MEMS Reliability: The Challenge and the Promise

William M. Miller, Danelle M. Tanner, Samuel L. Miller and Kenneth A. Peterson
Sandia National Laboratories, P.O. Box 5800, Albuquerque NM 87185-1081
http://www.mdl.sandia.gov/Micromachine

ABSTRACT

MicroElectroMechanical Systems (MEMS) that think, sense, act and communicate will open up a broad new array of cost-effective solutions only if they prove to be sufficiently reliable. A valid reliability assessment of MEMS has three prerequisites:

1. statistical significance
2. a technique for accelerating fundamental failure mechanisms and
3. valid physical models to allow prediction of failures during actual use.

These already exist for the microelectronics portion of such integrated systems. The challenge lies in the less well-understood micromachine portions and its synergistic effects with microelectronics. This paper presents a methodology addressing these prerequisites and a description of the underlying physics of reliability for micromachines.

INTRODUCTION

The Promise of MEMS

The technology of MEMS is developing rapidly. In 1989, MEMS were laboratory curiosities with very low power, short lifetimes and few practical proposed uses. Less than a decade later, MEMS have taken major roles in several industries. Micromachined accelerometers are now being used as sensors for airbag actuation in over 50% of the new cars being built [1]. Texas Instruments has commercialized its Digital Micromirror Device (DMD) [2] which is being used in tens of thousands of bright projection displays worldwide. Both of these utilize silicon surface micromachining (SMM), a technique based on traditional silicon microelectronics fabrication techniques. In SMM the micromachines are built into thin layers of polysilicon, laid down over a silicon dioxide sacrificial layer which is later dissolved away (Fig. 1).

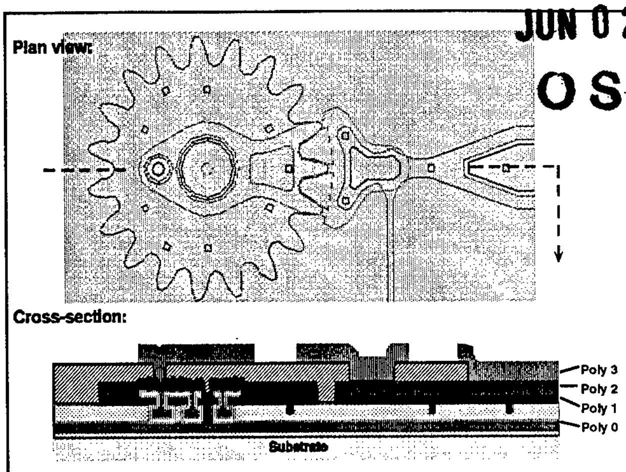

Figure 1. Cross-section of four level poly SMM process.

The final major area in which MEMS are playing a role today are in ink jet printheads in which channels are chemically cut into complete silicon wafers [3] by the bulk silicon micromachining process.

Spurred by applications such as these and micromachined gyroscopes, optical and electrical switches and new sensors, many industry experts believe that the market for MEMS will grow to over $30B (US) by early in the next century [4]

The Challenge of MEMS Reliability

The greatest challenge for the successful commercialization of this revolutionary new technology is in proving its reliability. This is true for four reasons. First, many of the promising applications of MEMS will be in critical systems where the cost of failure is very high. Second, MEMS is a new technology with potentially new and poorly understood failure mechanisms. Third, MEMS technology continues to evolve at a rapid rate. The relative importance of various reliability issues may change over time. Fourth, design tradeoffs must account for reliability, lest warrantee costs grow.

Failure to address known or potential reliability issues expeditiously in this new technology could result in unexpected failures with their concomitant costs, inability to reliably apply MEMS solutions to critical problems or perhaps the loss of confidence in MEMS as practical technology.

We can meet these business challenges only by meeting the technical reliability challenges inherent in any new technology. We must systematically apply the basic principles that have yielded success for reliability in other disciplines, especially that of microelectronics. These are:

1) statistical significance
2) a technique for accelerating fundamental failure mechanisms and
3) valid physical models to allow prediction of failures during actual use.

These three technical reliability challenges, when combined with the use of test structures, yield a methodology for rapidly addressing the issue of MEMS reliability.

