Dynamet
TECHNOLOGY

Final Report

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Contract DAAE07-01-C-L013
SBIR Phase 1

"Lightweight Durable Titanium Tracks Using Low Cost Powder Metal Titanium Composite Technology"

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13. ABSTRACT ***(Maximum 200 Words)***

The results of Phase I demonstrated the technical feasibility of this advanced powder metal titanium composite technology to find applications in lightweight tank track components, particularly as a material for center guides. The titanium composite materials have demonstrated wear resistance far superior to conventional titanium alloys and surpassing the wear characteristics achieved with more highly reinforced and less tough Al/SiC MMCs and ADI. The Phase I results also suggest that with further modification this titanium technology has the potential to match or exceed the wear resistance of 4140 steel. Using this technology, lightweight tank track designs can be developed and specific titanium components could be inserted into a variety of current and future track systems, including AAAV, Crusader, M109 Howitzer and Future Combat Systems. Models indicate that titanium track designs offering a 25–40 % weight reduction versus steel are feasible. This technology has also been demonstrated to provide significant robustness in regard to material properties, design flexibility and manufacturability by the CHIP powder metal process for cost-effective manufacture to near net shape of applicable tank track components.

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"Lightweight Durable Titanium Tracks Using
Low Cost Powder Metal Titanium Composite Technology"

1.0 Phase I Objectives

The primary objective of Phase I was to design and develop **lightweight track system concepts** with **reduced O&S costs** which would meet **the operational conditions experienced by the medium weight vehicles (including Crusader, and other potential lightweight track systems)** and to demonstrate technical feasibility of Dynamet's powder metal titanium alloy and composite technology to provide sufficient wear resistance for application to critical track components.

Based upon Dynamet's 28 years of titanium alloy development and P/M manufacturing technology of titanium alloy and titanium MMC components combined with KRC's 15 years of experience conducting military track research, design and development, preliminary titanium track concepts were developed in Phase I. The designs are based upon KRC's armored vehicle track structural design load history that has been verified on numerous track programs as well as wear test results on advanced titanium alloy and composite materials manufactured and tested during the Phase I program.

More specifically the Phase 1 effort addresses the following proposed enumerated objectives:

1. Establish a **baseline titanium track design** that could be expected to meet the performance requirements of the conventional steel design at a significantly lighter weight. Address the total **weight savings** that could be achieved over the conventional steel design through the engineered titanium alloy/titanium MMC designs based upon the T158 and XT166 ProE models.
2. Determine the feasibility for particulate reinforced titanium composite materials to provide sufficient **wear** resistance to be considered for tank track shoe components (grouser, center guide vanes, etc.). Determine baseline wear properties on candidate titanium MMC compositions for application to components such as ***shoe body end plates and grousers, center guides, and end connectors***.
3. Establish an MMC composition (particle loading) for the severe wear condition of the center guide component.
4. Identify potential advantages in **life cycle costs** through powder metal manufacturing (near-net shape manufacture, tailored material properties) and through product application (lighter weight, reduced fuel consumption, improved durability).

2.0 Research Conducted

In the Phase I Program, the proposed tasks enumerated below were conducted. The effort proceeded as planned. The ASTM G-65 wear tests provided very promising results while also indicating that still further improvements were feasible. Based on this analysis a second iteration of samples with compositional modifications were produced for ASTM G-65 wear testing within the scope of the Phase I (and potentially the Phase I Option period). Details of the research conducted in Phase 1 are provided below.

Task 1. Design and Analysis of Tank Tracks

Task 1.1 Review current track designs for Crusader

KRC and Dynamet reviewed current track designs. The three viable shoe design categories considered were 1) double pin-double block similar to T158LL, 2) single pin – single block similar to T157I and 3) double pin – single block similar to XT166. Design, material and manufacturing process issues were studied as they related to potential designs to be proposed and evaluated in this program. Potential designs and system applications were discussed with TACOM. It was agreed that double pin designs similar to T158 or XT166 should be pursued.

Task 1.2 Identify components for weight reduction

Component designs for lightweight substitution using the advantages of titanium or titanium composite manufacturing techniques were addressed. As each component will be subjected to different loading and boundary conditions, unique material properties are required for each component. For structural loading, the material must have good yield strength and fatigue properties. For impact events, fracture toughness is required. For multi-body contact, good wear resistance is required. Stiffness is also a concern for uniform loading of the elastomers, primarily the rubber bushings.

Preliminary analysis suggested that the shoe body could definitely be designed using titanium, with additional wear resistance added where the shoe contacts the ground. Center guides could be made using titanium composite material in the wear areas and potentially integrated with traditional titanium alloy in the structural parts. End connectors or sprocket windows require good wear, impact fracture toughness, and good high strength. Track pins require high stiffness, fracture toughness, and fatigue properties. Design attributes and material selection for each component is being assessed.

Task 1.3 Develop ProEngineer model and weight calculations of revised shoe body and components

ProEngineer solid models of various track concepts have been constructed at KRC to optimize the weight of the shoe and all components, including calculating the total weight of the system(s). The structural members' thickness has determined from past models, but no finite element calculations was included within the scope of Phase I of this SBIR.

Task 2. Screening Testing for Wear Resistance of Candidate Materials

Task 2.1 Material Composition Selection

Based on the design analysis, candidate materials were selected by Dynamet for initial screening of wear properties using ASTM G-65. The test materials will include the workhorse Ti-6Al-4V, a higher strength production-proven P/M Ti-6Al-6V-2Sn alloy (to match the strength of the steel), and at least two TiC-reinforced titanium alloy compositions (using the Ti-64 or Ti-662 alloy as the matrix), and any other control or alternative compositions deemed appropriate. A total of twelve (12) compositional variables were selected. Based upon the excellent results and positive trends identified, a second iteration including four (4) modified compositions was selected within the Phase I program.

Task 2.2 Manufacture of Test Material

Dynamet produced tooling for the manufacture of 1" x 3" x ½" rectangular ASTM wear specimens. Blends were produced from powders for each of the compositions. Wear samples as well as witness bars (approx 5/8" dia x 5" long) were manufactured by Dynamet's powder metal CHIP processing technology of cold isostatic pressing, vacuum sintering, followed by containerless hot isostatic pressing. Baseline material evaluation (room temperature tensile tests) were performed on specimens machined from the witness bars processed with the wear samples. The P/M wear samples were supplied to KRC for surface grinding and wear testing under ASTM G65-94. Material for iteration 2 samples was similarly manufactured and prepared for testing.

