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Engineering Report

Preliminary Sizings for an Integrated SME Actuator System for the STAR system

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Background

Shape Memory Alloys:

The Shape Memory Effect (SME) is due to a first order martensitic phase transformation from a low modulus martensitic phase to a high modulus austenitic phase. Relevant phase transformation temperatures are denoted as M_f (Martensitic finish temperature) below which the material is fully martensitic and A_f (Austenitic finish temperature) above which the material is fully austenitic. The shear modulus generally changes very dramatically as the material becomes martensitic, from approximately (10 to 4)x10^6 Psi (68 GPa to 26 GPa). Macroscopically, when martensitic the material is easily deformed and can accommodate up to 8% local strain. When heated through the transformation, the material reverts to its so-called hot shape, which is set by constrained annealing at 923 °F (500°C).

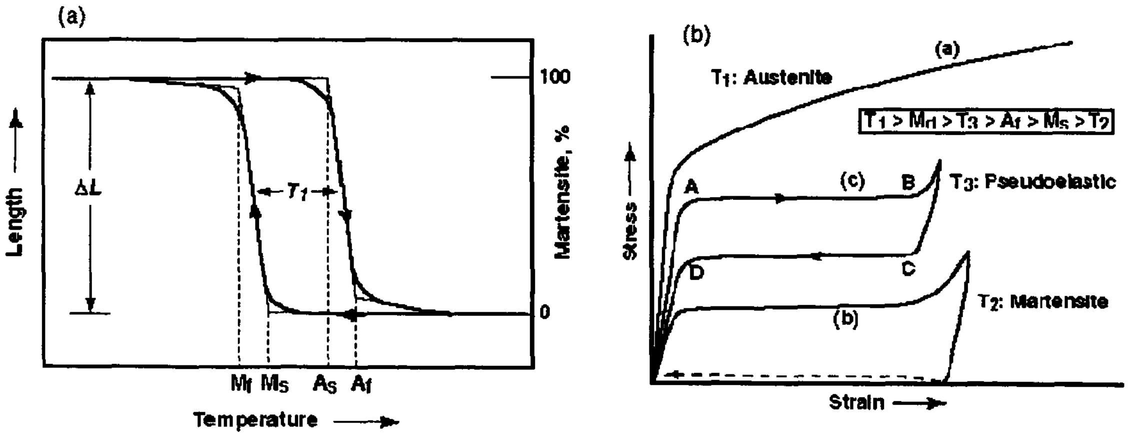

Figure 1: (a) The SME transformation is defined by four temperatures. Of particular relevance to device applications are Mf, the martensite finish temp and Af, the austenite finish temperature. Above and below these temps, the alloy is entirely in one phase. (b) Schematic of a typical stress-strain curves with for TiNi. In its Pseudoelastic or Superelastic range at T3, the closed loop hysteretic behavior can be used as a pressure switch.

TiNi, a binary mixture of Titanium and Nickel, has become the alloy of choice for Shape Memory applications. Of primary importance is that the material can be tailored for a variety of transformation temperatures, which is primarily based on the precise alloy composition and secondarily influenced by heat treating, external stresses and coatings. Because of this, the alloy can exhibit two main stress-strain behaviors at room temperature, depending on whether the alloy transforms above or below room temperature. For alloys with transformation temperatures above room temperature, the stress-strain behavior is shape memory effect, where the low temperature martensitic phase is easily deformed and reverts to the high temperature austenitic hot shape when heat is applied. Without external loads, the material will recover all of its hot shape. If the alloy transforms below room temperature (say at 32 °F), then at 70 °F the material is austenitic, however the application of stress will cause the material to transform to martensite isothermally, at which point it can be deformed. Upon removal of the external stress, the material will attempt to retransform back to austenite, and consequently exerts a positive force to recover back to its original shape. This is the so-called super-elastic effect.

Competitive materials

What makes SMA's attractive over the other "smart" actuator materials is their unique ability to handle large strains (up to 8%). Piezoelectric and magnetostrictive materials can certainly handle the thermal extremes encountered in low earth orbit, however the 0.2% maximum top strains and the brittle nature of the materials makes conformal integration of actuators challenging. In addition, their sensitivity to stray electric and magnetic fields provide additional challenges to their integration at the system level.

