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SERAPHIM: A Propulsion Technology for Fast Trains

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ABSTRACT

The Segmented Rail Phased Induction Motor (SERAPHIM) is a compact, pulsed linear induction motor (LIM) offering a unique capability for very high speed train propulsion. It uses technology developed for the Sandia coilgun, an electromagnetic launcher designed to accelerate projectiles to several kilometers per second! Both aluminum cylinders and plates were accelerated to a kilometer per second (Mach 3) by passing through a sequence of coils which were energized at the appropriate time. Although this technology was developed for ultra-high velocity, it can be readily adapted to train propulsion for which, at sea level, the power required to overcome air resistance limits the operational speed to a more modest 300 mph. Here, the geometry is reversed. The coils are on the vehicle and the "projectiles" are fixed along the roadbed.

In the 1970's, the Federal Railroad Administration tested a 200 mph train riding on passive wheels and powered by a conventional LIM. In a LIM, electrical windings generate a backward moving wave of magnetic flux in a conducting reaction rail, producing a forward force. SERAPHIM operates not by embedding flux in a conductor, but by excluding it. In this propulsion scheme, pairs of closely spaced coils on the vehicle straddle a segmented aluminum reaction rail. A high frequency current is switched on as a coil pair crosses an edge and remains off as they overtake the next segment. This induces surface currents which repel the coil. In essence, the pulsed coils push off segment edges because at the high frequency of operation, the flux has insufficient time to penetrate. In contrast to conventional LIMs, the performance actually improves with velocity, even for a minimal motor consisting of a single coil pair reacting with a single plate.

With either distributed onboard power, a passive wheeled train powered by a SERAPHIM is an attractive alternative to one which is levitated using superconducting magnets (MAGLEV) and propelled by switched electrified coils in the roadbed.

This paper will present results of proof-of-principle tests, electromagnetic computer simulations, and systems analysis. It is concluded that this new linear induction motor can be implemented using existing technology and is a promising alternative propulsion method for very high speed rail transportation.

INTRODUCTION

The application of pulsed, linear induction motor technology for high speed trains is being assessed at Sandia National Laboratories in a project called SERAPHIM (SEgmented RAil PHased Induction Motor). This concept involves the use of rapidly-pulsed magnetic fields and a segmented reaction rail, as opposed to the low frequency fields and continuous reaction rails found in conventional linear induction motors (LIM). This gives a high-traction, compact, and efficient linear motor for high speed operation. The pulsed linear induction motor uses technology developed for the Sandia electromagnetic launch program in which projectiles have been accelerated electromagnetically to more than 1 km/s in devices similar to that shown in Figure 1. In the application presented here, the roles are reversed. The coils are on the train and sections of a segmented aluminum rail play the role of the projectile.

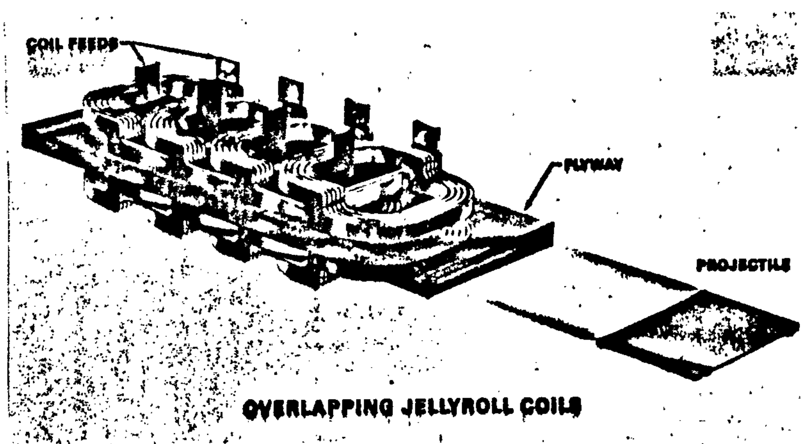

Figure 1: The Sandia Electromagnetic Plate Launcher

Linear induction motors were used in high speed rail experiments conducted by the Federal Railroad Administration during the 1970s. Tests at the Transportation Test Center in Pueblo, Colorado were conducted at speeds over 200 mph with demonstrator vehicles that used a conventional linear induction

motor and passive steel wheels. In a conventional LIM, electrical windings generate a backward moving wave of magnetic flux in a conducting reaction rail, producing a forward force. SERAPHIM operates not by embedding flux in a conductor, but by excluding it. In the double-sided version, pairs of closely spaced coils on the vehicle straddle a segmented aluminum rail, as in Figure 2. The current is pulsed as the coils cross an edge, as shown in Figure 3, and remains off as they overtake the next segment. This induces surface currents which repel the coil. In essence, the pulsed coils push off the edges because at the high frequency of operation, the flux has insufficient time to penetrate. Braking can be achieved by reversing the phasing of coil pulsing so that current is applied as a coil overtakes a plate.

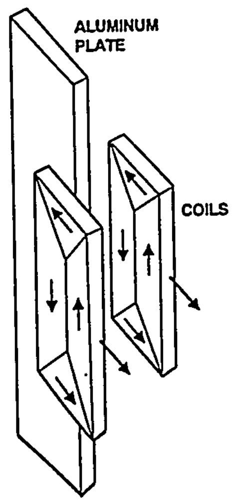

Figure 2. Coil pairs straddle an aluminum plate and push off the edge. For single-sided operation, only one coil is used.

