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QUASI-WELD-FREE BELLOWS

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Final Report

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13. Supplementary Notes

14. Abstract This research investigated the merits of certain novel bellows designs for use in Stirling and pulse tube cryocooler compressors as an alternative to the present state of the art which uses flexure bearings. The Quasi-Weld-free (QWF) bellows incorporates the low dead volume of welded bellows and high fatigue life of formed bellows. There was also a secondary goal to investigate the merits of alternate materials. The design started with Roark-Laupa approximations to develop a preliminary baseline. The primary design effort started by developing a curve fit from the Expansion Joint Manufactures Association (EJMA) handbook (applicable to many different applications). The final design work was accomplished using Finite Element Analysis (FEA). The design analysis found the following: life is very sensitive to small changes in operating parameters, variable thickness bellows are promising, EJMA and FEA showed reasonable agreement. No hardware was fabricated but techniques were investigated.

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Executive Summary

Cryocoolers for space applications require a 5 - 7 year life with low vibration, and high efficiency. Stirling and pulse tube cryocoolers present two of the primary options for meeting the present space cryocooler needs. The state of the art for these types of cryocoolers use the flexure bearing approach to suspend an oscillating piston which generates an oscillating pressure wave. The primary disadvantage to this approach is that it requires extremely close tolerances and alignment to maintain a clearance seal gap. The primary objective of the research was to investigate an option to the flexure bearing compressor through the use of "Quasi Weld Free Bellows" (QWF). A secondary objective was to investigate the merits of alternate materials and manufacturing techniques.

Bellows offer their own strengths and weaknesses when applied to long life cryocoolers. Standard formed bellows offer the rounded formed convolutions necessary for long fatigue life. However, these rounded formed convolutions inherently have a large void volume which drastically decreases the compressor efficiency. Another option is the standard welded bellows which have sharp convolutions known for shorter fatigue life but a low dead volume leading to better efficiency. The QWF approach attempts to apply the best of both approaches to one design. The proof of concept models were to bond the inside radius of formed bellows to the outside radius of welded bellows. Thus, the formed bellows approach would be used in the area of highest fatigue stresses and the welded bellows used in the area of lower fatigue stresses to reduce the void volume.

The approach was broken into 6 tasks. The tasks were as follows.

Task 1: Functional Definition and Design. This task sought to define typical applications and design variables.

Task 2 and 3: Design Analysis and Detailed Design. These tasks called for applying various analytical methods to investigate the performance of various designs and to seek optimal designs. Specifically, these tasks started with Roark-Laupa approximations to develop a preliminary baseline. The primary design effort started by developing a curve fit from the Expansion Joint Manufacturers Association (EJMA) handbook (applicable to many different applications and possibly the most useful knowledge gained in this program). The final design work was accomplished using Finite Element Analysis (FEA).

Task 4: Manufacture. This task called for the fabrication of typical prototype bellows. This task was not actually accomplished due to funding.

Task 5: Test Program. This task called for the preliminary fatigue testing of the prototype bellows fabricated in Task 4. This task was not actually accomplished do to funding.

Task 6: Final Report

The primary investigator had two sets of performance goals for which to design. The two sets of goals were provided by a commercial partner and the Air Force technical monitor. The commercial partner goals were as follows:

Stroke:	≥ 5 inches (2 extension and 3 compression)
Inside Diameter:	≥ 1.25 inches
Outside Diameter:	"Reasonable" (taken as < 6 inches)
Maximum Length:	30 inches
Pressure:	50-100 psi
Temperature:	Room to moderately high (taken as 300° F)
Frequency:	400 RPM
Life:	10^8 cycles
Dead Volume:	Not significant
Other:	Must be inexpensive enough for commercial use (taken as a few hundred dollars)

Several problems were experienced in this effort because there was not enough money available to perform the large spectrum of work originally planned. The end result was that no hardware was fabricated or tested. However, some fabrication techniques were investigated which included furnace brazing, inertial welding, and electromagnetic discharge machining (EDM). The studies found none of these approaches suitable for QWF bellows. In addition, alternate materials and fabrication techniques were investigated. These included electroformed nickel, machined bellows and other materials. The only promising approach was electroformed nickel but the cost could be prohibitive for commercial use.

In conclusion, a possible design for the commercial application was found (none was found for the Air Force space application) but not fabricated or tested. The design analysis found the following: life is very sensitive to small changes in operating parameters, variable thickness bellows are promising, EJMA and FEA showed reasonable agreement. An additional useful tool from this study was development of a curve fit of EJMA design factors which are applicable to a wide spectrum of application.

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1.0 INTRODUCTION

This is the final report for a six-month Phase I SBIR project (started May 1994) whose goal was to investigate the merits of certain novel bellows designs that have the potential to greatly extend bellows life.

Nominally, the novel design being investigated was a "Quasi Weld Free Bellows" (QWF) that incorporated the low dead volume of a welded bellows and the high fatigue life of a formed bellows (see Figure 1). However, there was also a secondary goal to investigate the merits of alternate materials (nano crystalline nickel in particular) and manufacturing techniques (such as electroforming). During the course of this project, the merits of variable cross section bellows also became apparent. In what follows, all of these options are included in what is referred to as the "QWF" design.

The work carried out in this project includes:

- A refined project definition. In the course of addressing the original tasks for this project (see below) it became apparent that the number of design approaches, materials, applications and application specifications, and possible areas of investigation were very large. It thus became necessary to modify our original plan to investigate those areas which appeared most fruitful or to resolve unexpected issues, as is appropriate to a research Phase I effort.

  In particular, our efforts to resolve many of the new issues which arose caused us to curtail our efforts to fabricate a prototype bellows, and did not allow us to perform any preliminary tests on prototypes. While this development is unfortunate, we believe that the issues which we did investigate were necessary prior to performing any successful fabrication and testing. These points are presented in the body of this report.

  Further, while this report does present our final Phase I results, project staff continues to investigate further some of the issues discussed herein, as well as investigate other related concepts and approaches.

- The developing of a precise definition of the specific bellows applications. Two specific applications were defined (a commercial compressor and a cryo-cooler), so as to provide a basis for demonstration of the benefit of the design features being investigated.