THE FIRST RELIABILITY CHALLENGE: STATISTICAL SIGNIFICANCE

Traditional reliability characterization requires large numbers of parts to be stressed under accelerated use conditions. Typically, these are the final product, implying a baselined technology and final design. With a new and rapidly changing technology such an approach is impractical. However, the basic requirement remains, to test large numbers of parts quickly. We use test structures (Fig. 2) with design features that mimic those to be found in any final design [5].

Analogous to the life test equipment used in the integrated circuit industry, we have created a large capacity (256 part) packaged part MEMS reliability test system [5] (Fig. 3) to stress many test structures at once. Such a system has proven critical in identifying MEMS failure mechanisms. This system contains a method for interfacing electrical signals (both to stimulate and electrically-monitor the structure), a method to optically monitor and record data on the MEMS structure and a method to control the test environment.

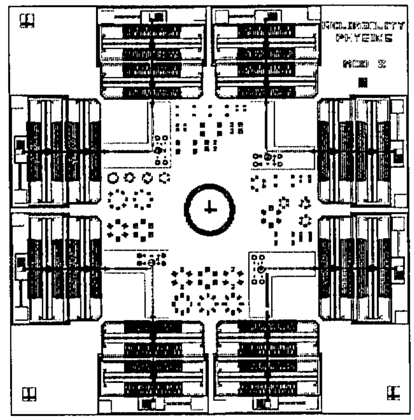

Figure 2. Actuator reliability test structure design, showing four microengines.

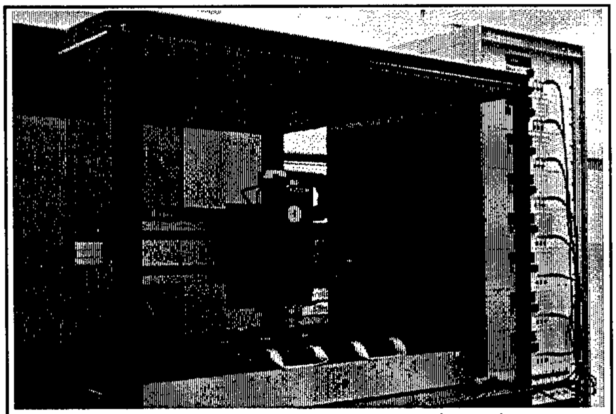

Figure 3. 256 part MEMS reliability packaged part system

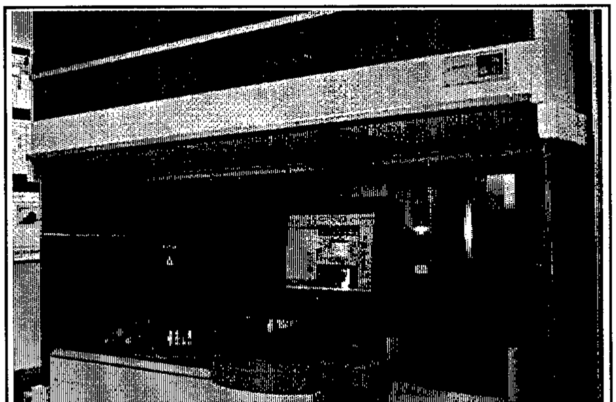

Figure 4. MEMS wafer level reliability test system.

We believe that the next logical step in MEMS reliability testing must also follow the path followed in the IC industry, to wafer level reliability testing. While this will result in faster testing of statistically significant numbers of parts, it will also allow the complicating effects of packaging to be removed from the study. Just as for the packaged part system, this system must contain a method for interfacing electrical signals, optically monitoring the MEMS structure and controlling the test environment, especially humidity and temperature. The first two of these three requirements have been implemented (Fig. 4) in a Cascade Microtech PS21 prober installed in a Class 1 (measured) airshower. Once fully operational this wafer prober will allow released but undiced MEMS structures to be tested and returned to the fabrication line.

THE SECOND RELIABILITY CHALLENGE: IDENTIFYING AND ACCELERATING MEMS FAILURE MECHANISMS

Practical long-term reliability tests cannot be performed at use conditions due to the excessively long tests that would be required. In order to achieve practical failure times during the reliability tests, the failure mechanisms of interest must be accelerated by some means. However, it is important that the conditions under which the test is performed are not excessive enough to excite additional failure mechanisms. Therefore, an understanding of the fundamental failure mechanisms of MEMS and their underlying physics is a major challenge that must be met.

