LABORATORY DEMONSTRATION ELECTROMAGNETIC LAUNCHER

D.W. Deis, Program Manager

Preliminary Hazard Analysis

Contract DAAK-10-79-C-0110
ARPA Order 3732

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ARRADCOM
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Westinghouse R&D Center
General Order Reference RBD-10969-CE

Westinghouse R&D Center
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LABORATORY DEMONSTRATION ELECTROMAGNETIC LAUNCHER - PRELIMINARY HAZARD ANALYSIS

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ABSTRACT

The results of the preliminary hazard analysis on the Laboratory Demonstration Electromagnetic Launcher are described. This analysis was based on system concepts and inherent known hazards. This work has concluded that although serious hazards do exist, a properly designed laboratory and detailed operating plan can ensure personnel safety and minimize the potential for system or component damage.

I. INTRODUCTION

The Laboratory Demonstration Electromagnetic Launcher system (referred to herein as EMACK) is being designed, constructed, and commissioned at the Westinghouse R&D Center for DARPA and ARRADCOM under contract DAAK-10-79-C-0110. After commissioning the system will be delivered to ARRADCOM for their future use. The design of this system has been described in detail in a previous report.[1]

The analysis presented here followed the procedure of first identifying all hazards, both to personnel and to the equipment itself and then defining equipment or procedures to minimize the personnel risk and potential equipment damage from these hazards. In all cases the approach has been conservative and personnel safety has been considered to be the paramount concern. In several instances, outside experts and consultants have been used when their experience would improve the validity of this work.

II. SYSTEM DESCRIPTION

An overall view of the main components of the EMACK system is shown in Fig. 1. These components and their functions are:

Homopolar Generator - This is an inertial energy storage, high current dc generator. At maximum operating conditions (6735 rpm) the 3000 lb rotor stores 17.5 MJ of energy and will produce an output of 1.5 MA at a peak voltage of 105 V.

Toroidal Coil - At 1.5 MA this coil stores 6 MJ of energy. During operation peak voltages of 2 kV are produced. The internal magnetic field is 90 kG and externally a maximum of 50 G at a distance of 1 m.

Rail Switch - This switch uses a linear sliding armature to generate two arcs whose voltage will commutate the coil output current into the breech of the barrel. An arrestor system of crushable aluminum honeycomb is used to stop the sliding armature.

Barrel - The barrel is 5 m long and is the accelerator section of the launcher system. A cross sectional view is shown in Fig. 1. During operation a peak magnetic field of ∿200 kG is generated between the two conductors (rails). At the muzzle a resistor is positioned to absorb any energy remaining in the system after the acceleration period.

Launch Package - The package to be accelerated is shown in Fig. 2. The total mass is 300 grams and at maximum velocity (3000 m/s) it has 1.35 MJ of kinetic energy.

Range Tanks - These tanks interface with the barrel to provide physical isolation between the projectile and the laboratory and also as an interface for ballistic instrumentation. The last range tank is the catch tank which is used to stop the projectile.

Auxiliary Systems - The principal systems which need to be considered in this analysis are:

Oil Lube System - This unit supplies bearing lubrication oil to the homopolar generator.

Drive System - This is a 100 hp variable speed drive unit which accelerates (decelerates) the homopolar generator rotor.

(The following auxiliaries are not part of the EMACK system but will be used in its commissioning at Westinghouse. Since ARRADCOM may install similar equipment they are included in this report for the sake of completeness.)

X-Ray System - Three 150 kV flash x-ray units are used to obtain x-ray photographs of the projectile while it is under acceleration.

Flash Photography System - This system employs a 5 J Q switched ruby laser to illuminate the projectile while in flight to obtain photographs of its condition after acceleration.

III. OPERATING SEQUENCE

The sequence of events which occur during the EMACK system firing are:

1. Pre-shot Preparation - Since EMACK is a one shot system, prior to beginning the experiment a new launch package must be placed in the barrel and the switch armature must be returned to its prefiring position where it serves as a short circuit across the coil output leads.