Piezoelectric and MR actuators have relatively low Curie temperatures. For example a standard PZT-5H ceramic has a Curie temperature of 190C while Terfenol-D (MR actuators) has a Curie temperature of 300C. Furthermore, the operating temperatures for these materials are typically limited to approximately half of the Curie temperatures (e.g. PZT-5H 90C). In addition to operating difficulties at elevated temperatures, these materials do not perform well below 100 °C, due to polarization/magnetization limiting events.

TiNi, as a thermally controlled material, is insensitive to stray electromagnetic fields. Thermal variations in standard rotorcraft operations can be severe, however by selecting an alloy with transformation temperatures about the thermal noise level, actuation authority is achieved. So, the key to space based applications for TiNi is the selection of the correct alloy composition. SME transformation temperatures are very sensitive to the chemical composition of the alloy. Compositional deviations of 1% Ni rich will dramatically change the A_f to -100 °C. As seen in Figure 2, there are known compositions of the alloy which would fit well into aerospace applications. Typically a 50 at.% Ti-Ni composition is used, which then transforms at 100C and therefore achieves the required actuator control. Dopants such as Hf, Pd can be added if necessary to generate higher transformation temperatures.

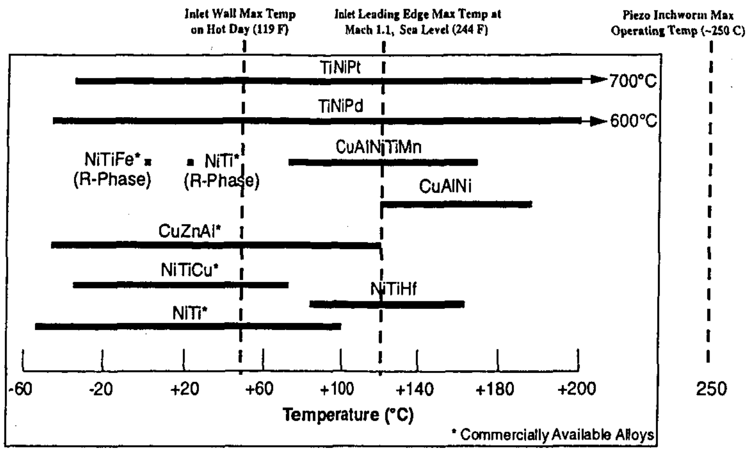

Figure 2: Phase transformation temperatures for TiNi and Cu based Shape Memory Alloys.

MEMS device has been the subject of intensive study for a wide variety of controls; examples include flow control, industrial machine motion control, and actuators for medical devices and for space deployment. Of the systems investigated, shape memory alloys have higher (i.e., an order of magnitude) work density than any other actuator materials. A comparison is shown in the following table:

MEMS Actuator Materials

Actuator Type	Work Density 10^6 J/m^3
Shape Memory Alloy	50
Solid Liquid Phase Change	4.7
Thermo-pneumatic	1.2
D.C, Magnetic	0.9
Bi-Metallic	0.5
Thermal Expansion	0.4
Electrostatic	0.4
Piezoelectric	0.1

The high work density of the shape memory devices equates to a conformal actuator n that would be much thinner for membrane actuation and still provides output forces high enough to overcome the inertial resistance in the polymeric membranes.

Frequency: As a thin film, the frequency response of the TiNi actuators are rapid. Projected response times depend on the thermal mass of the thin film, with response time decreasing with decreasing thermal mass, but primarily due to good conduction thermal paths. In room temperature operation, we have driven the thin film to 100Hz. With optimized cooling paths, this actuation frequency can increase. Modeling efforts suggest that 2 KHz is the likely upper bound for practically sized TiNi thin films, although inefficiencies and less that ideal conditions will decrease the operational frequency response.

Engineering Design for the STAR Configuration

1. Feasibility and sizing studies of the actuation requirements (force, frequency, displacement) for the STAR configuration.