Task 2.3 Wear Testing

KRC conducted tests in accordance with ASTM G65-94 on all 12 materials supplied by Dynamet. Results of these tests were analyzed and discussed with TACOM technical personnel. Based on the data and technical discussions a compositional down-selection was made regarding component specific testing to be performed in Task 3. Analysis of the data suggested that testing of additional material with compositional modifications could offer further advantage. It was decided to manufacture additional samples and to test within the Phase I effort if possible.

Task 3. Wear Guide Specimen Testing of Selected Material

Task 3.1 Manufacture of Test Material

Dynamet has manufactured 24 wear guide specimens from the selected composition (Ti-6Al-6V-2Sn+12TiC) from Task 2. To demonstrate the capability for selective locating the titanium composite within a product design, Dynamet is producing these wear specimen preforms with the titanium MMC to remain in the wear test region only, while producing the bulk of the preform from conventional titanium, from powder using CHIP the process. The P/M preforms are being machined to the final test configuration per KRC Dwg 971111.001 as shown in **Figure**

1. Witness bars 5/8 inch dia x 5" long have also been produced from the titanium MMC and available for further property testing.

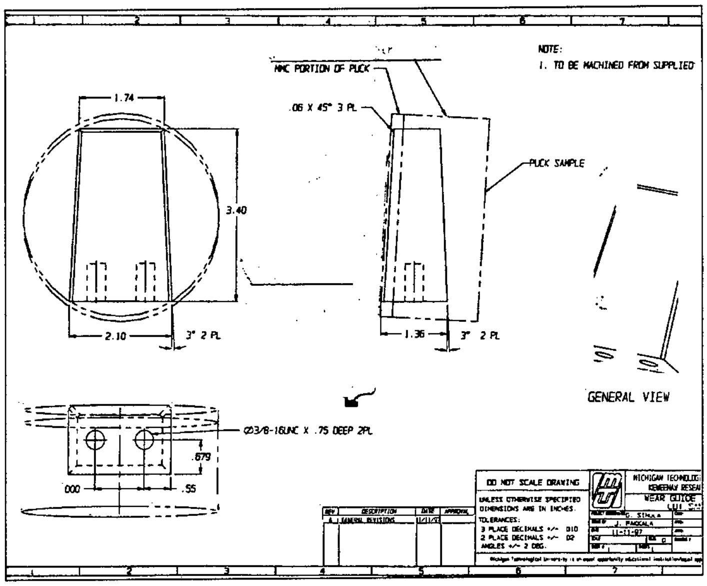


Figure 1. KRC Wear Guide Specimen

Task 3.2 Wear Guide Laboratory Tests

Testing of the prepared specimens will be conducted on the KRC center guide wear machine. This custom test machine has been used to evaluate forged steel, austempered ductile iron, aluminum metal matrix composites, and different surface modifications such as plasma coatings for military track applications. Test results from this program will be compared against past laboratory and field test results.

Task 4. Thermal Management Design Feasibility

Design issues specifically related to increasing the life of the elastomeric track materials (primarily track bushings) were explored. Heat is generated on a track shoe through hysteretic heating of the bushings, backing rubber, and track pad. Thermal conduction takes place throughout the shoe, and between the pad and ground and between the backing rubber and road wheels, along with convection to the surrounding air. As the bushing endurance life is very sensitive to operating temperature, the thermal management of the shoe has to be designed to minimize the bushing temperature while accounting for a reduction in thermal conductivity of titanium as compared to steel (approximately one half of steel).

To verify the thermal conduction approach on bushing life, Dynamet has produced a Ti-6Al-4V alloy bushing (machined from conventional wrought barstock). The bushing has been supplied to KRC for standard MIL-DTL-11891 bushing endurance tests. During the Phase I KRC has conducted initial testing using the sample titanium bushing bore and a baseline steel bushing bore. This provides a material baseline comparison with production steel bushing bores as the bore design is the same.

Thermal management is being addressed in two methods: (1) Reduction in hysteretic heating of the backing rubber by using a low hysteretic heating polyurethane. KRC has already conducted laboratory and field tests on a polyurethane backing stock for the XT172 MMC shoe on the Bradley with good results. This design information will be leveraged on this program. (2) Design of the shoe body to maximize heat conduction from the bushings to a heat sink area of the track shoe. The shoe design will maximize the heat conduction using traditional design techniques. The track pad backing plate could be made from aluminum, with no rubber on the backside of the plate. This will allow good contact with the titanium binocular tubes to maximize heat conduction. Also several ribs could be placed on the external binocular tubes to help conduction. Finally, the track backing rubber will be designed to be confined inside the shoe body similar to XT172 design to increase convection as a traditional T158 rubber coating detrimentally insulates the binocular tubes.

KRC has been conducting research on new bushing geometries for the T158LL, T157I, and XT172 track systems. The prototype T157I bushings have shown a 40% endurance life increase in limited laboratory tests. Additional laboratory tests will be conducted on all three bushings, with field tests to be conducted during the 2001 summer at YPG. These improved bushing designs may mitigate any detrimental effects due to the decreased thermal conductivity of titanium. Thus, this bushing development knowledge will be leveraged on this program.

Task 5. Finalize Preliminary Titanium Track Concept

The Dynamet/KRC team has prepared solid models of the shoe body, track pins, end connectors (if applicable), center guides, bushings and pads along with a detailed component weight calculation for a titanium track ("XT-175") appropriate for application to medium weight vehicles.

Task 6. Program Review and Reporting

Interim Reports have been submitted on schedule and this Final Report has been prepared and submitted in accordance with contractual and SBIR requirements.

3.0 Findings and Results of Phase I

3.1 Specimen Manufacture - Resulting Density:

Two titanium alloys, Ti-6Al-4V and Ti-6Al-6V-2Sn without particulate additions were manufactured as baseline materials to provide wear properties for "conventional" titanium materials. These two alloys, along with the softer commercially pure (CP) titanium were also used as the matrix materials for particulate additions aimed at providing enhanced wear properties.

Based on prior work at Dynamet, three types of particle additions were utilized: titanium carbide (TiC), titanium boride (added as TiB_2, transforms to TiB during processing), and tungsten (W, which partially provides solid solution strengthening and partially behaves as composite particulate addition). The compositions selected provide both for addition of particles individually, or in combination.

Table 1 provides a summary of the compositions produced along with their calculated theoretical density and the resulting measured density after CHIP processing. These results are provided both for the "plate" which corresponds to the wear sample and the "bar" which corresponds to the witness bar from which tensile properties were tested. Almost all materials achieved the target 99% minimum measured theoretical density using Dynamet's standard processing.