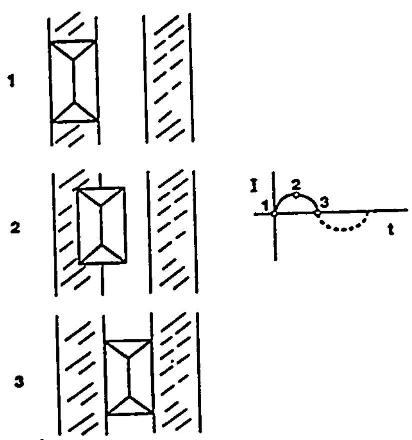

Figure 3. Current is pulsed as coils leave plate and remains off as they move onto the next one.

Figure 4 shows the schematic of the power distribution, coil sets, and reaction rail. The coils are each capable of producing up to 3 kN thrust. Two power cars, one at either end of the train, provide 6 MW (8,000 hp) each. Power modulators provide the pulsed DC voltage (5 kV nominal) to the coils. Each modulator powers 6 coil pairs and there are five modulators on each car, giving 39 coil sets per car. The coils must be pulsed in synchronization with the reaction rail segments. This is provided by a sense-and-fire circuit that controls the pulsing of the power modulators. Each power modulator provides about 625 kW average power, in pulses of 2 ms half-width, 1900 J per pulse, at frequency from 100 - 230 Hz.

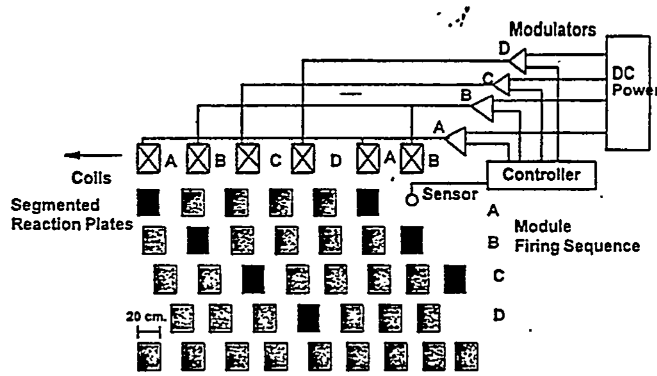

Figure 4. Schematic of the SERAPHIM power circuit.

The maximum speed is limited primarily by the available power, aerodynamic drag, and grade. For cruise at 200 mph on straight and level track, a power of 6.3 MW (8,500 hp) is required. To meet Federal Railroad Administration specifications for acceleration, however, a maximum power of 12 MW is provided for accelerating from 0 to 210 km/hr (130 mph) in 4 minutes and a distance of 11.7 km (7 miles). With this power capability, the four-car train could climb a 2% grade at 250 km/hr (150 mph). This power could be delivered by either an on-board or external power source. For a rail line that has the external power capability already in place, such as the North-East Corridor, the use of catenary or third-rail power lines is the obvious choice. However, for rail lines that do not have the external power lines in place, an on-board power unit may be preferred for near-term implementation. Two gas turbine-generator sets on each of two power cars could fulfill this role.

Linear induction motor technology is mature and has been demonstrated on a limited basis in high speed rail applications. The performance improvements that can be achieved with pulsed coils allows the LIM to be made compact light weight. Since locomotives need no longer be heavy to insure traction, the use of advanced vehicle fabrication techniques and materials could reduce the train weight considerably and thus lower the overall power requirements.

Three SERAPHIM train concepts are shown in Figure 5. Electrified coils on the train react against a segmented reaction rail mounted on the roadway. In Figure 5a the reaction rail is composed of aluminum plates mounted horizontally between the tracks, while Figure 5b shows a configuration in which a segmented aluminum rail is mounted along side the track. Figure 5c depicts an elevated 300 mph vehicle in which the segmented rail is overhead. The trains are supported by wheels, either with conventional truck-axle arrangement or independent wheel suspension. The use of the linear induction motor provides high thrust with less rail wear than with conventional high speed locomotives. The reaction rail does not come into mechanical contact with the train, does not experience severe heating or mechanical loads, and thus will be less prone to wear and damage.

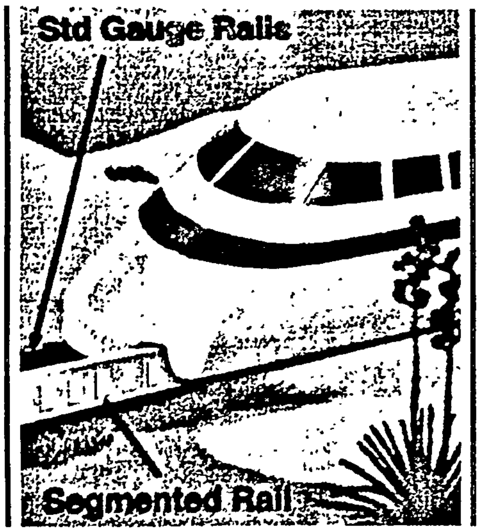

Figure 5a. SERAPHIM train with single-sided motor. Reaction plates lie between the rails.