2. Homopolar Generator Charging - The drive system is used to bring the generator rotor to the desired speed with the brushes in the up position. If full power is used, this takes ∿12 minutes.

3. Coil Charging - With the generator at the desired speed the brushes are actuated downward onto the rotor causing the output current to rise from 0 to maximum in the coil. At maximum energy this is 1.5 MA. The maximum time to charge the coil is ∿150 ms.

4. Switch Operation - At peak current the switch armature is released allowing it to accelerate to the end of the switch conductors where two arcs are formed which commutates the current into the breech of the barrel. This operation takes ∿3 ms.

5. Acceleration - With current flowing in the barrel the launch package is accelerated to maximum velocity ($\leq$3000 m/s) in ∿3 ms.

6. Ballistic Phase - Upon leaving the muzzle of the barrel the launch package travels through the range tanks into the catch tank where it is stopped. This phase takes ∿1-2 ms.

7. Post Shot Phase - As soon as the launch package exits the barrel a brief muzzle arc commutates the remaining current into the muzzle resistors. These resistors then dissipate all the remaining energy in the system bringing the generator rotor to a stop. This energy dissipation process takes <5 s.

IV. HAZARD IDENTIFICATION AND SAFETY PROCEDURES

Although the EMACK system is itself unique, it is made up of components and subsystems which are in themselves familiar. We feel that this has allowed for a comprehensive identification of potential hazards. Westinghouse personnel were assisted in this analysis by a number of consultants and subcontractors having specific relevant expertise as discussed below. Appendix I contains the detailed Test Sequence Checklist (TSC) which is the primary instrument used to ensure safe operation of the system. During a test shot, a designated Safety Engineer is responsible for seeing that all items on the checklist are performed. This person has no other responsibility and thus is not distracted from this task. A separate person, the Experiment Leader, is responsible for the technical details of the test. The following list is a summary of the identified hazards and the procedures recommended for controlling their potential impact on personnel and equipment safety. For reference, a layout of the laboratory is shown in Fig. 3.

1. Magnetic Field Exposure - Whenever output current is being provided by the homopolar generator high magnetic fields are produced by the toroidal coil and the barrel. The current limit for personnel exposure to short duration (minutes) magnetic fields is 2000 G.[2] The closest personnel to these components will be located in the control room where the maximum magnetic field produced is ≤ 2 G. Magnetic fields outside the walls of the laboratory will in all cases be less than this value.

2. Electrical Shock Hazard
   a) Power Line Equipment - The maximum power line voltage used is 440 V. All equipment is installed and connected according to accepted industrial practices.

b) Exposed Buswork - The maximum operating voltage of exposed buswork is 2000 V which can be present whenever current is flowing. The TSC requires all personnel to be out of the laboratory space when current is present in the system. Interlocks on all entrances will automatically shut the system down if the lab is reentered.

c) High Voltage Power Supplies - Two high voltage diagnostic systems are used, a 150 kV x-ray unit and a 9 kV pulsed laser. Both of these are commercial systems, fully enclosed and interlocked.

d) High Voltage Signals - Signal leads are attached at numerous points on the system which either measure kV level signals or which can float at kV common mode levels. In order to eliminate dangerous voltages in the control room these signals are attenuated and/or optically coupled for isolation prior to entering the control room.