    1. The Star configuration as shown in Figure 3 consists of three legs of an aperature of total diameter of 2.5 m diameter. For the purposes of this initial study for actuator requirements, several assumptions were made. For support, we assumed that the membrane was Upilex of a thickness of 0.010" thick, and with a modulus of approximately YYY. Upilex was chosen as being relatively commercially available and is compatible with either TiNi or AuCd manufacture.
    2. We confined the areas in which we could apply actuators to the shaded areas in Figure 3, which were three strips of length 2.5 meters and width of 0.1 m. This brings the problem to a solution of a strip.

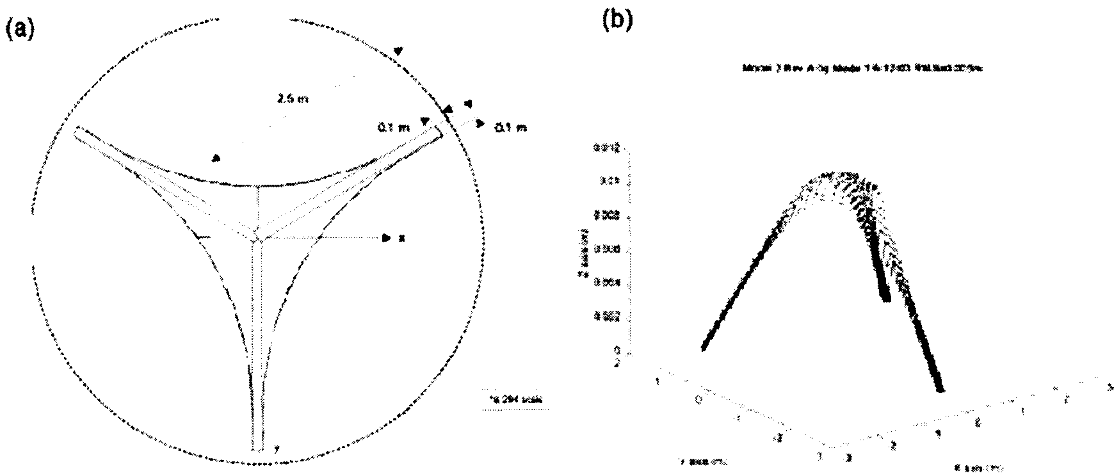

Figure 3(a) Schematic of the 1/3 rd scale version of the STAR radiometer aperture. Blue areas indicate areas in which SMA materials could be applied. (b) RMS first mode displacement data from modeling efforts by NASA LARC, demonstrating large 0.12m displacements in the STAR membrane at 0g.

Typically, 8 microns of TiNi material can be used for actuation. In the first case, we consider a continuous sheet of TiNi/Upilex material. Taking a resisitivity of 80 micro-ohm-cm for TiNi, then the sheet resistance is 2.5 ohms.

There is a certain lack of definition in terms of membrane material and thicknesses, as well as connection schemes, which will ultimately affect the distribution and geometry of the SME thin film actuators chosen. Consequently, for the purposes of calculation, several assumptions were made.

1. We assumed a CP-1 membrane approximately 100 microns thick. This assumption is relatively safe, the stiffness modulii of either CP-1, Kapton or Upilex are relatively similar as compared to TiNi.
2. Based on assumption (1), a 10 Hz correction rate for shape correction of the mode shape, based on a simple circular membrane of 2.5 m in diameter. This genereated 3 modes for Upilex, each with modes in the sub-Hertz frequency. If we consider a leg of the element to be 2.5 m by 0.1 m, and each edge is simply supported, then the range of 1^{st} resonance frequencies is approximately 50 Hz. This is complicated by the addition of effective point masses which are distributed around the Stars configuration. For the purposes of argument, we have assumed that they are sufficiently small and light to have no effect on the vibration properties of the membrane, although this is reminiscent of approximating a horse to be a sphere.
3. Due to the thinness of the membrane, and the sandwiched layer it is composed of, Pro-E FEM models become unwieldy to use due as the grid size and number of elements becomes too large for our computation capacity. Consequently, where possible we used exact analytical solutions to demonstrate feasibility of the technology.
4. The initial parabolic set of the STAR configuration is not established at present. As such, several differing ratios of z to d were considered, where z is the maximum displacement of the paraboloid from its planar condition and d is the diameter of the paraboloid. As the membrane is actuated under fixed edge conditions, the mirror contracts a maximum displacement Δz, as defined by Figure 4.