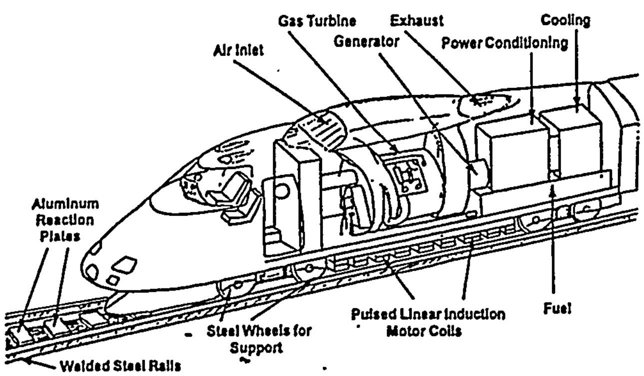

Figure 5b. SERAPHIM train with segmented rail on side of track.

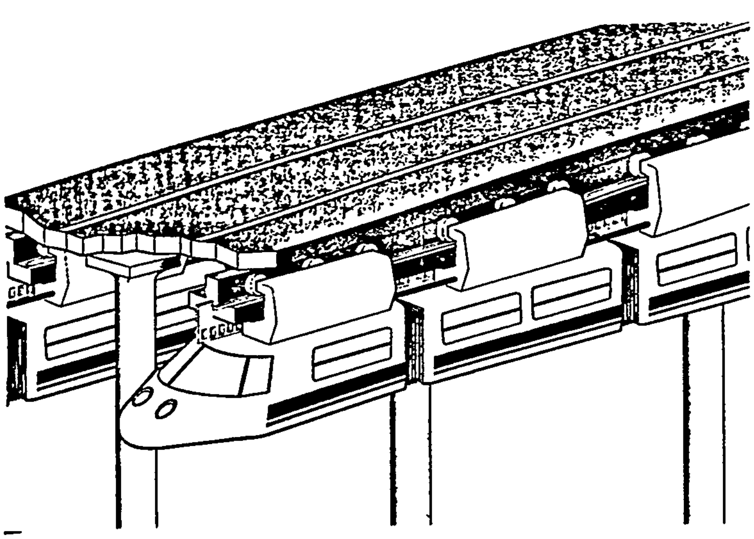

Figure 5c. Very high speed elevated SERAPHIM train with overhead motor.

PROOF-OF-PRINCIPLE DEMONSTRATION

Experiments were conducted to demonstrate the feasibility of the pulsed induction motor and to collect data for scaling. A three-stage motor demonstration was built which accelerated a 14.4 kg (32 lb) aluminum plate (20 x 40 x 2 cm) down a 4 m track to speeds of over 15 m/sec (34 mph). The experiment configuration is shown in Figure 6. Peak thrust up to 18 kN (4000 lbf) per coilset was demonstrated. The coils were full scale and operated at much higher field intensity and impulse than required for a passenger train but did not operate repetitively. The energy gain and efficiency were shown to increase with velocity as predicted by circuit calculations. The driving frequency, vehicle velocity, excitation phase, and energy were all varied and the velocity measured at each stage with fiber optic traps and video framing cameras.

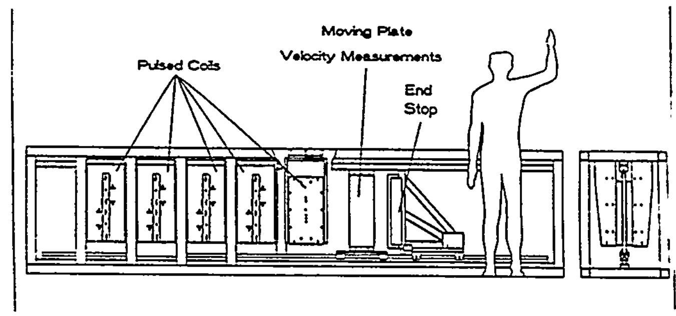

Figure 6. Three coil SERAPHIM proof-of-principle demonstration which accelerated an aluminum plate.

Each coil had two windings of 51 turns of 0.040 x 0.500 inch kapton-dacron insulated copper strap. The coils were all driven with identical damped ringing waveforms triggered with appropriate timing by fiber optic position sensors. Each stage had its own pulse generator, switched by a single ignitron switch. Simulations predict an inductance of 3.74 mH for the series connected coils of a stage in free space. The presence of the plate can reduce the inductance by almost a factor of two. The total energy per stage was 5 kJ for most of the testing and the pulse width was about 7 milliseconds.

Further tests were conducted with a smaller capacitor, solid state switching, and an energy recovery circuit. This circuit used a 263 μfd capacitor charged up to 4 kV, with energy of up to 2.1 kJ. The thrust provided by this capacitor discharging into the coil-set was measured from a static start. The average thrust, over one complete discharge cycle, for 2 kJ initial energy, was 6.5 kN, or 3 kN/kJ.

The drive circuit that appears best suited to the SERAPHIM motor is illustrated schematically in Figure 7. This drive circuit is basically a pulse modulator which generates a high current pulse train required to energize the drive coils and can be operated at a continuously variable pulse repetition rate from single pulse to approximately 500 Hz. Prime power is supplied by a DC generator or an AC alternator/rectifier.