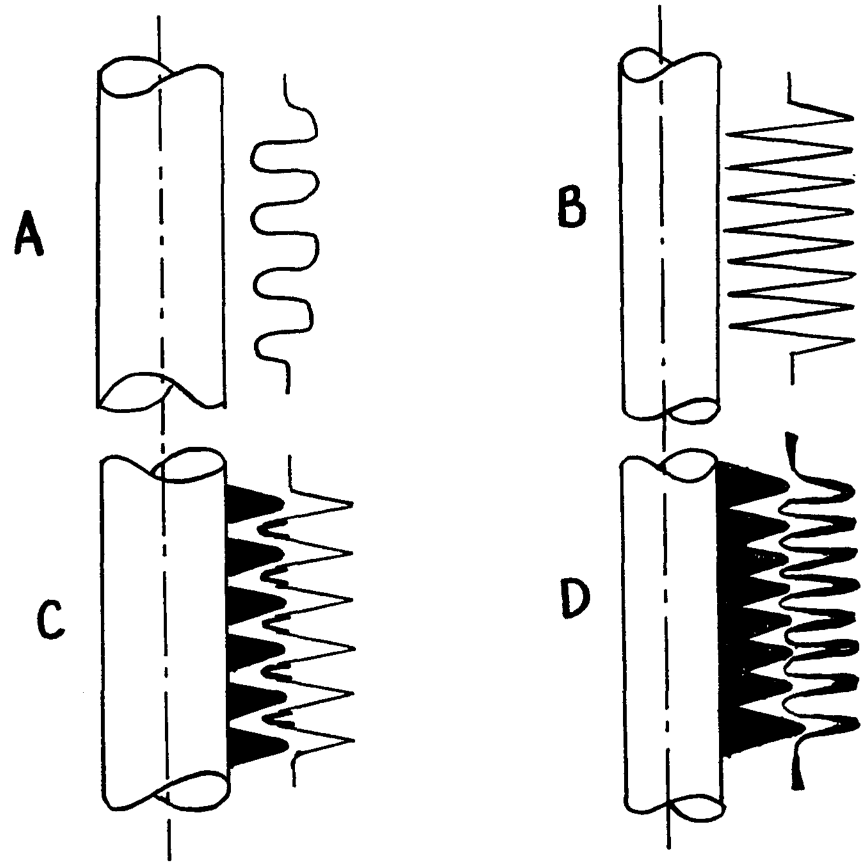

Figure 1. Schematic presentation of bellows concepts.

1. Standard formed bellows. Easy to manufacture, has rounded convolutions which lead to loner fatigue life. Has limits on inner to outer radius ratio which reduce optimality of structural design. Has dead volume which can reduce optimal thermodynamic performance.

2. Standard welded bellows. Can have close to zero dead volume, which leads to improved thermodynamic performance. Can also have almost any inner to outer radius ratio, hence be more optimal structurally. However, has sharp convolutes with weld stress zones which leads to reduced fatigue life.

3. QWF fabricated design. Uses rounded formed convolutions on the inside to reduce stress concentration and increase fatigue life. Fabrication allows almost any inner to outer radius ratio. Can have near zero dead volume because it uses sharp convolutions on the outside and moving spacers to take up the volume on the inside (not drawn to scale). Careful choice of the moving spacer material and design is required to avoid contamination of the working fluid by wear, offgassing, or chemical conversion.

4. QWF continuous variable thickness design. Using techniques such as electroforming, a variable thickness bellows can be manufactured, with thickness continuously changing to meet optimal structural (fatigue) requirements, and using both sharp corners and moving spacers to get near zero dead volume.

- The development of procedures and programs for EJMA and COSMOS FEA models of bellows. This involved the exercising of these programs in the analysis of various bellows and to produce optimal designs for specific applications.

- A compilation of stainless steel fatigue data at very high numbers of cycles (1 to 100 million cycles).

- An investigation into the bellows manufacturing possibilities and properties of electroformed nano-crystalline nickel.

- An investigation into defining a bellows figure of merit.

- Investigations of various fabrication techniques, and the consideration of a number of alternate design approaches, applications, and materials.

Aside from Task 6 (writing of the final report) the original tasks for this project were as follows:

Task 1: Functional Definition and Design. This task sought to define typical applications and design variables.

Task 2 and 3: Design Analysis and Detailed Design. These tasks called for applying various analytical methods to investigate the performance of various designs and to seek optimal designs.

Task 4: Manufacture. This task called for the fabrication of typical prototype bellows.

Task 5: Test Program. This task called for the preliminary fatigue testing of the prototype bellows fabricated in Task 4.

Our achievement on each of these tasks is presented in the following sections.

2.0 TASK 1: FUNCTIONAL DEFINITION AND DESIGN

In order to compare the QWF bellows to traditional bellows, specific design requirements must be set. That is, there are so many application of bellows, with so many variable design parameters (size, pressure, elongation, etc.), that a general and comprehensive comparison would be impossible. We pursued two specific design requirements: one for a commercial gas compressor, and one for a military cryo-cooler.

The specific commercial gas compressor bellows application was based on a gas compressor designed by Fluitron of Pennsylvania. Mr. Chiccarine of Fluitron provided engineering specifications for their compressor seal, which are summarized as follows:

Stroke:	>= 5 inches (2 extension and 3 compression)
Inside Diameter:	>= 1.25 inches
Outside Diameter:	"Reasonable" (taken to be < 6 inches)
Maximum Length:	30 inches
Pressure:	50 - 100 psi
Temperature:	Room to moderately high (taken as 300° F)
Cyclic Rate:	400 RPM
Maximum Dead Volume:	Not significant
Life:	>= 100,000,000 cycles
Other:	Must be inexpensive enough for commercial use (taken as a few hundred dollars)

The military cryo-cooler parameters, supplied by Captain Jeffrey Wiese of the USAF Phillips Laboratory, are:

Swept Volume:	20 cc
Inside Diameter:	No restrictions (taken as 0.2 inch)
Outside Diameter:	"Reasonable" (taken as 3 inches)
Maximum Length:	"Reasonable" (taken as 3 inches)
Pressure:	200 psi
Temperature:	Mildly cryogenic to 0°C
Cyclic Rate:	1800-3600 RPM
Maximum Dead Volume:	To be minimized
Life:	>= 20,000,000,000
Other:	Must have minimum induced vibration Must be hermetically sealed

3.0 TASK 2 AND 3: DESIGN ANALYSIS AND DETAILED DESIGN

3.1 ANALYSIS APPROACHES

Some preliminary analysis was done using simple shell model equations (Roark-Laupa approximations). This led to a preliminary base line design. Further design of the bellows used two methods. The first is from the guidelines provided in the Expansion Joint Manufacturers Association (EJMA) design handbook. Note that this technique is only applicable for hydro-formed stainless steel bellows, and it predicts cycles to failure directly. While limited as indicated, it does provide a good starting point for a design and provides an industry standard check for the second method, Finite Element Analysis (FEA), as discussed below.

We created a curve fit for the EJMA design factors for stainless steel bellows to allow for their use in design calculations via an EXCEL spreadsheet (see example and term definition in Table 1). The factors are denoted by D, F, and P, which approximate the EJMA coefficients Cd, Cf, and Cp, respectively. These approximations are as follows, using the EJMA definitions:

B1	=	4*Cm - Cu - 3
B2	=	2 + 2*Cu - 4*Cm
Cu	=	1.75*z*Y**(-0.2216) + 1.75*(1-z)*Y**(-2.477)
Cm	=	1.25*z*Y**(-0.292) + 1.25*(1-z)*y**(-2.477)
X	=	q/(2*W)
Y	=	q/(2.2*SQRT[dp*tp])
z	=	1.0 when X<1.0 and 0.0 otherwise
D	=	1 + 1.25*X*(2.15 + 0.3*Y - 0.53*Y**2 + 0.085*Y**3)
F	=	1 + B1*X + B2*X**2
P	=	1 - (0.441 - 0.035*y + 0.035*y**2)*SIN(Pi*X/2)
Pi	=	3.14159 ...

Table 1. Example EXCEL spreadsheet and EJMA term definitions.

	1	2	3	4	5	6	7	8
	p (psi)	**e** (in)	**O.R.** (in)	**I.R.** (in)	**d** (in)	**q** (in)	**t** (in)	**w** (in)
1	100	0.00505	1.36	0.625	1.29	0.2	0.02	0.715
2	100	0.00505	1.904	0.625	1.29	0.2	0.02	1.259
3	100	0.00505	2.72	0.625	1.29	0.2	0.02	2.075
4	100	0.003535	1.36	0.625	1.29	0.2	0.02	0.715
5	100	0.003535	1.904	0.625	1.29	0.2	0.02	1.259
6	100	0.003535	2.72	0.625	1.29	0.2	0.02	2.075
7	50	0.00505	1.36	0.625	1.29	0.2	0.02	0.715
8	50	0.00505	1.904	0.625	1.29	0.2	0.02	1.259
9	50	0.00505	2.72	0.625	1.29	0.2	0.02	2.075
10	50	0.003535	1.36	0.625	1.29	0.2	0.02	0.715
11	50	0.003535	1.904	0.625	1.29	0.2	0.02	1.259
12	50	0.003535	2.72	0.625	1.29	0.2	0.02	2.075
13	100	0.00505	1.36	0.625	1.29	0.2	0.015	0.72
14	100	0.00505	1.904	0.625	1.29	0.2	0.015	1.264
15	100	0.00505	2.72	0.625	1.29	0.2	0.015	2.08
16	100	0.003535	1.36	0.625	1.29	0.2	0.015	0.72
17	100	0.003535	1.904	0.625	1.29	0.2	0.015	1.264
18	100	0.003535	2.72	0.625	1.29	0.2	0.015	2.08
19	50	0.00505	1.36	0.625	1.29	0.2	0.015	0.72
20	50	0.00505	1.904	0.625	1.29	0.2	0.015	1.264
21	50	0.00505	2.72	0.625	1.29	0.2	0.015	2.08
22	50	0.003535	1.36	0.625	1.29	0.2	0.015	0.72
23	50	0.003535	1.904	0.625	1.29	0.2	0.015	1.264
24	50	0.003535	2.72	0.625	1.29	0.2	0.015	2.08
25	100	0.00505	1.36	0.625	1.29	0.2	0.015	0.72
26	100	0.00505	1.904	0.625	1.29	0.2	0.015	1.264
27	100	0.00505	2.72	0.625	1.29	0.2	0.015	2.08
28	100	0.003535	1.36	0.625	1.29	0.2	0.015	0.72
29	100	0.003535	1.904	0.625	1.29	0.2	0.015	1.264
30	100	0.003535	2.72	0.625	1.29	0.2	0.015	2.08
31	50	0.00505	1.36	0.625	1.29	0.2	0.015	0.72
32	50	0.00505	1.904	0.625	1.29	0.2	0.015	1.264
33	50	0.00505	2.72	0.625	1.29	0.2	0.015	2.08
34	50	0.003535	1.36	0.625	1.29	0.2	0.015	0.72
35	50	0.003535	1.904	0.625	1.29	0.2	0.015	1.264
36	50	0.003535	2.72	0.625	1.29	0.2	0.015	2.08
37	100	0.00505	1.36	0.625	1.29	0.1	0.02	0.715
38	100	0.00505	1.36	0.625	1.29	0.4	0.02	0.715

Table 1. Concluded.