3. Acoustic Hazards - Under normal operation the most intense sound level is generated inside the switch by the arcs. This sound level has been conservatively estimated to be a maximum of 250 db. A sound attenuation enclosure surrounds this source, which when combined with normal air and structure attenuation will reduce the level in the control room to $\leq$150 db. Sound protection head gear will be worn which will reduce this level to 115 db. Allowable maximum sound level for personnel is 140 db. A second "normal operation" sound pulse will be generated by the barrel muzzle arc. This sound pulse is contained within the range tanks which are evacuated. This pulse will be $\leq$90 db at the control room. The failure of any electrical insulation in the system between the coil and the barrel can potentially allow an electrical fault arc to form. The peak sound level from such a

fault would be $\leq$190 db at the source and $\leq$140 db within the control room. All potential sound levels can then be rendered safe through the use of protective head gear (foam ear plug) within the control room. Sound levels outside of the laboratory for all these potential sources will be $\leq$140 db. The Westinghouse R&D Acoustics Research group has reviewed these calculations and consulted on the design of the sound enclosure for the switch.

4. X-ray Radiation Hazard - The x-ray pulses produced are 70 ns long at 150 kV. Personnel present when they are operated should be restricted to not be closer than ten feet to the source and should be equipped with radiation monitoring film badges. Based on the TSC personnel will not be present in the laboratory when the units are operated.

5. Laser Radiation Hazard - Two types of lasers are used in the laboratory, a 4 mW He-Ne laser and a 5 J Q switched ruby laser. The operation of the He-Ne laser must be restricted to trained personnel but does not require special safety precautions. The ruby laser however must only be operated either with the laboratory evacuated or by personnel wearing protective goggles specific to this laser wavelength.

6. Electrical Breakdown Hazards
   a) Joint Failure - A 1.5 MA system naturally contains a large number of high current electrical joints. If sufficient contact pressure is not provided internal arcing and damage can occur with the possibility of liquid metal ejection. The science of contact design is well established and the required pressures have been calculated to be: 66 kips @ 1.5 MA, 18 kips @ 0.75 MA, and 5 kips @ 0.38 MA. All exposed joints have been designed to a minimum of four times these values. All bolts are provided with belleville spring washers to ensure that creepage will not

reduce the available pressure. Internal connections within the switch and barrel and their interconnecting jumpers are designed to two times the required load. The load for these joints is provided by a combination of mechanical and magnetic forces. All of these joints are surrounded by insulation and mechanical structure. In the event of a catastrophic joint failure, an arc would form which would cause structural damage. Personnel are protected from such an event by isolation in the control room.

b) Insulation Failure - An insulation failure anywhere in the system will lead to arc formation and structural damage at that point. Such an arc will cause melting with the ejection of molten metal and intense radiation over a broad spectrum. Personnel are protected from such an event by isolation in the control room. Procedures to prevent such an occurrence include Hipot tests of the system to 3 kV prior to operation.

7. Copper Vapor Hazard - Electrical arcs as described in item 6 will produce some quantities of copper vapor. Due to the very low vapor pressure of copper at room temperature this vapor will condense very rapidly and will not present a hazard to personnel in the control room.

8. Mechanical (Structural) Failure Hazards - All components in the EMACK system have been designed according to accepted engineering practice. The effects of cyclic loading, temperature, and shock loading have all been evaluated in detail using state of the art finite element analysis. The maximum operating points for all components are the lesser of 40% UTS or 67% YTS. To reduce this hazard the most highly stressed components are monitored during low power tests to confirm the design data prior to operations at full power. In addition they will be monitored during the

life of the equipment to ensure safe operating stress levels have not been exceeded. Even so, the potential exists for failure of a mechanical component. The most likely occurrence of this nature would involve the barrel structure. In such a case low energy projectiles could be produced in the laboratory. Personnel are protected from such an occurrence by the physical isolation of the control room.