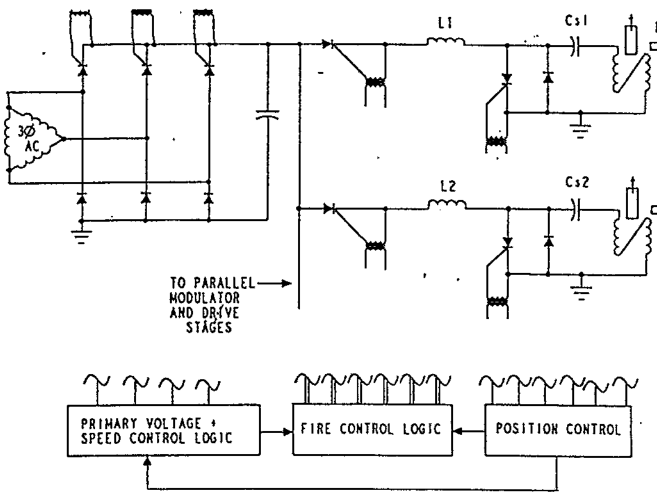

Figure 7. SERAPHIM drive circuit.

An important feature of the modulator is that it provides energy recovery following each pulse. With the circuit configured as shown in Figure 7, a full sinusoidal current cycle is delivered to the coils, as shown in Figure 8a. Energy not lost to heat or converted to motion by the coil and reaction plate is returned to the storage capacitor Csn during the second half-cycle and is trapped by the anti-parallel diode Dsn at the original polarity of Csn when the current goes to zero (Figure 8b). Preliminary measurements of the energy recovery efficiency of this circuit indicates over 80% recovery of the energy that was originally in Co. A demonstration model for this modulator circuit has been fabricated and tested. This circuit has been used in pulsing a coil-set and measuring thrust, as discussed in the previous section. The energy recovery efficiency has also been measured, exceeding 80%. The modulator was made from off-the-shelf capacitors and solid-state thyristor switches.

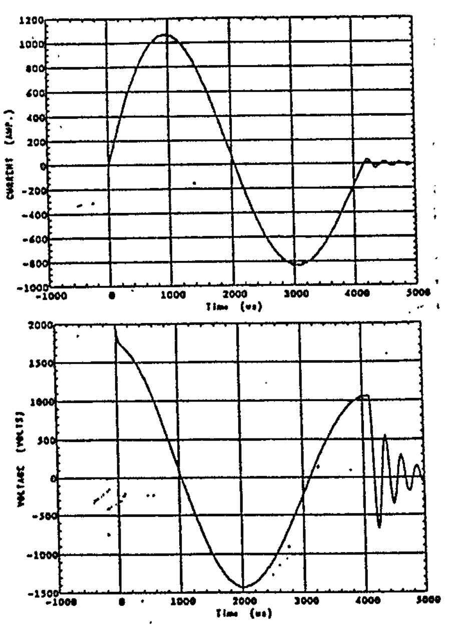

Figure 8. Waveforms for; a) current and b) voltage showing the recharging of the capacitor for energy recovery.

Table 1 gives a summary of the weight and volume estimates for the power switching electronics for a power modulator sized for a single coil set (125 kW). This modulator could be mounted at the location of the coil-set, or more likely housed within the power car or locomotive body and connected to the coils by high voltage cables. Some volume reduction can be gained by combining these modules into power packs that drive multiple coil-sets, for example, 6 coil-sets driven by each modulator power pack. The optimum design of the power modulator system will be controlled by convenience of location, accessibility, cable connections, and cooling requirements.

Table 1
125 kW Power Modulator Weight and Volume Estimate

	Weight/lb	Volume/ft^3
Charging Thyristors, Tcn	1.0	0.1
Charging inductors, La	10.0	0.5
Charging diodes, Dcn	1.0	0.05
Pulse drive thyristors	10.0	0.5
Charge recovery Inductor/Diode, Lrn & Drn	5.0	0.2
Driver Capacitor, Dsn (with cooling)	50	0.7
Misc. (brackets, containers, fans, etc.)	15	2.0
Totals	**86**	**4.05**

SERAPHIM can be configured either with double-sided coils, as shown in Figure 2 and tested in the feasibility demonstration, or single-sided, as shown in Figure 5a. In the single-sided design, the reaction rail lies flat on the ground between the steel support rails. The disadvantage is that, for a given amount of input energy, a smaller force is exerted. Since the force is the change in energy divided by the relative distance traveled by the plate, the configuration which produces the most energy difference is the more effective. The two-sided geometry is the more efficient in converting to mechanical force. The single sided motor also experiences a net normal force. This does not mean, however, that the single-sided configuration is unacceptable. With energy recovery in the power circuit, good overall efficiency can still be maintained for the single-sided configuration. The price to be paid is in increased circulating power for the single-sided configuration.

WHEEL AND SUSPENSION

A key component of the SERAPHIM concept is the use of wheel-on-rail support for the high speed vehicle. Standard forged steel wheels of good quality are capable of handling speeds over 200 mph as long as there is no tread braking. (Ref. 1) The French TGV demonstrated 515.3 km/hr (309 mph) on a straight track as part of demonstration tests. TGV wheels have a diameter of approximately 1 meter and are made from UICR7, a heat treated 0.6% carbon steel. (Ref 2) This wheel composition overlaps American Association of Railroads (AAR) Specification M-107-83, Classes A and B. A preliminary material specification similar to the TGV wheels would include specific melting and material cleanliness standards, a nominal carbon content of 0.55 - 0.65% carbon, and rim heat treatment to a Brinell hardness of about 300 BHN.