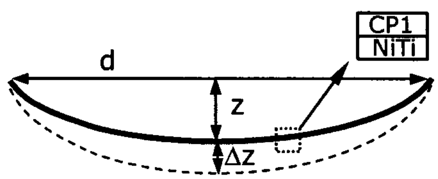

Figure 4: Initial geometry considered for the displacement of the mirror under actuation.

First Case: Uniformly Coated TiNi mirrors for Deployment:

Using the case of a uniformly coated SME TiNi membrane over 75 microns of material, and again assuming a circular membrane, the strains generated on actuation of either 3% for reproducible actuation or 8% for an effective "one-shot" actuator performance will generate a large amount of force and will also allow the article to deploy into a parabolic shape. As seen in Figure 5, there is a net contraction of over 0.30m for a 5 diameter circular membrane.

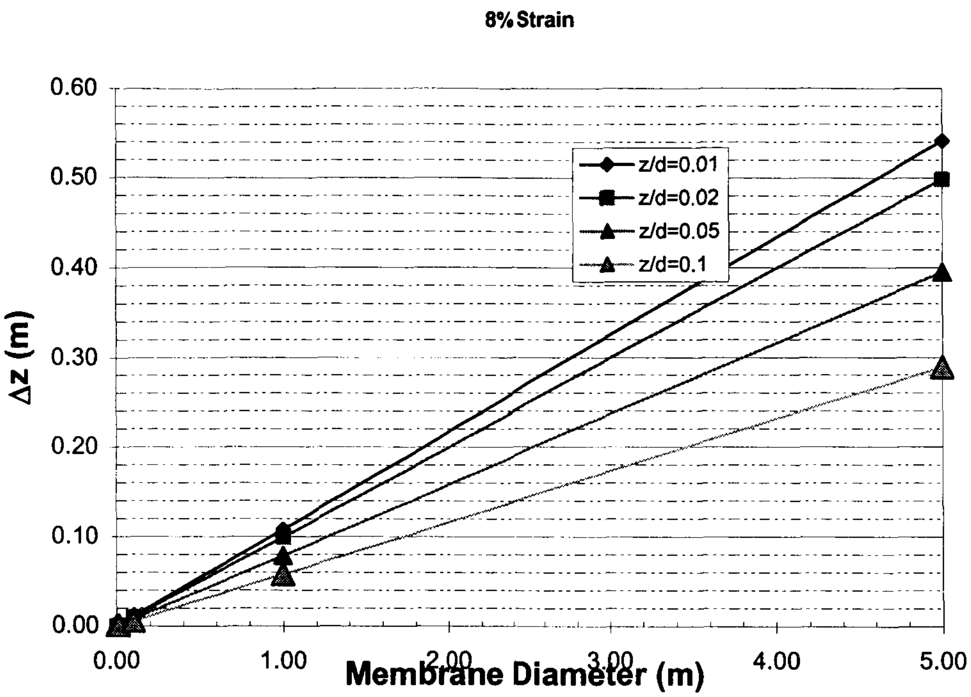

Figure 5: At 8% transformational strains, as the ratio of z/d decreases, the maximum amount of displacement (Δz) increases to 0.56 m, demonstrating a large amount of displacement at 8% strain for (z/d) ratios of 0.1 or less.

As mentioned in the introduction, the fatigue life of the actuators is extremely limited at 8% strain. However, at 3% strain, the fatigue life is on the order of 100,000 cycles, and Figure 6 demonstrates the amount of strain that can be expected for varying z/d ratios of paraboloids. At 5 meter diameter, the maximum displacement is seen to be on the order of 0.12m, which implies a large amount of total corrective power over the range of 5 m. As the diameter of the membranes decreases, there is a linear decrease in the displacement Δz.