One special case of a mechanical hazard is the homopolar generator which involves a high stored energy rotor. The operational safety of this component should be equivalent to that of a traditional motor driven generator. The drive consists of a small high speed motor directly coupled to the generator. The motor is constructed with conventional technology and should be as safe as traditional motor drives. The direct coupling of the motor to the generator eliminates the hazards associated with belts breaking on a belt driven unit. The generator has a solid steel and aluminum rotor which has no protrusions and should exhibit mechanical strength superior to any other traditional rotor technology. The generator stator, by the nature of a homopolar machine, is much more massive than conventional machine stators and completely encircles the rotor. Therefore, this type of generator is inherently less likely to produce a dangerous projectile (since there are no fans or windings on the rotor) and the massive, encircling stator of the machine is inherently more likely to contain projectiles than traditional machines. The generator rotor does operate at a speed which is higher than traditional motors and generators (3600 rpm). The speed does not however approach that commonly employed in high speed commercial turbines and compressors. On the whole, mechanical operation of the generator is judged to be less hazardous than a conventional large motor driven fan, pump, or compressor.

9. Oil Lube Subsystem Hazards - The oil lube subsystem contains 40 gallons of Gulf Harmony 55 lubricating oil which it supplies to the generator bearings at 15 psig. In the event of a power failure a backup pump connected to an auxiliary motor generator will maintain oil flow. If a supply or drain pipe is completely broken while the generator is at speed, oil pressure will be lost before the generator can be stopped. In such an event the rotor will be stopped by friction in the bearings which will then require replacement. Potentially the rotor shaft surfaces will need to be remachined as well. The only personnel hazard is associated with the potential for an oil fire in the laboratory. The control room is provided with a separate exit to allow evacuation without entering the laboratory. Halon fire extinguishers are required to control such a fire and are strategically located.

10. Switch Armature Hazards - At full power the switch armature will have ∿150 kJ of kinetic energy when it strikes the arrestor system which is composed of aluminum honeycomb energy absorbing blocks. A catastrophic failure of this system would allow the armature or other material to escape into the laboratory. The orientation of the switch is such that in this event the projectiles will escape at 90° with respect to the control room and will not endanger personnel.

11. Launch Package Hazards

    a) Mechanical Failure or Jamming - Since the mechanical forces in the barrel are determined by the current level a jammed launch package will not increase the forces above those experienced in normal operation. Energy dissipation in the barrel rails could be increased depending on the location where the projectile jams but in the worst case melting would not occur. If the launch package fails mechanically and disintegrates within the barrel it will be ejected into and contained by the range tanks.

b) Launch Package Containment Hazards

i) Barrel - When the launch package is accelerating in the barrel it is closely confined by the rails and the insulating spacers and cannot attain adequate transverse velocity to penetrate either the spacers or the rails. Therefore, the package cannot escape from the barrel.

ii) Range Tanks - The range tanks have been specifically designed to contain the launch package during flight. The wall material and thickness were chosen to prevent penetration of the projectile under the most severe conditions of impact velocity and obliquity which could conceivably occur. The design was performed by the University of Dayton Research Institute Ballistics Research Group which has 17 years' experience operating similar systems.

iii) Catch Tank - The launch package is arrested in this tank. Its design is sufficient to contain a competent projectile with up to 2.5 MJ of kinetic energy ($\sim$ twice maximum operating conditions).

V. CONCLUSIONS

This preliminary hazard analysis has identified all potential hazards and systems or procedures which are employed to ensure personnel safety and minimize system damage. Obviously a key part of personnel safety is the use of the TSC in Appendix I. The one paramount requirement to ensure personnel safety is the evacuation of the laboratory prior to test operation. Within these limits the EMACK system can be operated safely under all potentially hazardous conditions.

VI. ACKNOWLEDGEMENTS

The author is grateful to Dr. J.P. Barber for many valuable contributions to this assessment based on his operating experience with the Australian National University railgun facility.

