerospace Corporation: I was at Hughes Aircraft when these were built and I was actually the guy who was building them and first the good news is the cell went 17,500 cycles at 23 degrees centigrade which is astounding.

Mueller, McDonnell Douglas Astronautics Company: That is the one that just failed yes this one went 10,000.

Milden, Aerospace Corporation: Considering that's a first generation of the first fifty that were produced in any quantity, it's astounding that they went that far. There have been a number of changes made in the design as a result of the learning experiences. One of them is that the positive electrode tabs are performed now so that there's not quite a sharp a edge there so that shorting path would be a little bit different. Also in one program that area has been redesigned and improved significantly. The electrodes were an early attempt and very very far from optimum in terms of lower orbit electrodes. And it's amazing that they went that far. So for first generation air force design production cells actually pre-production since they were advanced development it's astounding.

Q. Kunigahalli, Bowie State College: Could you please tell me what was the volume of the electrolyte in the cell?

A. Mueller, McDonnell Douglas Astronautics Company: I'm sorry I can't tell you any details about the cell construction.

Q. Kunigahalli, Bowie State College: What was the condition of the separator?

A. Mueller, McDonnell Douglas Astronautics Company: The separators toward the end of the stack were actually in very good condition and in fact they were not, did not adhere to the positives very much. In some cases they did adhere to the positives, but we were able to get them off usually in one piece, some shredding some adherence. But really not bad at all.

Q. Kunigahalli, Bowie State College: Because my experience of nickel cadmium cells you know most of the time the separator would be very strongly sticking to the negative due to the cadmium migration. So I was wondering what is the situation in nickel hydrogen?

A. Mueller, McDonnell Douglas Astronautics Company: I'm always sticking to the positives. The negatives have teflon coating on them.

Q. Kunigahalli, Bowie State College: Excuse me one last question. By any chance did you take the same pictures of the positives? Were there any crystal growth or anything like that?

A. Mueller, McDonnell Douglas Astronautics Company: All we did was a tear down of visual inspection. We did do a chemical analysis of the separator to verify it was asbestos. It was kind of amazing to us that it was hanging together so well if it was asbestos.

A. Kunigahalli, Bowie State College: Thank you very much.

Q. Unidentified: Vern, you did mention that they had a reservoir in the building stack. Did it have a wall wick also?

A. Mueller, McDonnell Douglas Astronautics Company: Well it had one the standard wick on wall yes. As I mentioned it was wet they must have had very good electrolyte retention.