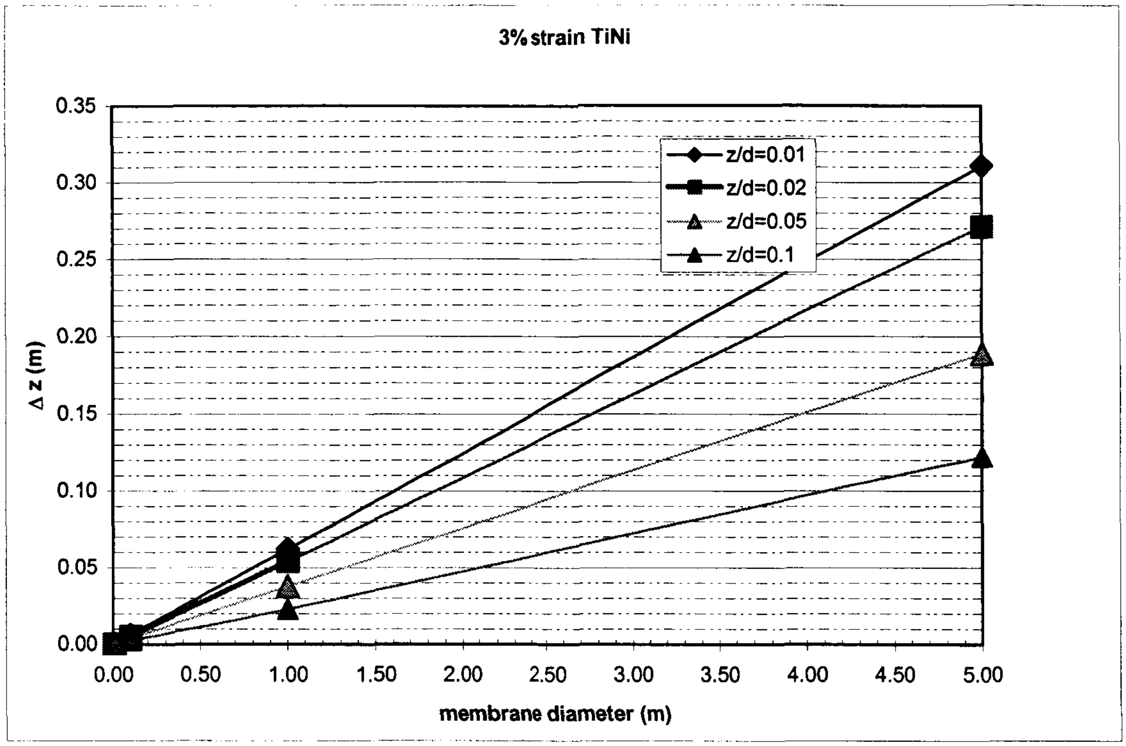

Figure 6: At 3% transformational strains, corresponding to a cyclic fatigue life of 10^5 cycles, the maximum displacements Δz is still large, demonstrating a large amount of shape control on these membrane structures.

Power:

The amount of shape control is far higher than that which can be utilized in for optical correction, unless this is for deployment. In this case, optical heating from solar radiation could be used to generate the shape change, with the choice of a suitable low temperature SME alloy. If this was be powered using electrical energy, which then gives complete actuation authority over the membrane, then the electrical current and power to actuate a continuous thin film membrane would be expected to be relatively high.

To perform these calculations, it was assumed that the radiometer was essentially three legs of 0.10 by 2.5m rectangular legs. The results are shown in Figure 7, which plots the actuation frequency f(dt) against the required current required I(dt). The curmnent requirements for continuous sheets are clearly difficult to see as feasible for active surface control at 20 Hz, but are likely supportable for slow deployment manueuvers.