	9	10	11	12	13	14	15	16	17	18	21	23	25	26	27	28	29	30	31	32	34	36	37
	dp	tp	X	Y	z	Cu	Cm	B1	B2	F	D	P	S3	S4	Fw^3	S5	S6	Z	St	Nc	A	fl	R
	(in)	(in)	graph coord	graph coord	0 or 1	unity appx	mid appx	coeff	coeff	appx for Cf	appx for Cd	(psig)	(psi)	(psi)	(in^3)	(psi)	(psi)	(psi)	(psi)		in^2	(lbs/in)	fig of merit
1	2.01	0.016	0.1399	0.5069	1	2.034	1.524	1.06	-0.029	1.148	1.384	0.91	2,228	89,971	0.42	43	5,343	69,926		10,695,609	3.16	939	133.2
2	2.55	0.0142	0.0794	0.4774	1	2.062	1.551	1.14	-0.082	1.09	1.219	0.95	4,424	370,459	2.176	6.6	1,736	264,161		1,658	5.1	161	1258.3
3	3.37	0.0124	0.0482	0.4453	1	2.094	1.583	1.24	-0.145	1.059	1.133	0.97	8,378	1,358,035	9.464	1.1	598	957,089		12	8.89	32.1	10959.9
4	2.01	0.016	0.1399	0.5069	1	2.034	1.524	1.06	-0.029	1.148	1.384	0.91	2,228	89,971	0.42	30	3,740	68,310		15,388,041	3.16	939	190.3
5	2.55	0.0142	0.0794	0.4774	1	2.062	1.551	1.14	-0.082	1.09	1.219	0.95	4,424	370,459	2.176	4.6	1,215	263,638		1,672	5.1	161	1797.6
6	3.37	0.0124	0.0482	0.4453	1	2.094	1.583	1.24	-0.145	1.059	1.133	0.97	8,378	1,358,035	9.464	0.8	419	956,909		12	8.89	32.1	15656.9
7	2.01	0.016	0.1399	0.5069	1	2.034	1.524	1.06	-0.029	1.148	1.384	0.91	1,114	44,985	0.42	43	5,343	37,656		#NUM!	3.16	939	66.6
8	2.55	0.0142	0.0794	0.4774	1	2.062	1.551	1.14	-0.082	1.09	1.219	0.95	2,212	185,230	2.176	6.6	1,736	132,952		46,271	5.1	161	629.2
9	3.37	0.0124	0.0482	0.4453	1	2.094	1.583	1.24	-0.145	1.059	1.133	0.97	4,189	679,017	9.464	1.1	598	478,844		151	8.89	32.1	5479.9
10	2.01	0.016	0.1399	0.5069	1	2.034	1.524	1.06	-0.029	1.148	1.384	0.91	1,114	44,985	0.42	30	3,740	36,040		#NUM!	3.16	939	95.1
11	2.55	0.0142	0.0794	0.4774	1	2.062	1.551	1.14	-0.082	1.09	1.219	0.95	2,212	185,230	2.176	4.6	1,215	132,429		47,328	5.1	161	898.8
12	3.37	0.0124	0.0482	0.4453	1	2.094	1.583	1.24	-0.145	1.059	1.133	0.97	4,189	679,017	9.464	0.8	419	478,664		152	8.89	32.1	7828.5
13	2.01	0.012	0.1389	0.5849	1	1.971	1.462	0.88	0.0941	1.124	1.379	0.91	2,996	162,703	0.419	24	3,961	119,974		85,206	3.17	396	317.4
14	2.55	0.0107	0.0791	0.5509	1	1.997	1.488	0.95	0.0436	1.076	1.217	0.95	5,928	665,280	2.172	3.7	1,292	471,142		161	5.12	67.8	2992.6
15	3.37	0.0093	0.0481	0.5141	1	2.028	1.518	1.04	-0.016	1.05	1.132	0.97	11,206	2,429,753	9.45	0.6	447	1,709,119		1	8.92	13.6	26036.8
16	2.01	0.012	0.1389	0.5849	1	1.971	1.462	0.88	0.0941	1.124	1.379	0.91	2,996	162,703	0.419	17	2,773	118,779		90,672	3.17	396	453.5
17	2.55	0.0107	0.0791	0.5509	1	1.997	1.488	0.95	0.0436	1.076	1.217	0.95	5,928	665,280	2.172	2.6	905	470,753		162	5.12	67.8	4275.2
18	3.37	0.0093	0.0481	0.5141	1	2.028	1.518	1.04	-0.016	1.05	1.132	0.97	11,206	2,429,753	9.45	0.5	313	1,708,985		1	8.92	13.6	37195.4
19	2.01	0.012	0.1389	0.5849	1	1.971	1.462	0.88	0.0941	1.124	1.379	0.91	1,498	81,352	0.419	24	3,961	61,980		112,095,587	3.17	360	158.7
20	2.55	0.0107	0.0791	0.5509	1	1.997	1.488	0.95	0.0436	1.076	1.217	0.95	2,964	332,640	2.172	3.7	1,292	236,219		2,694	5.12	67.8	1496.3
21	3.37	0.0093	0.0481	0.5141	1	2.028	1.518	1.04	-0.016	1.05	1.132	0.97	5,603	1,214,877	9.45	0.6	447	854,783		18	8.92	13.6	13018.4
22	2.01	0.012	0.1389	0.5849	1	1.971	1.462	0.88	0.0941	1.124	1.379	0.91	1,498	81,352	0.419	17	2,773	60,784		194,648,764	3.17	396	226.7
23	2.55	0.0107	0.0791	0.5509	1	1.997	1.488	0.95	0.0436	1.076	1.217	0.95	2,964	332,640	2.172	2.6	905	235,830		2,713	5.12	67.8	2137.6
24	3.37	0.0093	0.0481	0.5141	1	2.028	1.518	1.04	-0.016	1.05	1.132	0.97	5,603	1,214,877	9.451	0.5	313	854,649		18	8.92	13.6	18597.7
25	2.01	0.012	0.1389	0.5849	1	1.971	1.462	0.88	0.0941	1.124	1.379	0.91	2,996	162,703	0.419	24	3,961	119,974		85,206	3.17	396	0
26	2.55	0.0107	0.0791	0.5509	1	1.997	1.488	0.95	0.0436	1.076	1.217	0.95	5,928	665,280	2.172	3.7	1,292	471,142		161	5.12	67.8	2992.6
27	3.37	0.0093	0.0481	0.5141	1	2.028	1.518	1.04	-0.016	1.05	1.132	0.97	11,206	2,429,753	9.45	0.6	447	1,709,119		1	8.92	13.6	26036.8
28	2.01	0.012	0.1389	0.5849	1	1.971	1.462	0.88	0.0941	1.124	1.379	0.91	2,996	162,703	0.419	17	2,773	118,779		90,672	3.17	396	453.5
29	2.55	0.0107	0.0791	0.5509	1	1.997	1.488	0.95	0.0436	1.076	1.217	0.95	5,928	665,280	2.172	2.6	905	470,753		162	5.12	67.8	4275.2
30	3.37	0.0093	0.0481	0.5141	1	2.028	1.518	1.04	-0.016	1.05	1.132	0.97	11,206	2,429,753	9.45	0.5	313	1,708,985		1	8.92	13.6	37195.4
31	2.01	0.012	0.1389	0.5849	1	1.971	1.462	0.88	0.0941	1.124	1.379	0.91	1,498	81,352	0.419	24	3,961	61,980		112,095,587	3.17	396	158.7
32	2.55	0.0107	0.0791	0.5509	1	1.997	1.488	0.95	0.0436	1.076	1.217	0.95	2,964	332,640	2.172	3.7	1,292	236,219		2,694	5.12	67.8	1496.3
33	3.37	0.0093	0.0481	0.5141	1	2.028	1.518	1.04	-0.016	1.05	1.132	0.97	5,603	1,214,877	9.45	0.6	447	854,783		18	8.92	13.6	13018.4
34	2.01	0.012	0.1389	0.5849	1	1.971	1.462	0.88	0.0941	1.124	1.379	0.91	1,498	81,352	0.419	17	2,773	60,784		194,648,764	3.17	396	226.7
35	2.55	0.0107	0.0791	0.5509	1	1.997	1.488	0.95	0.0436	1.076	1.217	0.95	2,964	332,640	2.172	2.6	905	235,830		2,713	5.12	67.8	2137.6
36	3.37	0.0093	0.0481	0.5141	1	2.028	1.518	1.04	-0.016	1.05	1.132	0.97	5,603	1,214,877	9.45	0.5	313	854,649		18	8.92	13.6	18597.7
37	2.01	0.016	0.0699	0.2534	1	2.372	1.866	2.09	-0.721	1.143	1.193	0.95	2,228	94,595	0.418	44	6,201	74,021		4,912,438	3.16	943	132.6
38	2.01	0.016	0.2797	1.0138	1	1.745	1.245	0.24	0.5093	1.106	1.713	0.81	2,228	80,678	0.404	45	4,318	62,397		94,241,482	3.16	975	128.3