Much work has been done on the fracture mechanics of polysilicon [6]. Eventually, fracture may be an issue as designs are optimized for maximum force with minimum size. However, fracture is not currently a major reliability limiter [2, 7].

Stiction, the mechanism by which released MEMS structures are attracted and stick to each other [8], has been a major yield limiter. Improved release etches and drying schemes such as super-critical CO_2 drying have done much to lessen its impact. It is conceivable that under high humidity environments, stiction may also play a role in reliability by causing structures that should not be in contact to stick.

Evidence now exists [7] that wear is the primary failure mechanism for MEMS actuators that involve sliding motion (Figure 5). There are seven primary wear failure mechanisms observed for macroscopic mechanical systems [9]: adhesion, abrasion, corrosion, surface fatigue, deformation, impact and fretting wear. Due to the microscopic nature of these mechanisms, we would expect that one of them (as opposed to some other mechanism) would be responsible for the wear-out of micromachines.

Figure 5. Particles and out-of-round pin joint hole provide evidence for wear at sliding surfaces of MEMS actuator.

In a series of experiments detailed in reference [7] negligible radial force and 3 μN of tangential force was applied to drive micromachined gears. At forces above approximately 4 μN the nature of the frictional forces in these engines is known to change abruptly [10] and result in observable wear tracks [11] characteristic of abrasive wear [9]. No wear tracks were expected nor evident during these tests.

There was no evidence of corrosion byproducts, ruling this wear mechanism out. Finally, surface fatigue, deformation and impact wear typically require forces in excess of those for abrasive wear. Again such forces were not applied. Fretting wear occurs where

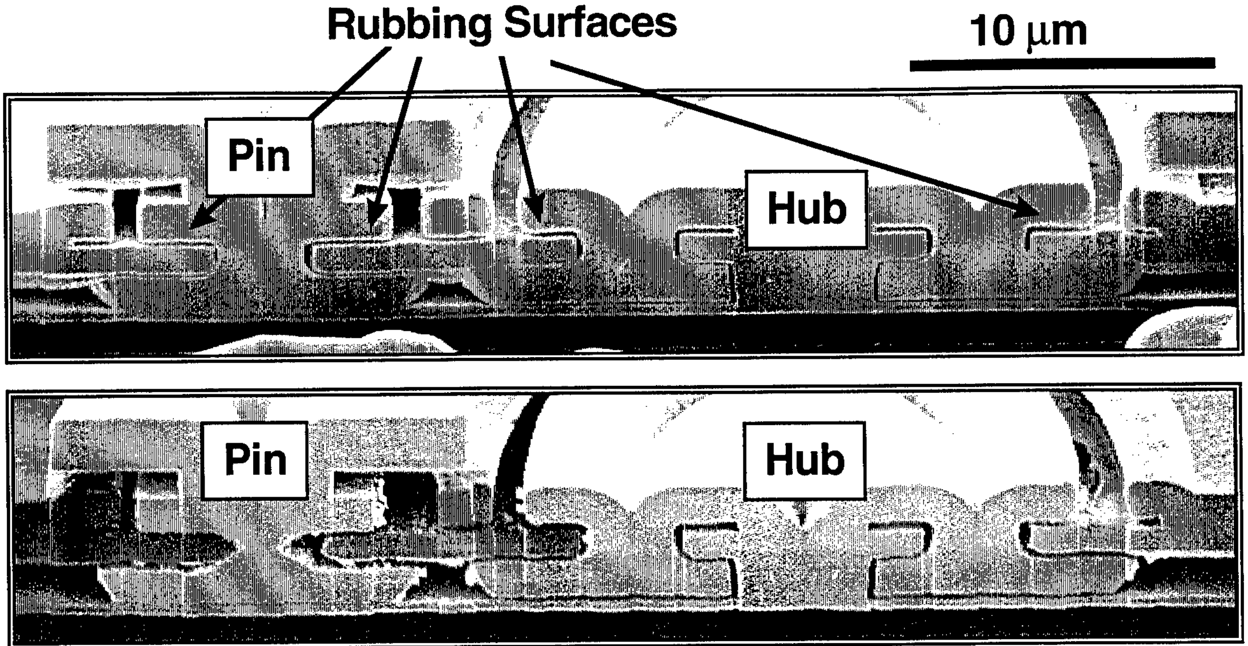

Figure 6. FIB cross sections of a microengine which was not tested (above) and shows no wear debris, and an engine which was tested to failure (below) in 480K cycles. Note the severe wear on the pin joint and wear debris at bearing surfaces.

machine elements experience fluctuating loads, leading to microcracks and fatigue failure. They have not been observed.