Table 1. Summary of Composition and Resulting Densities

	MATERIAL FOR WEAR PLATES:						Theo	HIPed Plate		HIPed Test Bar	
	BLEND No.	TITANIUM	TiC	TiB	W	s/n	Density g/cc	Density g/cc	% theo	Density g/cc	% Theo
Iteration 1:											
1	B-3307	Ti-6Al-4V				3	4.43	4.434	100.09%	4.438	100.18%
2	B-2767	Ti-6Al-4V	10 TiC			5	4.48	4.455	99.44%	4.428	98.84%
3	B-3333	Ti-6Al-4V	15 TiC			1	4.5	4.458	99.07%	4.459	99.09%
4	B-3281	Ti-6Al-4V		3 TiB_2		11	4.436	4.427	99.80%	4.423	99.71%
5	B-3200	Ti-6Al-4V		6 TiB_2		5	4.443	4.249	95.63%	4.076	91.74%
6	B-3315	Ti-6Al-4V	7 TiC	5 TiB_2		n/a	4.466	4.165	93.26%	n/a	n/a
7	B-3030	Ti-6Al-4V			10 W	7	4.79	4.812	100.46%	4.806	100.33%
8	B-3288	Ti-6Al-4V	10 TiC		5 W	8	4.6349	4.615	99.57%	4.613	99.53%
9	B-3318	Ti-6Al-6V-2Sn				3	4.54	4.547	100.15%	4.544	100.09%
10	B-3323	Ti-6Al-6V-2Sn	10 TiC			3	4.58	4.544	99.21%	4.55	99.34%
11	B-3326	CP Ti			10 W	21	4.88	4.904	100.49%	4.89	100.20%
12	B-3334	CP Ti	10 TiC		5 W	1	4.71	4.711	100.02%	4.705	99.89%
Iteration 2:											
13	B-3050	Ti-6Al-6V-2Sn	12 TiC			2	4.62	4.62	100.00%	4.59	99.35%
14	B-3343	CP Ti	10 TiC		10W	2	4.99	4.99	100.00%	4.94	99.00%
15	B-3344	Ti-6Al-4V	10 TiC		10W	2	4.90	4.90	100.00%	4.86	99.18%
16	B-3345	Ti-6Al-6V-2Sn	10 TiC		5W	1	4.79	4.79	100.00%	4.77	99.58%

3.2 ASTM G-65 Wear Test Results:

After machining the sample surfaces to a flat and acceptable surface finish to meet ASTM test requirements, all samples were tested by KRC in accordance with ASTM G-65. These results are summarized in **Table 2**.

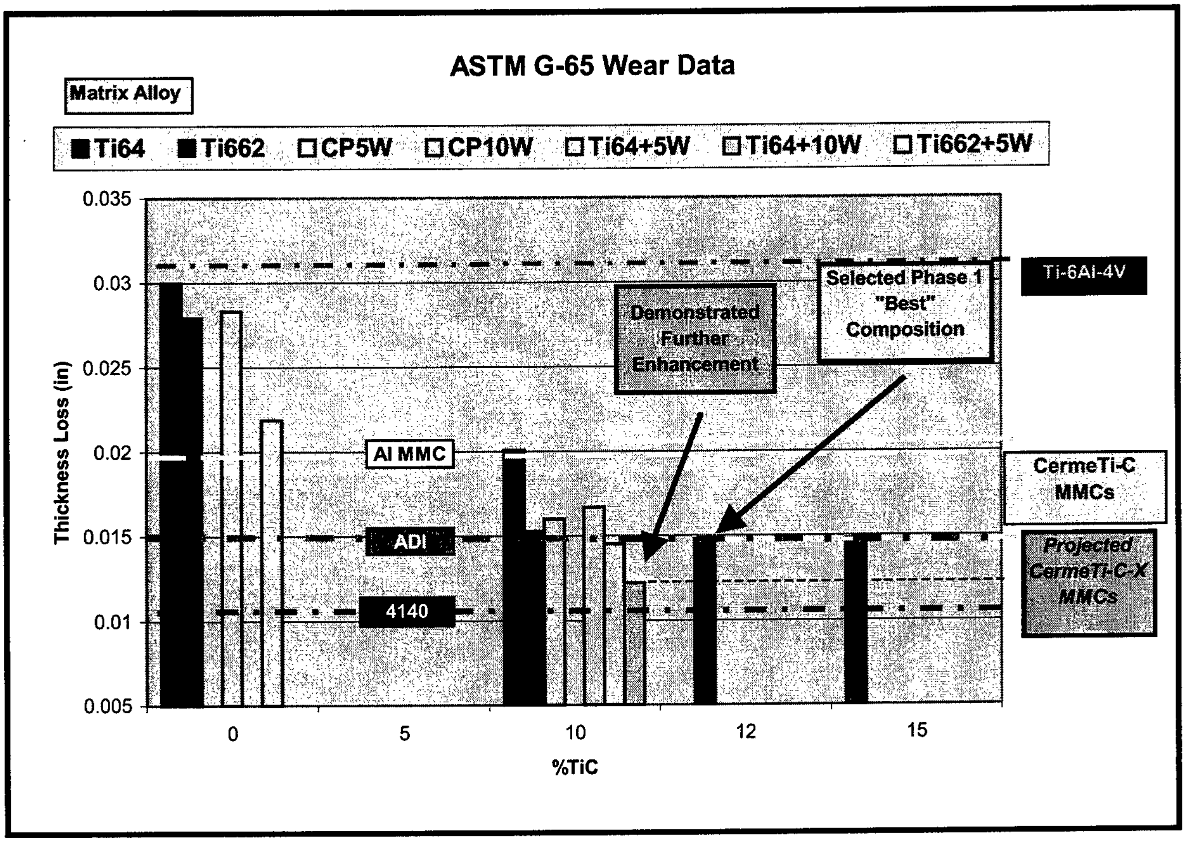
Table 2. ASTM G-65 Wear Test Results of Phase I Titanium Alloy and MMC Materials and Comparative Data for Al MMCs, Austempered Ductile Iron (ADI) and 4140 Steel