Wheel dimensional and dynamic balance characteristics are also critical to the successful use of wheel-on-rail support at high speeds. The TGV wheel specifications limit the out of round condition to 0.1 mm maximum per wheel. Additionally, wheels mounted on the same axle are specified to have less than 0.1 mm difference in size, and wheels mounted in the same bogie are required to have less than 20 mm difference in size. (Ref 2) All wheels are dynamically balanced. Similar requirements would be necessary for a SERAPHIM vehicle.

Long-term operation at speeds over 200 mph has not been evaluated, and could be an important issue for the full-speed SERAPHIM concept. However, this issue should be addressed during a detail design phase if the concept is pursued. The primary wheel loads of the fastest conventional trains in the US, up to 150 MPH, result from the thermal and mechanical loads of tread braking. The SERAPHIM concept would not utilize tread brakes, but would utilize a combination of electromagnetic braking at high speeds and disk brakes at lower speeds. Adequate inspection methods and frequencies will be specified to ensure that wheel integrity is maintained over the wheel design life.

Lightweight wheel design concepts could be pursued if deemed worthwhile during advanced design. Bimetallic wheels consisting of aluminum hubs with shrink-fit steel tires are already used in some light rail systems. These wheels are 35-40% lighter than an all-steel wheel having the same shape. Bimetallic wheels should be capable of operation up to speeds of 200 MPH although they have not been analyzed for operation in the high speed range. Advanced aerospace materials could be applied to produce lighter wheel hubs with appropriate stiffness characteristics. Detailed cost-benefit studies would be required to determine if using titanium alloys, high strength maraging steels, or composite materials would make sense for wheel applications in light of the operational and maintenance requirements.

The simplest means of attaching the wheels to the carbody structure is to use a conventional rail truck arrangement with solid axles and rigid side bolsters. A common arrangement has disk brakes mounted on the axles. Conventional trucks have been designed and tested for continuous service up to 200 mph. (Ref 3) TGV trucks and suspension components were tested to 309 mph as mentioned above.

Conventional trucks allow tuning of the ride characteristics through primary and secondary suspensions, and allow car tilting mechanisms to be incorporated. However, they tend to be massive and heavy. Advanced trucks have been designed and tested with independent wheels, i.e. each wheel mounted on a short, independent axle shaft, and have been found to be feasible. Designs of truck frame structures and axles using carbon fiber composites are being evaluated. An ultra-light truck assembly could be designed using carbon fiber composite frames and bolsters, with independent wheels or carbon fiber composite axles, and lightweight bimetallic wheels. This may be the most practical suspension design for an operational SERAPHIM vehicle because such a design would remove well over half the weight from a conventional wheel and truck assembly.

Alternative suspension concepts have also been envisioned. Since the fuselage of a high speed train vehicle will have structural characteristics similar to an aircraft fuselage, trucks could be incorporated into the frame of the carbody instead of being a separate unit. This could be done with or without axles connecting wheels. The weight of the suspension assembly could be significantly reduced by eliminating the trucks, and directly attaching the wheels to the car with a McPherson Strut type of assembly or trailing link/ torsion bar type of assembly. Independent wheels/suspension system requires that alignment be adjustable like a sports car, setting toe-in, caster, camber. This can be used to advantage by setting wheels to track straight without the "hunting" (side to side dynamic instabilities) which can occur with conventional truck assemblies at specific speeds due to fixed geometry of wheels tied to a solid axle. An advanced design could allow wheels to tilt into curves slightly to minimize curve forces. If the suspension is mostly enclosed in the car body with only some portion of the wheels sticking out of slots in the fuselage, this could improve the noise level and possibly the aerodynamics of the vehicle. All of these concepts would require significant design effort to assess feasibility and evaluate the effect on total vehicle cost and performance.

AERODYNAMICS

Because of the high speed (up to 300 mph) projected for the SERAPHIM train, aerodynamic drag will be the primary factor determining power requirements at near maximum train speeds. The aerodynamic drag, D_a, is given by $D_a = (V^2/2)C_dA_s$, where ρ is the air density, V is the air speed, C_d is the drag coefficient, and A_s is a reference area, typically taken as the cross-sectional area. Drag power, P_a, is $P_a = VD_a$.

Drag force derives from two basic mechanisms, pressure drag and turbulent skin friction drag. The pressure drag on the train aeroshell is largely a function of the shape of the nose and tail ends of the train, and is usually only weakly dependent on length. Pressure drag due to distributed components, such as suspension trucks, is proportional to train length. Likewise, skin friction drag is directly proportional to train length.