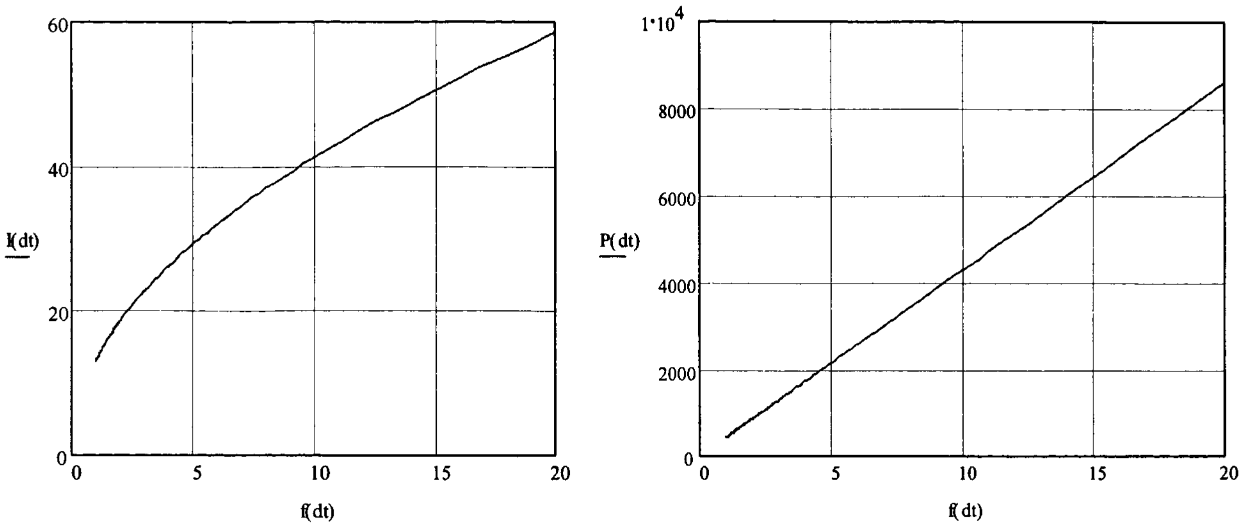

Figure 7: Current I(dt) and Power P(dt) with frequency. As the frequency increases, the power demands escalate dramatically to 9KW for continuous thin film membranes. However, the power and current requirements for deployment are reasonable, with about 1KW required for active deployment at 1Hz. Slower deployments or the use of solar radiation will reduce power demands proportionally or to zero , respectively.

The amount of shape control required is clearly far in excess of what will be required, based on the mode data seen in Figure 3b. As complete actuation of continuous sheets is likely not supportable by subsystems power, a patterned system of SME elements is envisioned on the surface to give us the requisite shape control magnitude at the required frequencies.

Second Case: Patterned Membrane Structures for Continuous Shape Control

A membrane patterned with SME thin film can address the need for continuous shape control. Patterning of the continuous sheets of SME thin film into either continuous line elements or into small circular components increases the effective resistance of the elements while dramatically reducing the current and power requirements. The only concern is that in going from a continuous sheet to line elements, some possibility of actuator bleed-through can occur, but this is more relevant for optical membranes rather than the STAR configuration.

There were several configurations that we looked at both from the point of view of dimensional control actuator sizings and from the point of view of power. Again, as the requirements are still relatively ill-defined, we chose a zigzag line element of width 0.1 cm decorating the 3 arms of the STAR article, and a central membrane to dampen the center of the article, on which to generate power–current relationships and a simple circular actuators to demonstrate shape control to the dimensional level required for the STARS configuration.

The current J(dt) and power P(dt) are shown in Figure 9. As seen the power requirements are dropping substantially, and at 20 Hz operation, the power requirements are approximately 120W.