Test Load (lbs)	30
Test Time (min)	10

Sample	Initial Mass (g)	Final Mass (g)	Mass Loss (g)	Mass Loss %	Initial Thickness (in)	Final Thickness (in)	Thickness Loss (in)	Sand Used (mL)	Sand Flow (g/min)	Friction Start (lbf)	Friction End (lbf)
Dynamet Technology Powder Metal Titanium Alloys and MMC's - Various Grades											
Iteration 1:											
B-2767	70.4087	70.0490	0.3597	0.5109	0.4000	0.3799	0.0201	2750	0.0726	11.3	12.2
B-3030	72.5364	71.8347	0.7017	0.9674	0.3818	0.3599	0.0219	2760	0.0729	10.1	9.4
B-3200	64.0842	63.6382	0.4460	0.6960	0.3997	0.3831	0.0166	2780	0.0734	10.5	10.4
B-3281	73.2831	72.6964	0.5867	0.8006	0.4004	0.3791	0.0213	2700	0.0713	10.3	10.9
B-3288	71.3879	70.9251	0.4628	0.6483	0.3819	0.3652	0.0167	2750	0.0726	10.5	9.5
B-3307	63.8285	62.9224	0.9061	1.4196	0.3600	0.3300	0.0300	2720	0.0719	11.3	11.7
B-3315	69.9950	69.5217	0.4733	0.6762	0.3899	0.3735	0.0164	2800	0.0740	11.2	9.5
B-3318	74.4189	73.5586	0.8603	1.1560	0.3915	0.3636	0.0279	2780	0.0734	11.4	11.8
B-3323	73.2803	72.8684	0.4119	0.5621	0.3916	0.3763	0.0153	2800	0.0740	11.1	9.7
B-3326	71.6128	70.6905	0.9223	1.2879	0.3599	0.3316	0.0283	2770	0.0732	11.0	11.2
B-3333	70.7487	70.3629	0.3858	0.5453	0.3816	0.3668	0.0148	2750	0.0726	11.6	9.9
B-3334	71.5762	71.1219	0.4543	0.6347	0.3825	0.3665	0.0160	2760	0.0729	10.9	9.9
Iteration 2:											
B-3050	71.2108	70.8222	0.3886	0.5457	0.3890	0.3742	0.0148	2875	0.0759	10.6	9.6
B-3343	74.4142	73.9317	0.4825	0.6484	0.3798	0.3603	0.0195	2870	0.0758	10.7	9.6
B-3344	75.5767	75.1801	0.3966	0.5248	0.3802	0.3657	0.0145	2850	0.0753	10.5	9.1
B-3345	74.6997	74.3287	0.3710	0.4967	0.3884	0.3762	0.0122	2850	0.0753	10.8	9.3
ADI											
Sample	Initial Mass (g)	Final Mass (g)	Mass Loss (g)	Mass Loss %	Initial Thickness (in)	Final Thickness (in)	Thickness Loss (in)	Sand Used (mL)	Sand Flow (g/min)	Friction Start (lbf)	Friction End (lbf)
ADI 1	128.4615	128.0102	0.4513	0.3513	0.3759	0.3616	0.0143	2200	0.058118	10.7	?
ADI 2	128.1898	127.7460	0.4438	0.3462	0.3758	0.3613	0.0145	2350	0.06208	?	?
Average	128.3257	127.8781	0.4476	0.3488	0.3759	0.3615	0.0144	2275	0.0601	10.7	#DIV/0!
ADI 3	128.2755	127.8288	0.4467	0.3482	0.3761	0.3622	0.0139	2500	0.066043	9.2	9.7
ADI 4	128.5764	128.1353	0.4411	0.3431	0.3759	0.3624	0.0135	2525	0.066703	9.5	9.4
Average	128.4260	127.9821	0.4439	0.3456	0.3760	0.3623	0.0137	2513	0.0664	9.4	9.6
Aluminum MMC 35% Test A39 Samples											
A39 - 4	44.5107	44.2270	0.2837	0.6374	0.4965	0.4764	0.0201	2400	0.063401	9.6	8.8
A39 - 6	44.7926	44.4687	0.3239	0.7231	0.4956	0.4760	0.0196	2440	0.064458	8.6	8.2
A39 - 8	44.6058	44.3116	0.2942	0.6596	0.4958	0.4760	0.0198	2435	0.064326	8.9	8.3
Average	44.6364	44.3358	0.3006	0.6733	0.4960	0.4761	0.0198	2425	0.0641	9.0	8.4
4140 Steel											
Sample	Initial Mass (g)	Final Mass (g)	Mass Loss (g)	Mass Loss %	Initial Thickness (in)	Final Thickness (in)	Thickness Loss (in)	Sand Used (mL)	Sand Flow (g/min)	Friction Start (lbf)	Friction End (lbf)
4140 1	27.0620	26.7434	0.3186	1.1773	0.0784	0.0670	0.0114	2050	0.054155	?	9.2
4140 2	27.3905	27.0358	0.3547	1.2950	0.0754	0.0671	0.0083	2250	0.059439	10.2	9.8
4140 3	27.9223	27.5683	0.3540	1.2678	0.0771	0.0665	0.0106	2225	0.058778	9.2	9.4
Average	27.4583	27.1158	0.3424	1.2467	0.0770	0.0669	0.0101	2175	0.0575	9.7	9.5

Results are presented in graphical from in **Figure 2**. These results include both the initial data and the later iteration 2 samples. The data shows the capability of the titanium MMC materials to provide superior wear resistance to the more highly loaded Aluminum MMC, and essentially equivalent wear resistance to austempered ductile iron (ADI) based upon ASTM G-65 performance. Further the data suggest the technical feasibility for these material systems to be further improved and potentially approach the wear resistance of 4140 steel.

Figure 2. Summary of ASTM G-65 for Candidate Tank Track Materials



3.3 Tensile Test Results:

Limited tensile testing (single specimen) was conducted from specimens machined from witness bars from each blend. These results are provided in **Table 3**. Results demonstrate the capability of the P/M processed titanium alloys (Ti-6Al-4V and Ti-6Al-6V-2Sn) to provide high strength with excellent ductility, comparable to properties achieved and specified for wrought titanium, and superior to commercial titanium castings. This table also includes the preliminary tensile results from the iteration 2 compositions (shaded green). Furthermore, the strength and ductility levels for both the titanium alloys and their modified more wear resistant compositions demonstrated on this program are far superior to aluminum MMCs with similar wear results based on preliminary screening tests conducted to date. This relative data is presented in Table 4.