Using the EXCEL spreadsheet of the EJMA equations, we can rapidly evaluate a bellows design and maximize its life or minimize its stress by varying any of several parameters (such as pitch, inside and outside diameters, and thickness), once given its operating parameters (elongation and internal pressure). The use of this approach yielded the following insights:

- Life is very sensitive to small changes in the operating parameters.
- Optimal parameters can increase life by large factors (ten or more) beyond a slightly non optimal design.
- In some cases, there is no optimal within reasonable parameter bounds. That is, in some cases, practical considerations such as minimum manufacturable pitch or reasonable limits on outside diameter control the optimal design.
- A reasonable agreement (within 30% accuracy in stress prediction) has been found between the EJMA and FEA results.

The second analysis method involves Finite Element Analysis using axi-symmetric elements to predict maximum stresses under imposed forces, displacements, or pressures. Once stresses are predicted, S/N curves are used for cyclic life prediction. A typical coding is illustrated in Figure 2. The code used was COSMOS, running on a 486 PC. The COSMOS program also allows for structural optimization. For example, the program will automatically search for the thickness that produces minimum stress. Optimization can also be carried out on several parameters (such as the independently varying thickness in three different sections of the bellows). Approximately 1-8 man hours are required per design change (PC running times are a few minutes for a standard analysis, and up to a few hours for an optimization run). Typical model parameters are:

Degrees-of-freedom:	500
Elements:	150
Nodes:	300

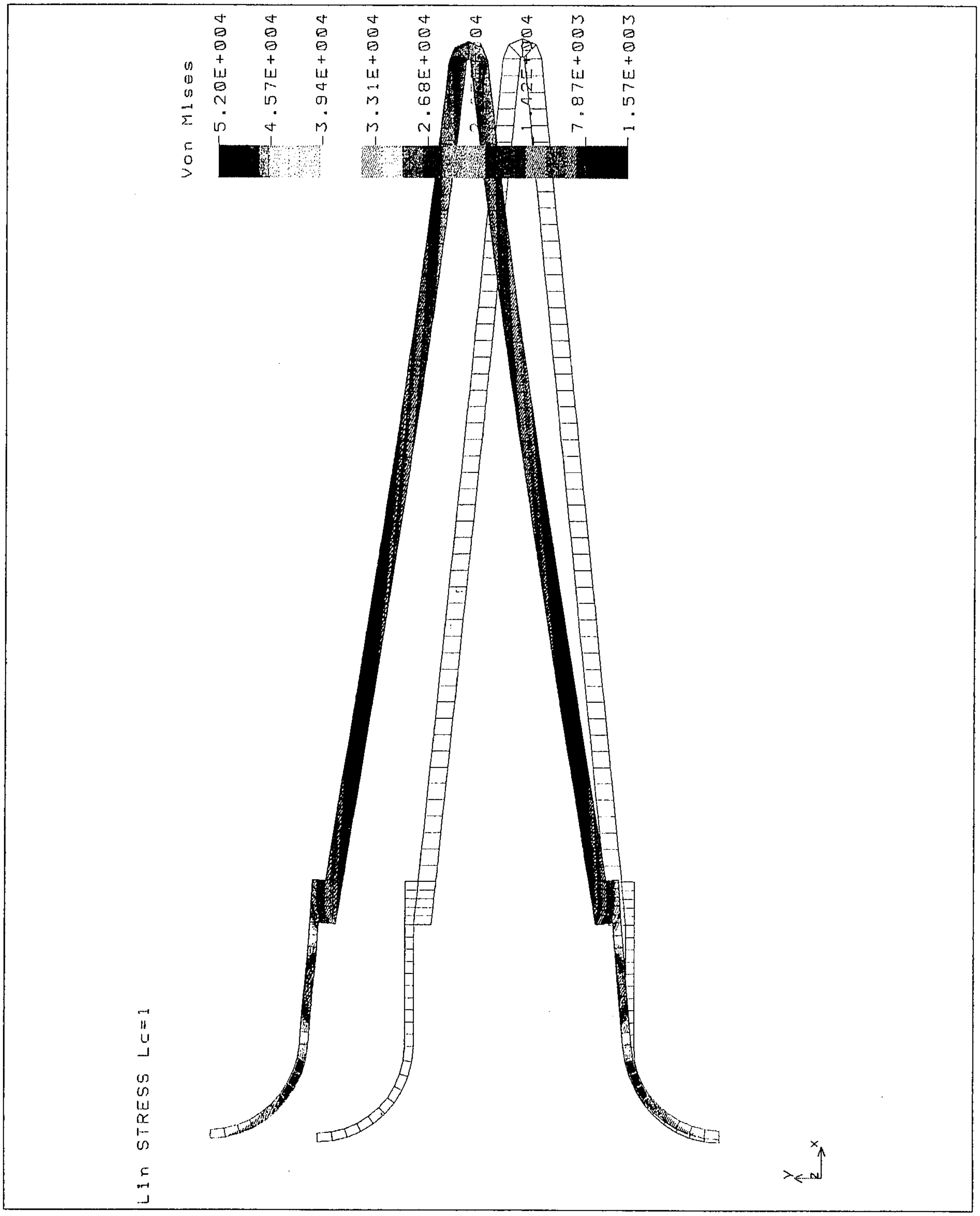

Figure 2. Typical QWF COSMOS configuration.

COSMOS is capable of exercising a large displacement model, but this was not used in these analyses, as simple calculations indicated it was not a factor. It may be useful in future analyses to use COSMOS to further check the effect of large displacements on these results.

3.2 RESULTS OF COMPRESSOR STUDY

With regards to the Fluitron compressor example, we achieved interesting and enlightening conclusions using the EJMA and FEA approaches. This example used the following additional parameters:

Inside radius:	0.625"
Pressure:	50 psi
Pitch:	0.3" (set at this lower limit by reasonable manufacturing limits)
Elongation:	0.03"/convolution (thus can get 3 inches with 100 convolutions and meet a 30-inch length limit)
Outside radius:	As discussed below
Thickness:	Allowed to vary to get optimal design, as discussed below.

The following four cases were run:

CASE A: Typical bellows with outside radius limited, by hydro-forming methods, to 1.4 times the inner radius (hence equal to 0.875"). The optimal thickness of this bellows was found to be 0.006", and it had a maximum VonMises stress of 78 ksi.

CASE B: As in Case A, but using an outside diameter of 1.904 and consequently having an inside diameter limited by the 1.4 factor of 1.36". The optimal thickness of this bellows was found to be 0.018", and it had a maximum stress of 62 ksi.

CASE C: A standard bellows, but one in which the outside to inside radius ratio is allowed to increase due to the possibilities allowed by the QWF manufacturing approach. For practical reasons, this outside radius was taken as 1.904" and the inner of 0.625" (a ratio of 3.05). This bellows was found to have an optimal thickness of 0.042", and a maximum stress of 41 ksi. Hence the radius choices offered by the

QWF design allows for a 0.53 - 0.66 reduction factor in peak stress from Cases A and B.

CASE D: A standard-shaped bellows with the 1.904 outside radius and 0.625 inside radius, but one in which the thickness of the bellows is allowed to vary in three areas (roughly the inner, middle, and outer 1/3 of the convolution). The optimal thickness of this bellows was found to be 0.0196", 0.0425", and 0.0658" in the three areas. The maximum stress was 28 ksi. Hence a variable thickness QWF bellows allows for a 0.36 - 0.45 reduction factor in peak stress from Cases A and B (and a 0.68 reduction factor from Case C).

These large stress reductions lead to greatly increased lifetimes. For example, Cases C and D are below the endurance limit of stainless steel and would probably have life in excess of 1,000,000,000. (This life can only be estimated roughly, as the fatigue data for stainless steel [and most materials] at one billion cycles is limited and uncertain.) Cases A and B, using standard bellows designs, are predicted to have lives under 1,000,000 cycles. This example indicates that the QWF approach has the ability to yield very significant improvements in bellows performance. Further, additional optimization of the design is possible (e.g., more regions of variable thickness).

3.3 RESULTS OF CRYO-COOLER STUDY

Analyses of this design were not conducted, within the limits of this project effort.

3.4 A BELLOWS FIGURE OF MERIT

The evaluation of bellows can be approached from the computation or demonstration of their anticipated life, or maximum stress. Alternately, some more general points can be made by reference to "figures of merit" which seek to compare bellows more generally, emphasizing their structural, thermodynamic, or longevity, or all three. Appendix A presents a discussion of such figures of merit.

4.0 TASK 4: MANUFACTURE

The goal of this task was to determine ways of manufacturing a QWF bellows, and to fabricate a prototype. Manufacturing techniques were identified and bellows components were fabricated. They were not assembled into a final bellows due to difficulties encountered in the bellows fabrication.

4.1 STANDARD FABRICATION TECHNIQUES INVESTIGATED

Standard fabrication techniques that were investigated included:

- Furnace brazing. This method has the ability to bond similar and dissimilar metals by placing a bonding (brazing) compound between the two surfaces to be joined, clamping the two pieces, and heating in an oven for up to several hours. The technique works well for lap joints but not, in general, for butt joints. Due to the elevated temperatures used, this technique may have possible effect on fatigue life, in that it may anneal the cold working of the formed component that leads to increased fatigue life. Evaluation of this effect would require actual fatigue testing of manufactured prototypes.

- Inertial (friction) welding has an even greater ability to weld dissimilar metals. However, our investigations indicated that its requirement of thick connection cross sections at the bond area probably make it unsuitable for QWF bellows manufacturing.

- EDM wire cutting capabilities to use hydro-formed bellows as feed stock for QWF manufacturing. This technique can cut very thin sections. However, some difficulty was encountered in trying to use EDM cutting on formed bellows, as discussed below.