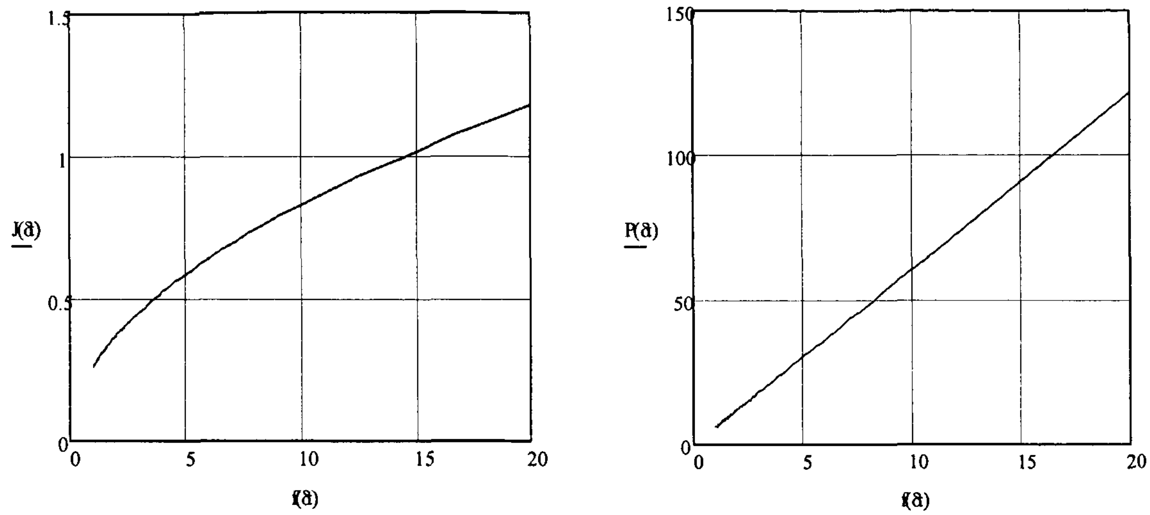

Figure 9: Current and Power Relationships for Shape Control using line elements

The following table was assembled to demonstrate that the scaling of the membranes is linear with membrane diameter. Three different transformational strains were considered, 8%, 3% and 0.3%, where the latter would be indicative of active control of the membrane. Parabolic depth ratios from z/d=0.01 to z/d=1.0 were addressed.

The modeling activities that we embarked upon have demonstrated that shape control can be achieved using thin film SME elements, and that at actuation forces approaching 20 Hz, a modest amount of power is required. The difficulties in generating more precise analytical predictions lies in the need for an iterative procedure to be developed such that the effect of the SME on the modal positions and magnitudes can be included in NASA models, which in turn can be used to develop more accurate TiNi thin film placements. For example, the TiNi SME material is a relatively lossy material when martensitic, which would dampen the RMS vibrations which would reduce the membrane diameters. and the power requirements. If the membranes now stiffen the structure, the RMS values are further decreased, but the modal frequencies increase, which would increase power requirements.

8% Strain					
d(m)	0.001	0.010	0.100	1.000	5.000
z/d=0.01	1.082E-04	1.082E-03	1.082E-02	1.082E-01	5.414E-01
z/d=0.02	9.970E-05	9.970E-04	9.970E-03	9.970E-02	4.982E-01
z/d=0.05	7.890E-05	7.890E-04	7.890E-03	7.890E-02	3.949E-01
z/d=0.1	5.700E-05	5.700E-04	5.700E-03	5.800E-02	2.887E-01

3% Strain					
d(m)	0.001	0.01	0.1	1	5
z/d=0.01	6.200E-05	6.200E-04	6.200E-03	6.200E-02	3.110E-01
z/d=0.02	5.430E-05	5.430E-04	5.430E-03	5.430E-02	2.714E-01
z/d=0.05	3.780E-05	3.780E-04	3.780E-03	3.780E-02	1.887E-01
z/d=0.1	2.300E-05	2.300E-04	2.300E-03	2.300E-02	1.221E-01

0.3% Strain					
d(m)	0.001	0.010	0.100	1.000	5.000
z/d=0.01	6.200E-05	6.200E-04	6.200E-03	6.200E-02	3.110E-01
z/d=0.02	1.010E-05	1.010E-04	1.010E-03	1.010E-02	5.080E-02
z/d=0.05	5.000E-06	5.000E-05	5.000E-04	5.000E-03	2.460E-02
z/d=0.1	2.720E-06	2.720E-05	2.720E-04	2.720E-03	1.340E-02

Table 1: Membrane deflections Δz (m) for parabolas with differing membrane diameters and z/d ratios, for deployment strains of 8%, long fatigue life strains of 3% and active control as represented by 0.3% strain.