Table 3. Preliminary RT Tensile Test Results from Candidate P/M Titanium Alloy and Composite Materials

MATERIAL FOR WEAR PLATES:			Theo	Measured		Tensile Test Data (RN 343555 & 347709):				
		s/n	Density	Density	% Theo	UTS	YS	El	RA	Modulus
Blend No.	Composition		g/cc	g/cc						
B-3307	**Ti-6Al-4V**	3	4.43	4.438	100.2%	137.4	123.0	19.0	38.7	16.3
B-2767	Ti-6Al-4V+10TiC	5	4.48	4.428	98.8%	111.9	111.9	2.1	0.0	18.2
B-3333	Ti-6Al-4V+15TiC	1	4.50	4.459	99.1%	131.8	131.8	1.9	3.2	19.5
B-3281	Ti-6Al-4V+3TiB_2	11	4.44	4.423	99.7%	151.4	138.4	7.2	8.6	18.1
B-3200	Ti-6Al-4V+6TiB_2	5	4.44	4.076	91.7%	52.2	52.2	2.0	2.7	14.6
B-3315	Ti-6Al-4V+7TiC+5TiB_2	n/a	4.47	n/a	N/a	x	x	x	x	x
B-3030	Ti-6Al-4V+10W	7	4.79	4.806	100.3%	163.9	153.0	16.4	36.6	15.9
B-3288	Ti-6Al-4V+10TiC+5W	8	4.63	4.613	99.5%	145.0	144.8	4.2	4.7	18.2
B-3344	Ti-6Al-4V+10TiC+10W	2	4.90	4.90	100.0%	144.0	144.0	1.0*	1.8*	n/a
B-3318	**Ti-6Al-6V-2Sn**	3	4.54	4.544	100.1%	147.9	134.9	20.6	38.5	16.2
B-3323	Ti-6Al-6V-2Sn+10TiC	3	4.58	4.550	99.3%	156.0	147.9	2.1	4.7	18.8
B-3050	Ti-6A-6V-2Sn+12 TiC	4	4.59	4.619	99.4%	149.0	149.0	0.6	2.2	19.4**
B-3345	Ti-6Al-6V-2Sn+10TiC+5W	1	4.77	4.79	99.6%	153.2	153.2	1.1***	1.8***	n/a
n/a	**CP Ti Matrix*:**	typ	4.5	4.5	100%	75.0	60.0	25.0	50.0	16.0
B-3326	CP Ti+10W	21	4.88	4.890	100.2%	115.5	93.8	20.9	45.1	15.2
B-3334	CP Ti+10TiC+5W	1	4.71	4.705	99.9%	108.0	96.4	5.0	3.3	17.7
B-3343	CP Ti+10TiC+10W	2	4.99	4.99	100.0%	112.8	99.5	1.9	2.5	N/A

* for reference - typical data from prior work, sample not produced on this program,

** modulus data from sample B-3319 s/n 2 (same composition as B-3050) measured per ASTM E1876

***broke in outer quarter of gage; may not be representative of the material

Table 4. Property Comparison of Selected P/M Titanium Compositions Versus Other Candidate Track Materials

ID	Alloys:	Density	UTS	YS	El	RA	Modulus
B-3307	P/M Ti-6Al-4V	4.43	137	123	19	39	16-17
REF	Wrought Ti-6Al-4V (min)[1]	4.43	130	120	10	20-25	16-17
REF	Cast Ti-6Al-4V (min)[2]	4.43	130	120	6	10	16-17
B-3318	P/M Ti-6Al-6V-2Sn	4.54	148	135	21	39	16-17
REF	A356 Aluminum	2.77	45	35	6	8	10
	TiC-Reinforced Titanium MMCs:						
B-3050	Ti-6Al-6V-2Sn+12TiC	4.59	149	149	1	2	19.4
B-3323	Ti-6Al-6V-2Sn + 10% TiC	4.58	156	148	2	5	19
B-3333	Ti-6Al-4V+15TiC	4.46	132	132	2	3	20
	W-Reinforced Titanium MMCs:						
B-3030	Ti-6Al-4V + 10 W	4.79	163	153	16	37	16
B-3326	CP + 10 W	4.88	116	94	21	45	15
	TiC + W-Reinforced Titanium MMCs:						
B-3345	Ti-6Al-6V-2Sn + 10 TiC + 5W	4.77	153	153	1	2	n/a
B-3288	Ti-6Al-4V + 10 TiC + 5W	4.63	145	145	4	5	18
B-3334	CP Ti + 10 TiC + 5 W	4.71	108	96	5	3	18
	Al MMCs						
REF	Al/SiC MMC (35%, A356)	2.77	45	40	0.1	N/A	14
	Steel						
REF	ADI Grade 3+	7.00	175	140	6	8	25
REF	4140	7.83	170	120	14	18	30

[1] *MIL-HDBK-5G, MIL-T-9046J, AMS 4911, AMS*
[2] *ASTM B367, Boeing MS 7-310*

3.4 Second Iteration ASTM G-65 Sample Manufacture and Test

The results from the 2nd iteration test samples have been incorporated into this Phase 1 Final Report and are included within the above tables and charts.

3.5 Center Guide Wear Specimen Manufacture

Center Guide wear preforms have been completed through the CHIP process and have all achieved above 99% density. The preforms are currently being machined to the center guide wear test configuration.

3.6 Center Guide Wear Test Results

Results from KRC wear testing will be provided as an addendum to the Phase 1 Final Report.

3.7 Titanium Bushing Endurance Tests

A Ti-6Al-4V adaptor was manufactured for bushing endurance testing. It was produced to KRCs drawing by machining from Ti-6Al-4V alloy bar. After machining (to 2.120" OD x 1.195" ID x 3.275" long) it was supplied by Dynamet to KRC for endurance testing for comparison to the baseline steel. Initial tests were conducted during this reporting period. Results demonstrate the acceptability of the Ti-6Al-4V compared with the baseline steel bushing and are included as Figures 3 and 4.

Figure 3. Summary of Ti-6Al-4V bushing results compared with Steel showing 84,000 cycles achieved with the titanium versus 98,500 achieved with steel (Note: 2nd steel test failed early due to manufacturing defect at 48,000 cycles).