These data suggest that adhesive wear is the most likely explanation for the wear and failure seen in MEMS gears. A micrograph (Fig. 6) of a focused ion beam (FIB) cross section, shows typical results both before and after stress testing.

THE THIRD RELIABILITY CHALLENGE: A PREDICTIVE PHYSICAL RELIABILITY MODEL

It is critical that a failure model be developed that describes the physics of failure and allows prediction of ultimate failure in any final design. To do so the failure mode(s) must be established from statistically significant data.

Adhesive Failure Model

Although a combination of wear mechanisms would probably provide the most complete model, we have proposed adhesive wear as the most likely prevalent mechanism responsible for failure in these micromachines [7]. Adhesive wear occurs when contact of asperities between two solid bodies (Figure 7a) leads to plastic flow and cold welding (Figure 7b). The asperity then tears away, leaving a particle transferred to one surface (Figure 7c). In this way, material can transfer from one surface to another and result in regions where the micromachine can begin to catch and then fail, as observed.

The derivation of the model for adhesive failure begins by assuming that there is some critical volume, V_c , of material that must be transferred in order to stop the motion of the micromachine. We anticipate that V_c is not a single number but is a distribution of values.

In adhesive wear, the relationship between the wear volume ΔV, and the length of the motion producing the wear, ΔL is given as [9]:

$$\Delta V = \Delta L\left(\frac{KF}{9\sigma_{yp}}\right) \quad (1)$$

where K is the adhesive wear constant
F is the force on the joint and
σ_{yp} is the uniaxial yield strength

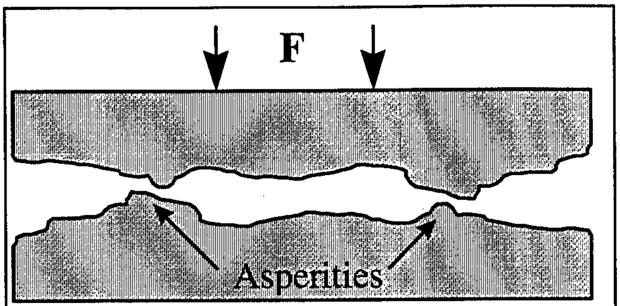

Figure 7a. Force F_r brings the two surfaces into contact at the asperities.

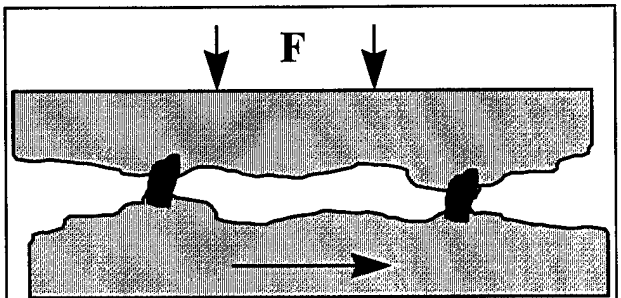

Figure 7b. As the lower surface moves the asperities cold weld together.

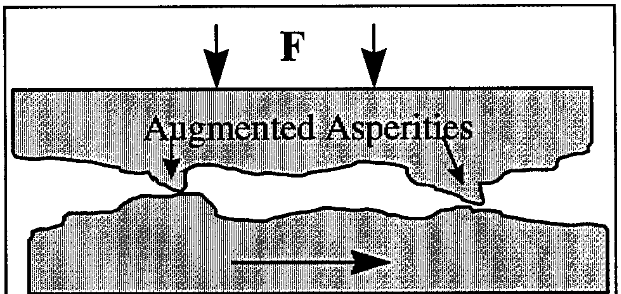

Figure 7c. As the lower surface continues to move, the metal breaks free again, leading to the augmented asperities on the upper surface.