4.2 ALTERNATE MATERIALS AND FABRICATION TECHNIQUES

This project also sought to evaluate the feasibility of using nano-crystalline nickel (or other unique materials) in bellows construction and to use unique manufacturing techniques (such as possible with electrodeposition and machined bellows). These issues were investigated by conducting 2-3 hour meetings with various experts:

- Richard Edwards and Glen Malone of Electroformed Nickel, a company involved with the design and manufacture of electroformed nickel products.

- William Darlington of Hydrodyne, a company involved in the machining of special purpose bellows.
- Ed Zezula, a private consultant in metallurgy and materials.
- Vance Stapleton of the Stapleton Company, a company involved with the electro-chemistry of nickel and with nickel forming and bellows production.

The conclusions from these meetings were as follows:

- Electroformed Nickel. Bellows have been constructed from electroformed nickel in the past. Further, fatigue data on electroformed nickel (much of which is available from INCO, the Nickel Development Institute in Toronto, and the Queens Institute in Kingston, Ontario) suggests that such nickel has fatigue properties, in some formulations, well superior to that of stainless steels (e.g., 10 million cycles @ 110 ksi). The fatigue qualities, however, are very dependent on both chemistry and electro deposition rates (the slower the better). The type of variable cross sections that are being suggested for the QWF design are possible, but both consultants with electroformed nickel experience agreed that the ability to produce such deep and controlled cross sections would require a significant amount of experimentation and special tooling (such as electrolytic brushes to build up a section in a thick area) and to avoid excessive build up in high electrical gradient configurations. These observations suggest that while electro formed nickel bellows with variable cross sections have great promise for military applications, their use to produce less expensive commercial products may be questionable.

- Machined Bellows. Machined bellows can have variable cross sections and be made of almost any material. This is their advantage over formed bellows. However, the machining process strongly limits the possible ratio of inner to outer radius, and requires a substantial inner radius to introduce the tooling. Machining is also limited in producing very thin inside pitch dimensions and cannot produce deep thin cuts. Further, the machining process can produce stress concentrations in corners and does not have the benefit of the stress-relieving grain flow that comes from forming. In conclusion, we believe that machined bellows are not a promising approach for high fatigue life QWF bellows or bellows components.

- Other Materials. Aside from nano crystalline nickel, we discussed the possible use of Maraging steels and an exotic organo-silicon material (Ormosil). The available data suggests that Maraging steels with endurance limits in excess of 100,000 psi are available and could be used to create parts for the QWF design. Maraging steels should be considered in any Phase II effort. The data on Ormosil (being developed at UCLA) is very preliminary, but suggests that its high elasticity may make up for a modest endurance limit. The use of such a material would involve many issues of formulation and property determination, probably years away, and its eventual utility in bellows can only be a matter of speculation at this time.

4.3 FABRICATION UNDERTAKEN

Bellows were purchased from a major formed bellows manufacturer (Robertshaw), based on preliminary calculations, to allow preliminary investigations into fabrication techniques (cutting, brazing, etc.), and for testing to evaluate effects of annealing due to furnace brazing. Other materials were obtained to perform basic fabrication.

The bellows were cut using EDM techniques. These preliminary efforts indicated a great difficulty in producing clean uniform cuts. Additional work needs to be done to show if this method of providing QWF base parts is practical.

Typical thicknesses of stainless steel in straight sections were furnace brazed to develop experience in this method. These proved to develop a very good bond. Further efforts are required to show that this method is practical for dished circular sections. These were not done due to the difficulties mentioned above with the cutting of the formed bellows.

5.0 TASK 5: TEST PROGRAM

Testing of prototype bellows was not conducted, as none were fabricated, within the limits of this project effort.

The intent of this task, in the event that additional efforts can be carried out in the future, was as follows. Two bellows were to be tested, one a standard formed bellows and one a fabricated QWF bellows. The testing was intended to demonstrate the higher fatigue life of the QWF bellows.

In order to perform the fatigue testing, ANCO was to use a fatigue testing fixture capable of, nominally, 30 cycles/second, 0.4 inch (1 cm) stroke, 50 pound (220 N) force, and 10 atmosphere pressure.

6.0 ADDITIONAL TASKS PERFORMED

As mentioned above, not all the original tasks were completed as originally envisioned. By its very nature, research cannot predict exactly at its onset what it will investigate and discover. In our initial proposal and contract, we proposed assembling a sample QWF bellows and fatigue testing it as an approach to determining the feasibility of a QWF bellows design. However, in the course of our work, we encountered difficulties in the manufacture that led us to investigate other manufacturing approaches. While we did not, in the end, fabricate and test a complete prototype (due to the discovery that EDM cutting was not immediately feasible), we did find out what we believe are very significant ways to fabricate optimal bellows.

When we encountered difficulty with the EDM method of producing QWF parts, and the FEM analysis indicated the great benefit of continuously varying wall thickness, rather than just two wall thicknesses, we began to look more closely at the advantages of electroforming and its ability to produce variable wall thickness, and especially electroformed Nickel. This led to extra efforts, summarized in the sections below. We investigated one newly discovered material (Ormosil) which also allowed for the possibility of variable wall thickness, and an alternate bellows design approach (non circular bellows). We also investigated to a greater extent than originally planned several additional commercialization possibilities.

6.1 NANOCRYSTALINE NICKEL

Additional work was performed to gather the properties of Nanocrystaline and electroformed Nickel, including conversations and contacts with INCO, the Nickel Development Institute in Toronto, and the Queens Institute in Kingston, Ontario. This work also sought additional information on the factors which affected the fatigue strength of electroformed Nickel, and the experience in producing bellows or bellows like objects by these methods. As discussed elsewhere in this final report, the use of electroformed Nickel to produce bellows of variable thickness optimized to a specific application is considered to be the most promising approach for future investigations for military and aerospace bellows that was identified by this study.

6.2 ORMOSIL

Professor McKenzie at UCLA has been investigating an organo-silicon compound he calls Ormosil. This material can be compounded with elastic properties ranging from soft rubber to hard plastics, and has been suggested for use in golf ball covers, shoe soles, artificial organ replacements, and many other mechanical devices. Of particular interest is the potential to cast Ormosil in almost any shape, including a variable thickness bellows. While only preliminary information is available on its elastic properties, and almost no data is available on its fatigue properties, its greater flexibility and operability over a very wide temperature range suggests that it may be useful in bellows design. The use of this material, in one of its many formulations, would involve many issues of formulation and property determination. Such information, we discovered, is probably years away, and its eventual utility in bellows design can only be a matter of speculation at this time.