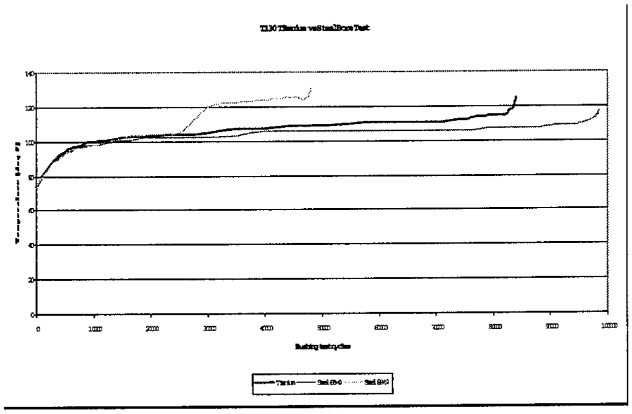
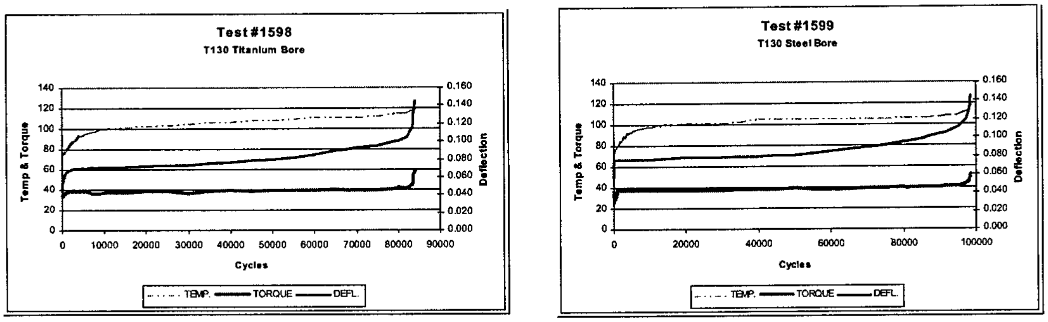


Figure 4. Details of T-130 bushing endurance results with Ti-6Al-4V (left) and Steel (right).



3.8 Design Analysis

Design analysis has been conducted at KRC. **Figures 5-8** depict the top and bottom view of each of 4 lightweight tank track designs geared for AAAV. **Table 5** provides track concept parameters and **Table 6** details the weight distributions associated with these designs. Concept designs geared toward T154 are also under consideration.

These track concepts demonstrate a weight of 56 – 65 pounds/ft. Weight comparisons to a 22" steel track of 100-120 pounds/ft. and 45 – 55 pounds/ft. for an aluminum track show a significant weight savings from a steel track. While slightly heavier than aluminum, a titanium track will provide better structural integrity as compared to aluminum.

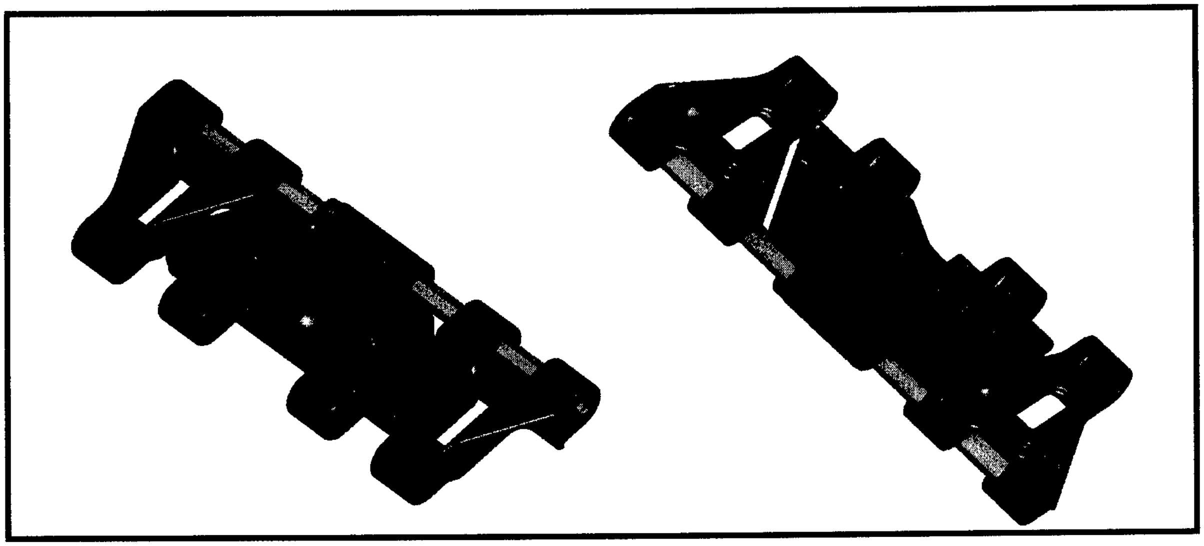


Figure 5. Multi-Block Track Concept (multi body, single pin, drive on steel end body) with Titanium Shoe and Pad Plate (top and bottom view)

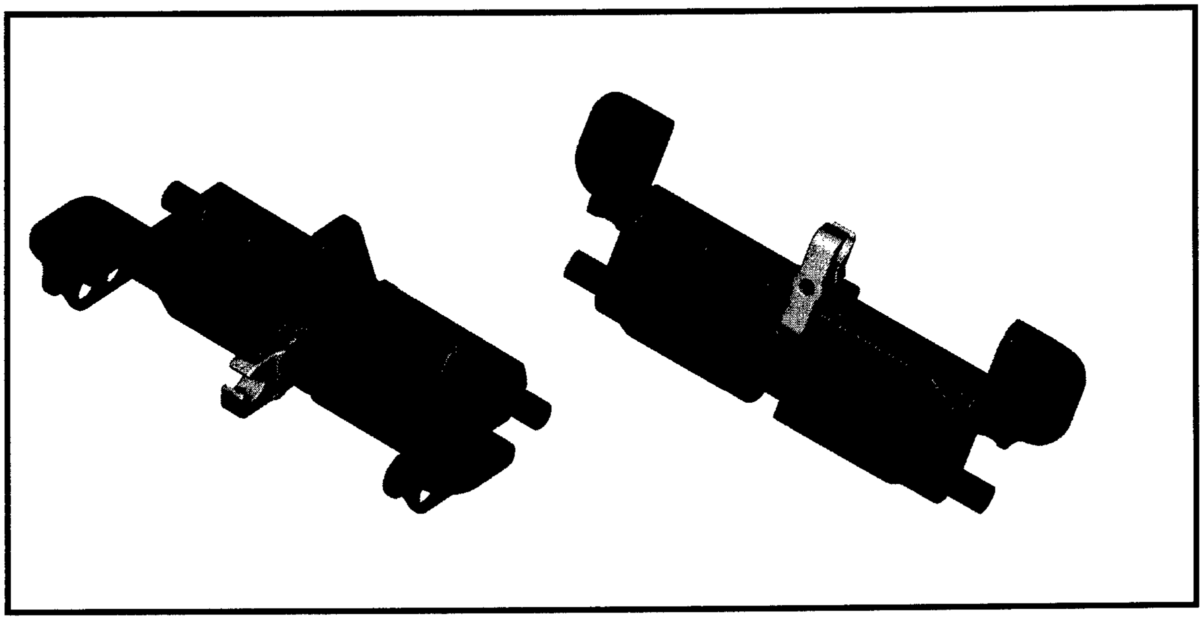


Figure 6. Big Block 4 Track Concept (single body, double pin, drive on steel end connector) with Titanium Shoe and Pad Plate Material (top and bottom view)