The total length of the motion creating the wear is then related to the radius of the joint, *r*, and the number of revolutions, *R*, that the engine makes by:

$$\Delta L = 2\pi r R \tag{2}$$

Bringing equations (1) and (2) together, setting ΔV to V_c, the critical volume for failure and R to R_f, the number of revolutions to failure and solving for R_f we get:

$$R_f = \left(\frac{9}{2\pi}\right)\left(\frac{\sigma_{yp}}{K}\right)\frac{V_c}{rF} \tag{3}$$

The true force on the joint will vary with excitation frequency, ω, as the critical frequency, ω_o, for resonance is approached provided that either the drive signal is a pure sine wave (which it is not) or is a custom signal intended to account for inertial effects (which it is) but applied to a system that has some play in the joints. The joints have approximately 50% tolerance as measured by the total diametrical gap divided by the joint size.

In such a case, the net force on the joint will increase as the frequency approaches the critical frequency as [12]:

$$F = F_n\left[\frac{1}{\sqrt{\left[1-\left(\frac{\omega}{\omega_o}\right)^2\right]^2+\left(\frac{1}{Q}\frac{\omega}{\omega_o}\right)^2}}\right] \tag{4}$$

where the term in large square brackets represents a "magnification factor" caused by approach to resonance and

- F_n is the nominal force applied to the joint,
- Q is the "quality factor" of the damped harmonic mechanical system and
- ω / ω_o is the ratio of the driving frequency to the resonant frequency of the system.

Combining equations (3) and (4) we now arrive at the complete description for the reliability of a MEMS actuator failing due to adhesive wear, where again R_f represents the median number of revolutions to failure.

$$R_f = \left(\frac{9}{2\pi}\right)\left(\frac{\sigma_{yp}}{K}\right)\frac{V_c}{rF_n}\left[\sqrt{\left[1-\left(\frac{\omega}{\omega_o}\right)^2\right]^2+\left(\frac{1}{Q}\frac{\omega}{\omega_o}\right)^2}\right]$$

Note that there are no adjustable parameters. All values are either physical constants that are material dependent and known or have been measured or set in running the experiment. V_c, the critical volume of adhered material, can be estimated from known physical parameters [7]. Table 1 has the values of the model parameters and the corresponding references. Figure 8 shows the measured reliability data as compared to the model. Note how well the model describes the data.

Table 1. Failure model parameters

Variable	Parameter	Value	Ref.
σ_{yp}	uniaxial yield strength	1.2x10^{-3} N/μm^2	[14]
K	adhesive wear constant	4x10^{-7}	[13]
V_c	critical volume	1.25x10^{-4} μm^3	[7]
r	pin joint radius	1μm	measured
F_n	applied force	3x10^{-6} N	[10]
ω_o	resonant freq.	1150 Hz	measured
Q	quality factor	1.1	measured

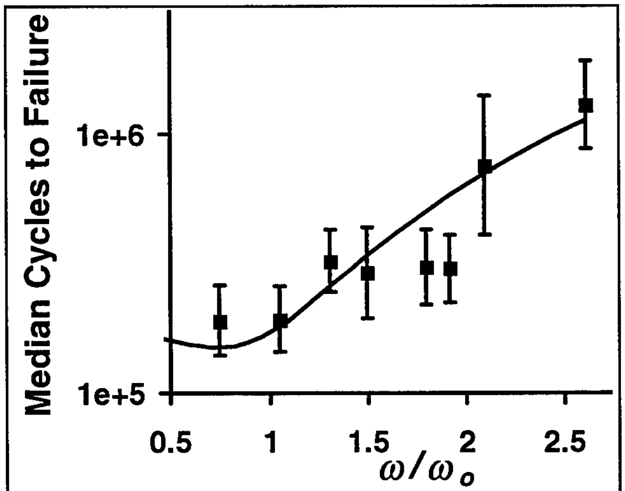

Figure 8. Comparison of failure data to the proposed adhesive wear model. The value of K = 1.1x10^{-7} was used in the model to generate the solid line.