Skojvist (Ref. 4) presents an evaluation of train drag for a variety of train types, including the highest-speed passenger trains in commercial operation, the French TGV, British HST, and Japanese Shinkansen trains. From published data of motive power versus velocity for still air and no grade, Skojvist has generated fits for the total drag of the form $D=a+bV+cV^2$, where the first term represents static drag, the second represents an effective rolling resistance proportional to velocity, and the third is the aerodynamic drag, D_a. For the TGV Sud-Est train (2 power cars and 8 passenger cars), Skojvist gives the total C_d from all sources as approximately 1.5, and also identifies the various individual contributions to aerodynamic drag. Forty percent of the drag is due to the pressure and skin friction drag on the power cars and passenger coaches (aeroshell, inter-car gaps). An additional 40% is due to the aerodynamic drag on the trucks and undercarriage. The remaining 20% is due primarily to the pantographs (overhead electric power), and other roof-mounted equipment. The contribution to the total C_d due to the engines and passenger cars alone (without trucks) is therefore 0.6, in excellent agreement with data, after adjustment for train length, given by Hoerner (Ref. 5) for a streamlined train.

The integrated C_d of the trucks and undercarriage is 0.6; this value is quite large and is a target for improvement. It is believed that the use of independent wheel suspensions and fairings could reduce the C_d of the wheels and undercarriage by up to 50%, to a value of approximately 0.3. The C_d of roof-mounted equipment for a catenary-powered train probably cannot be reduced significantly and is therefore taken to be 0.3. For a self-powered train, this drag source will not exist and total C_d should decrease to 1.0, or slightly less. For a catenary-powered train the minimum C_d will be approximately 1.2.

Total C_d is observed to vary approximately linearly with train length, with a minimum C_d of about 0.3 for a single car of optimum aerodynamic design. For such an optimized design, each additional car will increase C_d by about 0.075 (Ref. 5). For current high-speed train designs, typified by the TGV, Skojvist's data suggest that the incremental increase in C_d is about 0.10 per car.

It is noted that there appear to be very large variations in the curvefit-derived a, b, and c coefficients presented in Ref. 4. These variations are assumed due, in part, to uncertainties in P_a as a function of velocity, and train-to-train variations in drag area, train weight, and aeroshell and suspension design. They may also reflect fluctuations due to statistically-inadequate quantities of data. Of the coefficient sets in Ref. 4, we judge the values for the TGV to be the most reliable.

Analysis of Skojvist's data indicates that a, b, and c are each approximately linear with train length for high-speed trains. It is reasonable to assume that for a given train length, a and b will not be subject to significant improvement in future train designs. The improved value of c corresponding to C_d=1.0, as suggested above for a self-powered train of high aerodynamic efficiency, is c=0.00042. Using the TGV Sud-Est train data for a and b, we obtain $D=3.82+0.0390V+0.00042V^2$ kN for a ten-car train (two power cars and eight coaches). At 320 km/hr (200 mph), D = 46.8 kN (10500 lbf) and P = 4.2 MW (5400 hp). For a five-car train consisting of two power cars and three coaches and weighing 360000 kg, the drag coefficient reduces to 0.65 and total drag and power are 29 kN (6500 lbf) and 2.6 MW (3340 hp), respectively. These values are well below the FRA requirements for thrust, 180 kN, (40400 lbf) and power, 12 MW, (15400 hp) for acceleration and grade-climbing for a train of 360000 kg gross weight. Hence, although aerodynamic drag will largely dictate the energy efficiency for high-speed cruise, it does not affect the maximum thrust capability or the amount of installed power.

Based on the above analysis, C_d = 0.65 is suggested for initial predictions of airload power requirements for a wheeled, five-car, 360000 kg SERAPHIM train. Although this is a somewhat optimistic choice in that it assumes that a substantial reduction (~50%) in wheel set and undercarriage drag can be achieved through careful design, we believe it is not unreasonable. C_d for other train lengths can be estimated as indicated above.

SERAPHIM TRAIN

Table 2 is a summary of parameters for a 200 mph vehicle, similar to that illustrated in Figure 5a, design based on SERAPHIM propulsion. The individual cars carry 72 passengers each, and multiple cars are connected together for a train "consist." The train set may be powered either from a locomotive or from an electrified line. The SERAPHIM motor is inherently a distributed motor, with each power car having a linear motor consisting of 30 coils. In principal, each passenger car could be equipped with a linear motor, but the added complexity for powered passenger cars is not required for the traction force and power requirements at 200 mph.

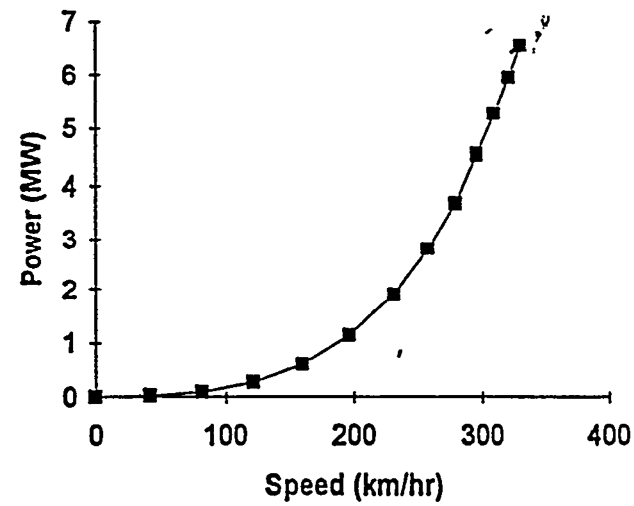

Figure 9. Drag power requirement versus speed.