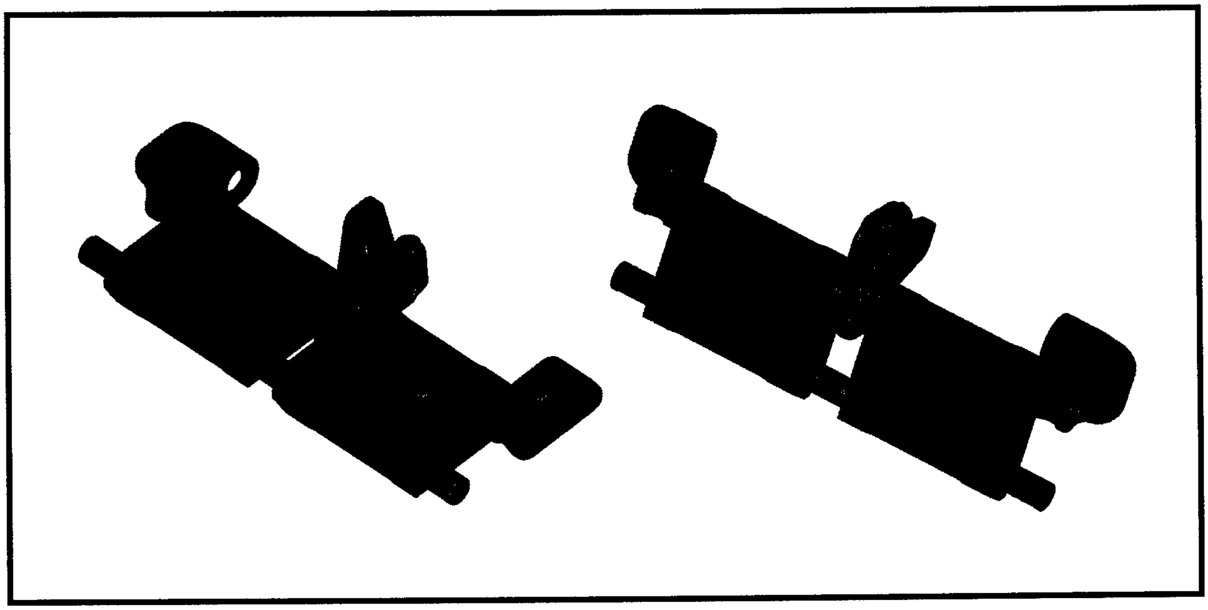


Figure 7. T158 Variant Track Concept (multi body, double pin, drive on steel end connectors) with Titanium Shoe and Pad Plate Material (top and bottom view)

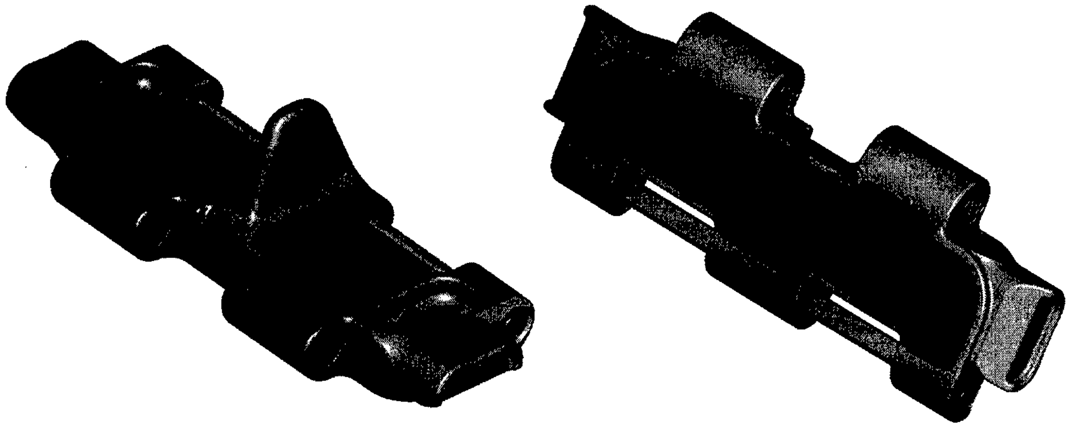


Figure 8. NSB Track Concept (single body, single pin, drive on outside of body) with Titanium Shoe and Pad Plate Material

The conceptual titanium track designs included both single pin and double concepts to determine track weight trade-offs. Each design has specific strengths, with the only high risk option being the NSB design by driving on the titanium track shoe block. All other versions drive on steel connectors. The high strength and good mechanical properties of the titanium alloys ensure a low risk for structural integrity of the track shoes. Other attributes include extended track life through greater bushing area in Big Block 4 (BB4), and high strength connectors in the Multi-Block design. ***All titanium concepts demonstrate a significant weight savings over steel.***