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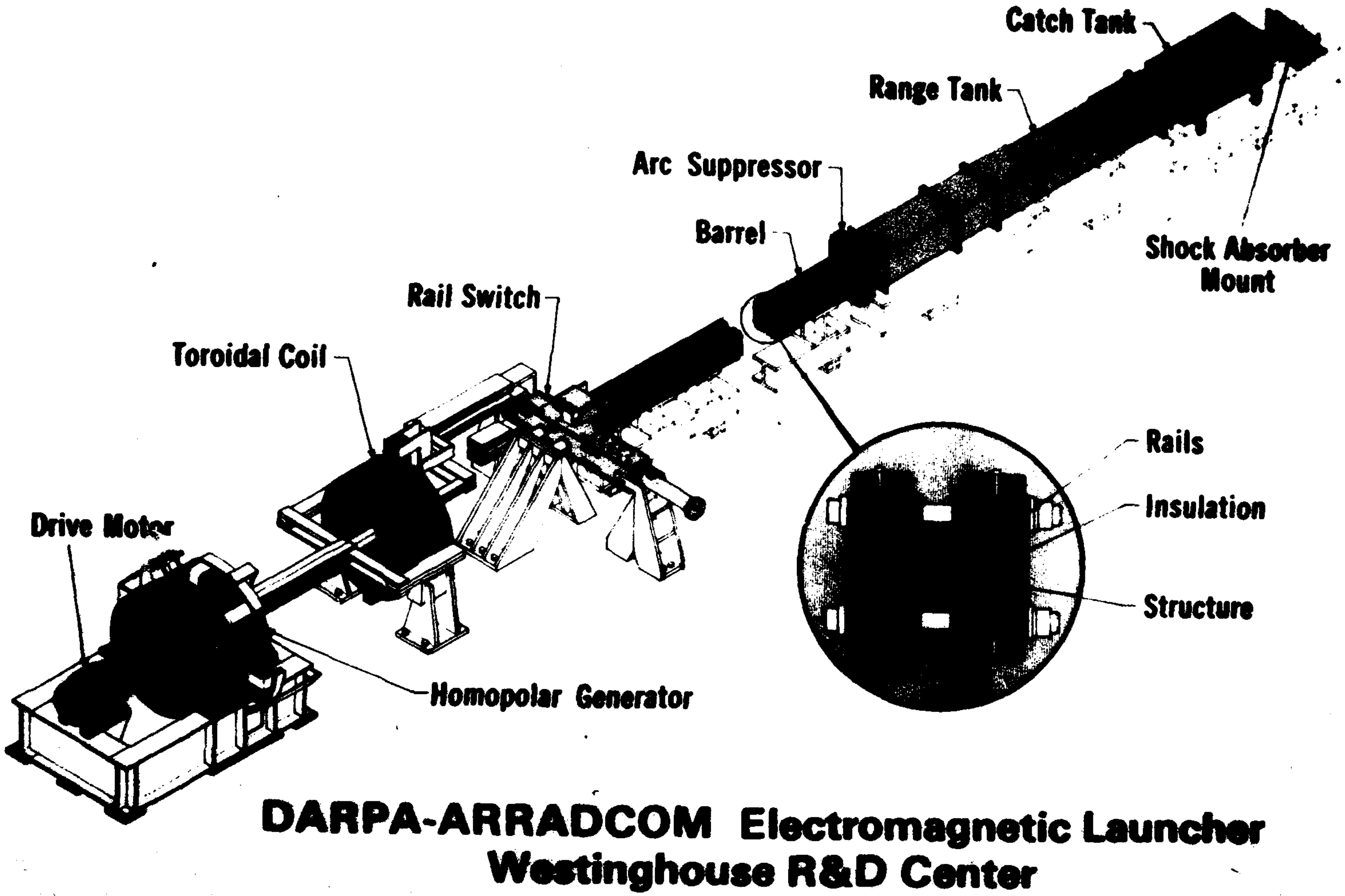

Figure 1. Shown above is an overall view of the launcher system and its components.