Power requirements are estimated from friction loss and aerodynamic drag, as discussed in a previous section. At 200 mph, the cruise power requirement is about 6.3 MW for a 5-car train set, as shown in Figure 9. Acceleration requirements are taken from the Federal Railroad Administration goals for the Next-Generation High Speed Rail Program (Ref. 6). The acceleration requirement from FRA is to travel a distance of 5.8 km (3.5 miles) in 2.5 minutes, and 11.7 km (7 miles) in 4 minutes. This requires an acceleration of 0.5 m/s2 for the first segment and an acceleration of 0.4 m/s2 for the second. For a train weight of 390,000 kg, the thrust must be 210 kN. The maximum power requirement is 12 MW. With this thrust, the train can climb a 2% grade at 170 mph.

If we assume an average thrust of 3 kN per coil, then each power car will need 30 coils to produce the required thrust with two power cars. Using the measured conversion factor of 3 kN/kJ, then each coil-set must be energized with 1 kJ per pulse. The maximum power from each coil set at peak frequency is 200 kW. The power dissipation from these coils will be similar to that experienced with the Linear Induction Motor Research Vehicle (Ref. 7). That test vehicle used forced air cooling for the propulsion coils.

Table 2

200 mph SERAPHIM Train Scoping Parameters

Number of passengers / vehicle	2
Width	3.5 m
Height	3 m
Length	18 m
Cross-section	10 m^2
Weight	66,000 kg
Locomotive weight	95,000 kG
Number of vehicles in train	5
Number of wheels per vehicle	8
Size of wheels	36 in diameter
Number of cars in consist	2 power cars 3 passenger cars
Power requirements	12 MW (9000 hp)
Maximum acceleration	0.5 m/s^2
Maximum thrust	210 kN (47,000 lbf)
Drag coefficient	0.35
Total drag	70 kN @ 200 mph
Maximum grade	2% @ 170 mph
Power per coil set	200 kW
Dimensions (L x W x H)	40 x 20 x 10 cm
Magnetic field	2 Tesla
Frequency	100-230 Hz
Thrust	3.5 kN
Number	30 per power car
Cost	$1000
Reaction Plate Dimensions	50 x 20 x 2 cm
Separation gap	2 cm
Cost	$350,000 / mile

The thrust profile for the SERAPHIM motor is shown in Figure 10. The thrust is assumed constant with speed (at peak pulse frequency), until becoming power-limited. Beyond this speed, thrust is inversely proportional to speed, since thrust multiplied by velocity is equal to power. The expected thrust for the SERAPHIM motor is compared with that which can be obtained with multiple modules of a conventional linear induction motor, represented by the LIMRV motor data (Ref. 7). For a given power level of 12 MW, about 50% more thrust is expected to be provided by the pulsed SERAPHIM LIM.

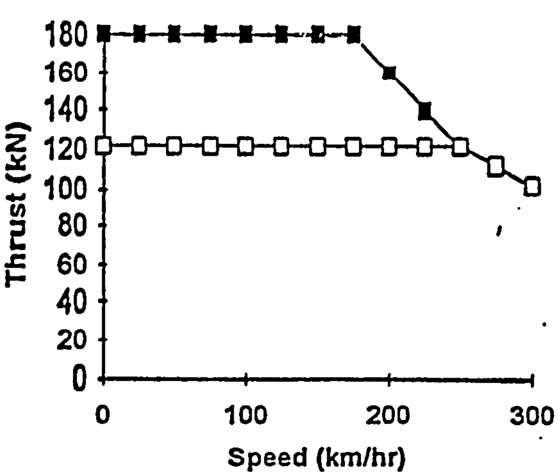

Figure 10. Comparison of thrust for SERAPHIM (SM) and conventional LIM (LMRV) for 10 MW power.

Figure 11 compares the expected thrust profile for SERAPHIM with the adhesion limit for conventional steel on rail propulsion. The adhesion limit is calculated from the Japanese National Railways Shinkansen Network Design Rules (Ref. 4), using two power cars weighing 90,000 kg each. As can be seen, the adhesion limit drops quickly with speed. The magnetic propulsion from SERAPHIM is not adhesion limited, and can maintain high thrust at high speeds, limited only by the available power. This additional thrust is important in providing acceleration and grade-climbing capability. The Federal Railroad Administration (FRA) acceleration goals (Ref. 6) are shown in Figure 12, showing the calculated distance and speed vs. time for the SERAPHIM-powered and conventional wheel and rail options. Note that SERAPHIM exceeds the FRA distance goals, and achieves a top speed of 340 km/hr (200 mph). The steel wheel on rail propulsion is limited by adhesion, does not meet the FRA goal for distance, and has a top speed of 230 km/hr (140 mph).

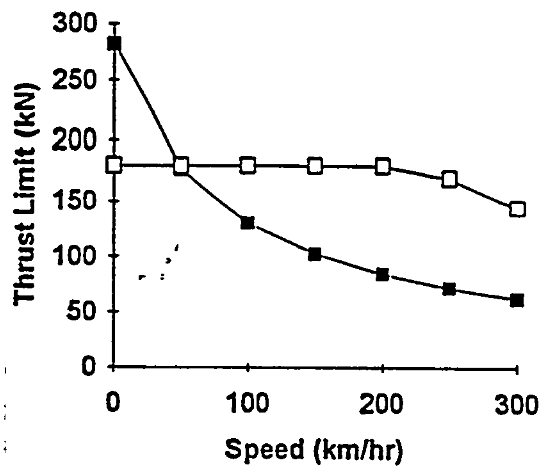

Figure 11. Comparison of thrust for SERAPHIM and adhesion limit for conventional steel wheel and rail (solid) propulsion.