Table 5. Final Concept Parameters for Various Titanium AAAV Track Designs

	Multi-Block	Big Block 4	UDLP - T158 Variant	NSB
Drive System	*Multi body, Single pin, Drive on steel end body*	*Single body, Double pin, Drive on steel end connector*	*Multi body, Double pin, Drive on Steel End Connectors*	*Single body, Single pin, Drive on outside of body*
Shoe Material	Titanium	Titanium	Titanium	Titanium
Pad Plate Material	Titanium	Titanium	Titanium	Titanium
Connector Material	----	Steel	Steel	----
Pin Type	Hex, hollow	Round, hollow	Round, hollow	Hex, solid
Pitch Length (in.)	6.000	6.250	6.000	6.000
Pitch Width (in.)	21.500	21.500	21.500	21.500
Estimated Pitch Weight (lb.)	29.6	29.2	28.3	32.5
Estimated Weight Per Foot (lb.)	59.2	56.1	56.5	65.0
Estimated Pad Area (sq in)	36.26	48.20	46.44	62.36
Number of Parts Per Pitch	20	20	20	16
No. of Component Types (Rubber Not Counted)	10	11	11	8
Number of Field Parts	9	16	15	7
Track Height (Road Surface to Road Wheel) (in.)	2.675	2.888	3.010	3.051
Shoe Height (Ignore CG)	2.125	2.338	2.485	2.401
Bushing Sleeve OD (in.)	1.125	----	----	1.063
Pin Outer Diameter (in.)	----	1.125	1.125	----
Pin Inner Diameter (in.)	0.400	0.690	0.650	----
Pin Width Across Flats (in.)	0.950	----	----	0.810
Pin Length (in.)	21.200	18.200	18.750	17.890
Pin Nut Height	0.750	----	----	0.777
Binocular Tube Inner Diameter (in.)	1.450	1.550	1.440	1.425
Binocular Tube Outer Diameter (in.)	1.900	2.150	2.000	2.025
Binocular Tube Wall Thickness (in.)	0.225	0.300	0.149	0.300
Effective Bushing Length (in.)	10.8/8.0	13.880	13.500	8.3/7.9
Bushing Ratio (Leading/Trailing)	1.350	1.000	1.000	1.051
Compressed Bushing Height (in.)	0.163	0.213	0.158	0.181
Center Guide Height (in.)	3.720	3.375	3.415	3.600
Pad Height from Grouser (in.)	0.500	0.500	0.525	0.600
Maximum Pad Height (Without Bolt) (in.)	1.788	1.188	1.535	1.525
Pad Bolt Dia.	0.425	0.500	0.625	0.500
Pin Span / Shoe (in.)	6.000	3.250	3.880	6.000
Pin Span / Connector (in.)	----	3.000	2.125	----
Estimated Pitch Diameter (Nominal - 11 Teeth)	21.297	22.184	21.297	21.297
Projected Shoe Area to Ground (sq. in.)	114.5	79.7	77.9	123.7
Width Betw Sprocket Engagement (Inside Edges)	13.800	15.200	15.337	18.690
Sprocket Window Width (in.)	1.600	----	----	----

Table 6. Weight Distribution for Various Titanium AAAV Track Concept Designs

	BB4				
	Piece Volume	Piece Density	Piece Weight	Pieces	Weight
Shoe Body	86.75	0.162	14.05	1	14.05
Backing Rubber	5.61	0.034	0.19	2	0.38
Pin	11.25	0.283	3.18	2	6.37
Pin Nut			0.00	0	0.00
Pad Plate	2.11	0.162	0.34	2	0.68
Pad Plate Bolt	0.38	0.162	0.06	2	0.12
Pad Plate Nut	0.16	0.162	0.03	2	0.05
Pad Rubber	20.84	0.034	0.71	2	1.42
End Connector	6.32	0.283	1.79	2	3.58
End Connector Bolt	0.46	0.162	0.07	2	0.15
End Connector Wedge	1.08	0.162	0.17	2	0.35
Mid Connector	6.5	0.162	1.05	1	1.05
Mid Connector Bolt	0.77	0.162	0.12	1	0.12
Bushing and Sleeve (1)	6.20	0.034	0.21	4	0.84
Bushing and Sleeve (2)			0.00	0	0.00
Bushing and Sleeve (3)			0.00	0	0.00
					29.18

Multi-Block				
Piece Volume	Piece Density	Piece Weight	Pieces	Weight
62.52	0.162	10.13	1	10.13
4.57	0.035	0.16	2	0.32
12.7	0.162	2.06	1	2.06
0.45	0.162	0.07	2	0.15
3.22	0.162	0.52	1	0.52
0.29	0.162	0.05	2	0.09
0.08	0.162	0.01	2	0.03
55.5	0.035	1.94	1	1.94
23.25	0.283	6.58	2	13.16
		0.00	0	0.00
		0.00	0	0.00
		0.00	0	0.00
		0.00	0	0.00
4.08	0.069	0.28	1	0.28
1.81	0.069	0.12	6	0.75
1.05	0.069	0.07	2	0.14
				29.57

	UDLP T158 Variant				
	Piece Volume	Piece Density	Piece Weight	Pieces	Weight
Shoe Body	34.56	0.162	5.60	2	11.20
Backing Rubber	11.34	0.034	0.39	2	0.77
Pin	11.83	0.283	3.35	2	6.70
Pin Nut			0.00	0	0.00
Pad Plate	2.67	0.162	0.43	2	0.87
Pad Plate Bolt	0.89	0.162	0.14	2	0.29
Pad Plate Nut	0.35	0.162	0.06	2	0.11
Pad Rubber	25.1	0.034	0.85	2	1.71
End Connector	6.62	0.283	1.87	2	3.75
End Connector Bolt	0.65	0.162	0.11	2	0.21
End Connector Wedge	0.62	0.162	0.10	2	0.20
Mid Connector	10.09	0.162	1.63	1	1.63
Mid Connector Bolt	0.77	0.162	0.12	2	0.25
Bushing and Sleeve (1)	4.28	0.034	0.15	4	0.58
Bushing and Sleeve (2)			0.00	2	0.00
Bushing and Sleeve (3)			0.00	0	0.00
					28.26

NSB				
Piece Volume	Piece Density	Piece Weight	Pieces	Weight
143.47	0.162	23.24	1	23.24
13.59	0.034	0.46	2	0.92
9.54	0.162	1.55	1	1.55
0.39	0.162	0.06	2	0.13
12.81	0.162	2.08	1	2.08
0.29	0.162	0.05	2	0.09
0.16	0.162	0.03	2	0.05
93.26	0.034	3.17	1	3.17
		0.00	0	0.00
		0.00	0	0.00
		0.00	0	0.00
		0.00	0	0.00
		0.00	0	0.00
4.36	0.08	0.35	3	1.05
1.99	0.08	0.16	2	0.32
		0.00	0	0.00
				32.59

4.0 Phase 1 Summary - Demonstration of Technical Feasibility

The results of Phase I clearly demonstrated the technical feasibility of the advanced powder metal titanium composite technology to find applications in lightweight tank track components, particularly as a material for center guides. The titanium composite materials having demonstrated wear resistance far superior to conventional titanium alloys and surpassing the wear characteristics achieved with more highly reinforced and less tough Al/SiC MMCs and ADI. The Phase I results also suggest that with further modification this titanium technology has the potential to match or surpass the wear resistance of 4140 steel. Using this technology, lightweight tank track designs can be developed and specific titanium components could be inserted into a variety of current and future track systems, including AAAV, Crusader, M109 Howitzer and Future Combat Systems.

Further models indicate that titanium track designs offering a **25 – 40 % weight reduction** versus steel are feasible.

This technology has also been demonstrated to provide significant robustness in regard to material properties, design flexibility and manufacturability by the CHIP powder metal process for cost-effective manufacture to near-net shape of applicable tank track components.