CONCLUSION

MicroElectroMechanical Systems offer great promise as sensors and actuators in several critical applications. In order for MEMS to achieve the full potential of their promise, the challenge of reliability must be met. In order to rapidly take advantage of this technology, reliability must be considered concurrently with technology development. Statistical significance of the reliability results requires a new class of test systems built to handle the electrical, optical and environmental requirements of MEMS. Custom systems meeting these requirements have been built, but the industry awaits major manufacturers to step up to the challenge of providing this infrastructure to the rapidly evolving MEMS industry. Given that MEMS reliability must be rapidly assessed, we must focus on the critical failure mechanisms and develop techniques to accelerate these failures. This will both require and result in the creation of physical models of failure that will allow the prediction of reliability from first principles and measured parameters. Initial work in this area indicates that fracture, which has been commonly studied as a major reliability limiter is not so. Rather wear, whether adhesive or abrasive, may be the ultimate limiter of reliability, at least in MEMS actuators.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the personnel of the Microelectronics Development Laboratory for fabricating, releasing and packaging the MEMS devices described in this paper. Special thanks goes to Paul McWhorter whose vision made Sandia's MEMS program what it is today and to Michael Callahan for funding much of the original work in the area.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94-AL85000.

REFERENCES

[1] Dr. R. S. Payne, Presentation 1.1, *1998 International Reliability Physics Symposium.*

[2] M. R. Douglass, "Lifetime Estimates and Unique Failure Mechanisms of the Digital Micromirror Device (DMD)," *1998 IEEE International Reliability Physics Symposium Proceedings,* pp. 9-16, (1998).

[3] S. Verdonckt-Vanderbroek, "Micromachining Technology for Thermal Ink Jet Products," in *Micromachined Devices and*

Components III, Proc. of SPIE, Vol. 3224, pp. 180-184, (1997).
[4] Sid Marshall, *Micromachine Devices*, 1997.
[5] D. M. Tanner, N. F. Smith, D. J. Bowman, W. P. Eaton and K. A. Peterson, " First Test of a Surface Micromachined Microengine Using SHiMMeR," in *Micromachined Devices and Components III*, Proc. of SPIE, Vol. 3224, pp. 14-23, (1997).
[6] W. Tang, C. Muhlstein and S. Brown, "Survey of MEMS Processes and Failure Mechanisms," Tutorial Notes, *1998 IEEE International Reliability Physics Symposium*, pp. 4a.1-4b.17, (1998).
[7] D. M. Tanner, W. M. Miller, W. P. Eaton, L. W. Irwin, K. A. Peterson, M. T. Dugger, D. C. Senft, N. F. Smith, P. Tangyunyong and S. L. Miller, "The Effect of Frequency on the Lifetime of a Surface Micromachined Microengine Driving a Load," *1998 IEEE International Reliability Physics Symposium Proceedings,* pp. 26-35, (1998).
[8] S. L. Miller, M. S. Rodgers, G. LaVigne, J. J. Sniegowski, P. Clews, D. M. Tanner and K. A. Peterson, "Failure Modes in Surface Micromachined MicroElectroMechanical Actuators," *1998 IEEE International Reliability Physics Symposium Proceedings,* pp. 17-25, (1998).
[9] J. A. Collins, *Failure of Materials in Mechanical Design*, New York, John Wiley & Sons, Inc., 1981.
[10] S. L. Miller, J. J. Sniegowski, G. LaVigne and P. J. McWhorter, "Friction in Surface Micromachined Microengines," *Proc. Of SPIE Smart Electronics and MEMS*, Vol. 2722, pp. 197-204, (1996).
[11] S. L. Miller, J. J. Sniegowski, G. LaVigne, and P. J. McWhorter, "Performance Tradeoffs for a Surface Micromachined Microengine," in Proc. of SPIE Micromachined Devices and Components II, Vol. 2882, pp. 182-191, (1996).
[12] C. R. Freberg and E. N. Kemler , *Elements of Mechanical Vibration, 2nd ed.,* New York, John Wiley & Sons, Inc. (1949).
[13] Ernest Rabinowicz, *Friction and Wear of Materials*, 2nd ed., New York, John Wiley & Sons, Inc., 1995.
[14] W. N. Sharpe, Jr, B. Yuan, R. Vaidyanathan and R. L. Edwards, "Measurements of Young's Modulus, Poisson's Ratio and Tensile Strength of Polysilicon," *Proc. MEMS 97, 10th IEEE Inter. Workshop on MicroElectroMechanical Systems*, pp. 424-429.

Report Number (14) SAND --98-0630C
CONF-980558--

Publ. Date (11) 199805
Sponsor Code (18) DOE/DP, XF
UC Category (19) UC-700, DOE/ER