For our concept study, we consider on-board power, so that the train can operate on non- electrified rail lines. The locomotive power is based on a gas-turbine power plant, generator and power conversion for 4 kV dc power. Gas-turbine information was supplied by Turbomeca Corporation. This company sells gas turbines for transportation applications, and is now testing a retro-fit of an Amtrak Turboliner locomotive with their Makila TI 1.2 MW gas turbine for Amtrak operation on the Northeast Corridor. This power car weighs about 95 tons, or 86,000 kg. The Eurodyn delivers 2.2 - 2.9 MW (2900 - 3900 hp) at a fuel consumption rate of 150 - 200 gallons per hour. Two of these engines would provide the power needed for each SERAPHIM power car. Textron-Lycoming also manufactures gas turbines for transportation applications. The TF40 engine delivers 5.3 MW (4,000 hp) continuous, 6.2 MW boost power. It weighs only 1325 pounds, is 4.3 feet long, and has a volume of 46 cubic feet. Fuel consumption for the TF40 gas turbine is 280 gallons per hour, using kerosene, diesel, or jet fuel.

Passenger-car parameters were taken from the present Amtrak fleet, the Grumman Maglev vehicle and the German Transrapid TR07 designs. The Amtrak heritage coach cars have 72 passenger seats, and weigh about 66,000 kg. The frontal cross-section is 10 m2. The passenger cars may be lightened if new materials and fabrication approaches are taken, as with the German Intercity Express (ICE) train. To estimate the minimum weight that might be achieved, the light-weight vehicle designs from the Maglev study were used. Maglev vehicle mass for the Bechtel, Foster-Miller, Grumman, and TR07 maglev vehicles are all around 600 kg/seat. Such a SERAPHIM passenger vehicle thus would weigh about 45,000 kg, or 99,000 pounds. In this case, the maximum power requirement is reduced to 10 MW.

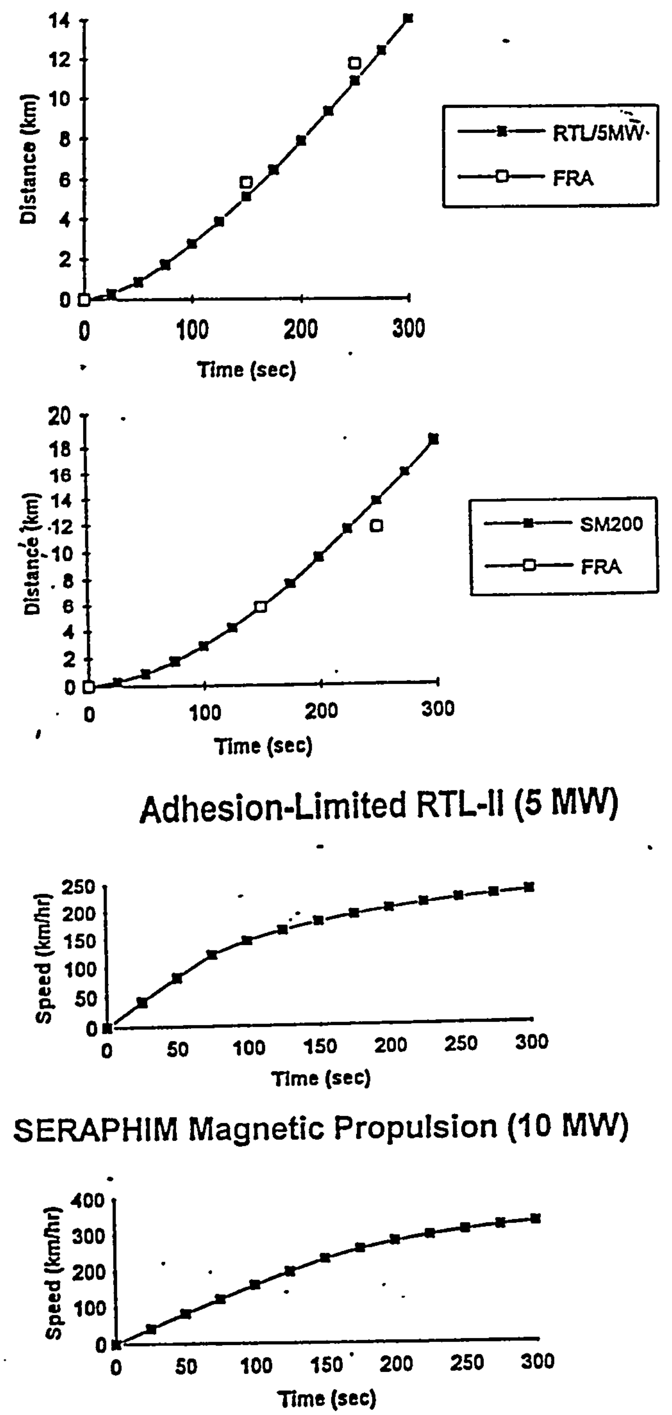

Figure 12. Distance and speed vs. time for SERAPHIM and steel wheel and rail propulsion.

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