6.3 NON-CIRCULAR BELLOWS

Some additional effort was spent on the investigation of non circular bellows in an effort to take the advantage of the low stresses in a large radius bellows (as opposed to a smaller radius bellows), and yet allow the larger bellows to be fit into a smaller space (see attached sketch). Methods of fabrication considered were cutting segments out of a large bellows and uniting them to produce an oblong bellows, and the stretch forming of corrugated sheet to produce segments that could be joined into an oblong bellows.

6.4 ADDITIONAL COMMERCIALIZATION OPPORTUNITIES

Several additional organizations were contacted to ascertain their interest in various bellows concepts, including the Gas Research Institute (gas compressors), the University of Houston (petrochemical product compressors), and Calstart (automotive gaseous fuel compressors).

7.0 CONCLUSIONS AND ANTICIPATED PHASE II RESEARCH AND DEVELOPMENT

7.1 CONCLUSIONS FROM PHASE 1

In summary, the conclusions of the Phase I effort are:

- The QWF design has the potential of much longer life than a standard formed bellows.
- The most promising design feature is a variable thickness bellows. Stress reductions of a factor of two or larger compared to a standard formed bellows is possible. This can result in an enormous increase in fatigue life. Such bellows can also have low dead volume.
- Nano crystalline electroformed nickel has the greatest potential for producing high performance military bellows, but may be too expensive for commercial products. This is especially true because of the ability to produce a variable thickness by electroforming.
- An optimal bellows can only be defined for a specific set of design parameters. Small changes in these parameters can significantly change the configuration of the optimal bellows.
- The EJMA computations, when implemented on a spreadsheet, are very useful for demonstrating trends and performing initial optimal designs. Preliminary results indicated that it, as well as the commercial design, would benefit greatly from a variable thickness design.
- FEA methods are essential for analyzing variable thickness bellows and are useful to produce optimal designs.
- Furnace brazing may be useful in producing fabricated QWF bellows. Friction welding and machining are not, although some additional investigation into friction welding may be warranted.
- Fatigue data is available for stainless steel, Maraging steel, and nickel at high numbers of cycles, but is just barely sufficient.
- Maraging steel may be superior to stainless steels for formed bellows.

7.2 RECOMMENDED PHASE II RESEARCH AND DEVELOPMENT

The successful conduct of Phase II will require a clear definition of the standard applications to be selected, and a reasonable number of design and design variables that will be investigated. This goal is primary, due to the multitude of facets facing the designer of a new bellows (geometry, material, fabrication techniques, applications, etc.).

In addition, the Phase II effort must be defined with a clear definition of commercialization possibilities. These will include input from compressor manufacturers such as Fluitron, cryo-cooler users, natural gas compressor users, nuclear applications, and others.

The following are among the tasks and issues to be addressed in a Phase II effort:

- Extensive evaluation of variable thickness electroformed nanocrystaline bellows should be made. This approach appears to be the most promising at this time.
- Several prototypes must be fabricated and fatigue tested.
- The EJMA analysis of the military cryo-cooler, not performed herein, should be carried out.
- Improved EDM technique should be further investigated, so as to determine if standard formed bellows can provide components of a QWF design.
- Large displacement FEA stress models should be checked to make sure that the small displacement assumptions are justified.

APPENDIX A

DISCUSSION ON BELLOWS FIGURES OF MERIT

The history of technology provides numerous examples of benefits resulting from identification and formulation of a single parameter which can be called a figure of merit. For example, in the design of hydraulic and pneumatic accumulators for the aerospace industry, a product similar to metal bellows in many respects, a significant improvement was made in the ratio of maximum energy stored to gross weight of the accumulator after this ratio was widely accepted as a useful figure of merit by much of the accumulator industry. Other segments of the aerospace industry have sometimes adopted efficiency and other dimensionless figures of merit. Among metal bellows, where dimensions can span a very large range of values, it would be more desirable if the figure of merit could also be dimensionless.

For years, a few preliminary design analysts have considered the ratio of maximum allowable thermodynamic work per cycle (pneumatic energy per stroke) to total strain energy per cycle as a preliminary criterion of the merit of a bellows. Accordingly, this ratio was one of several criteria used to compare some of the early designs aimed at meeting the above Fluitron bellows criteria. At best, it proved to be only somewhat helpful. This pneumatic-energy-to-strain-energy figure of merit is an oversimplification in at least two obvious ways. One is the omission of consideration of the bellows dead volume (the fully-compressed bellows clearance volume) as a factor in the formula. This is a big omission because many applications cannot tolerate a large dead volume and because large dead volume is often an easy way to enable a bellows to have less maximum stress.

Another deficiency in the above energy-ratio figure of merit is a sensitivity to how the loads are applied, particularly to the ratio of axial force and total axial pressure load. For example, a bellows compressed by a fluid can be expected to show a larger value of this particular merit figure than the same bellows cranked mechanically. In general, to be most simple and useful, the bellows figure of merit should be a function of bellows dimensions and parameters only. The above energy-to-ratio figure of merit does this if applied only to the case of a particular ratio of axial load to pressure load. It can be calculated entirely from data given in some stock bellows catalogs.

An effort was made to improve on the above merit formulation by introducing a dead volume term. Although dead volume is known to be an important part of the specification of bellows used in both cryo-coolers and compressors, the particular bellows specification that was recommended by Fluitron was somehow an exception to this. Even after numerous telephone calls, the reason for Fluitron giving zero weight to the dead volume term has not been understood. In the case of Stirling cycle cryo-coolers, even the simplest type of cycle analysis, the Schmidt analysis, provides a connection between dead volume and efficiency. Using that analysis, it is possible to make a good case for adopting a non-dimensional bellows figure of merit:

FM = (allowable work per cycle)/([dead volume] [maximum bellows stress])

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