Technology Development of a Full –Scale Article:

There have been two important internal advances since we initiated this preliminary study:

- SCT has received AFRL funding to develop a 1m scale TiNi/CP-1 articles with SRS technology.
- SCT has developed the technology for developing AuCd SME with AFOSR Phase I STTR funding. Although the Phase I is now coming to an end, results were demonstrated for a scaleable deposition technology for membrane diameters consistent with the full-scale STAR article.

Thin film TiNi is a more mature technology, but the practical dimensions to which it can be extended to have yet to be established. The development of 1m diameter material will be the largest area continuous TiNi optical membrane fabricated. Ultra-High Vacuum sputtering onto a roll of film is one-way to generate large surface area material, but only if can be developed to allow for the application of the TiNi onto another membrane structure that is nominally seamless and uniform in both adhesion and areal density. In the STAR configuration, with suspended radiometers, these issues may not be as important as for a optical mirror, where wrinkling and bleedthrough issues dominate.

In contrast, the AuCd route uses an electro-deposition technique which extends the diameter practically to extremely large dimensions. By effectively "painting" the material onto the membrane in air, and then annealing under modest temperature and vacuum conditions (220C, 10^{-3} Torr), this technique offers a reasonably straightforward route to the development of large area structures. The concern with the AuCd thin films is the palatable lack of data on the system from a thin film perspective. Consequently in adopting purely an AuCd route, there is some risk in terms of the fundamental materials science development needing further work.

The technology roadmap to a flight test article is seen in Figure 11. This roadmap is specifically addressing the development of TiNi and AuCd materials to generate a full-scale STARS article. For both materials, we have succeeded in moving the technology from a fundamental level of TRL 1 to TRL 2, although as stated previously, the AuCd work is significantly less mature than the TiNi work, which is probably a TRL 3 technology at the time this waterfall chart exists.

There are two key areas of development that require development, namely better modeling to easily handle membranes and the materials characterization, and these are stressed in the initial stages of the waterfall. Modeling of large scale membranes is not within the expertise of Shape Change Technologies, which specializes in near-net shape Shape Memory Alloy Development., and so is best put on the shoulders of NASA engineers or the Universities. SCT works closely with Prof Carman at UCLA and there are a number of new code packages emerging from NASA JPL which also address reasonably efficient modeling of complex membrane structures.

With sufficient funding both at NASA, universities and at SCT, a TRL level of 5 should be achievable by the end of 2006. Further maturity of the concept after that level is largely a NASA and SCT endeavour, as the testing of 5 m articles is out of the range of most small company resources.

The last series of waterfall tasks are largely speculative, as the problems involved in maturing any gossamer or membrane structure have not been attempted to the authors knowledge.

Summary

- The STAR configuration offers some unique challenges to thin film conformal actuators for shape control. Using several reasonable approximations, a power requirement of 120 W may be required for damping and shape control of the structure.
- Modeling to generate better data of the membrane system is clearly required in order to generate better estimates for power requirements, mode shapes and frequencies.

- Continous thin films, using solar power to heat, would seem to generate sufficient displacements for deployment.
- For the STAR configuration, TiNi rolls could be developed which would provide sufficient material maturity to generate large scale STAR membrane structures.

	2004	2004	2005	2005	2006	2006	2007	2007	2008	2008
	1st Half	2nd Half	1st Half	2nd Half	1st Half	2nd Half	1st Half	2nd Half	1st Half	2nd Half
[redacted]										
2	Materials Chem. Coupon Dev.	Coupon Test and Optimization								
3	system benefits study	modeling development	Sub-scale Panel Modeling	Sub-scale Panel Manufacturing						
4				Sub-scale Panel Test Facility Dev.	Sub-scale panel: cyclic testing					
5					Sub-Scale modelling correlations	Sub-Scale Panel: Temp, Vibration				
6						Full Scale Panel Design	Full Scale Panel Assemble			
7								Panel Subsystem Integration	Panel Subsystem Testing	
8										Flight Test

Figure 11: Technology waterfall for developing large scale membranes for the STAR system.