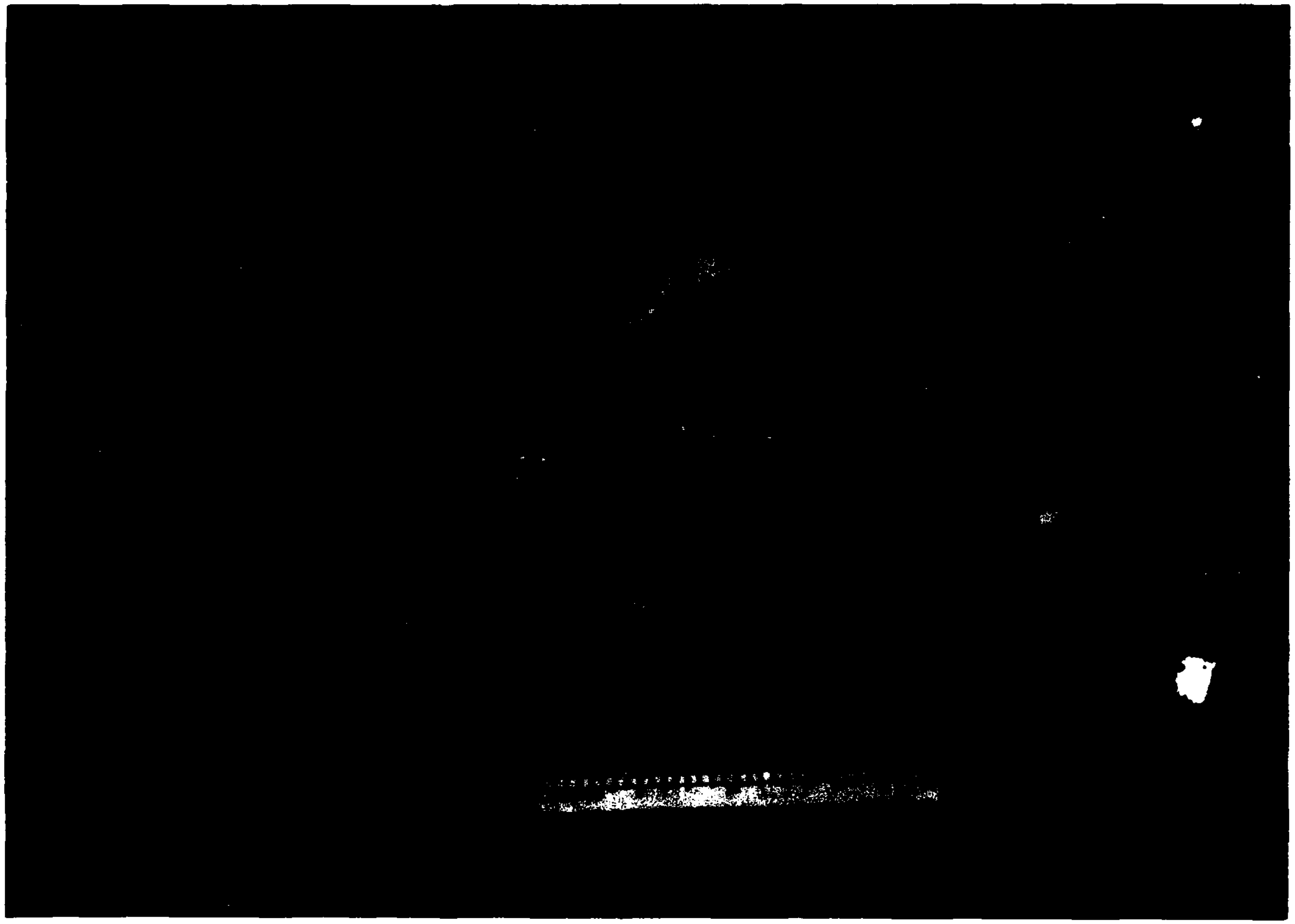

Figure 2. The projectile geometry to be used with the launcher employs six copper "leaves" as an armature and a lexan block for a payload. The entire package weighs 300 g and will have a kinetic energy of 1.35 MJ at 3000 m/s.

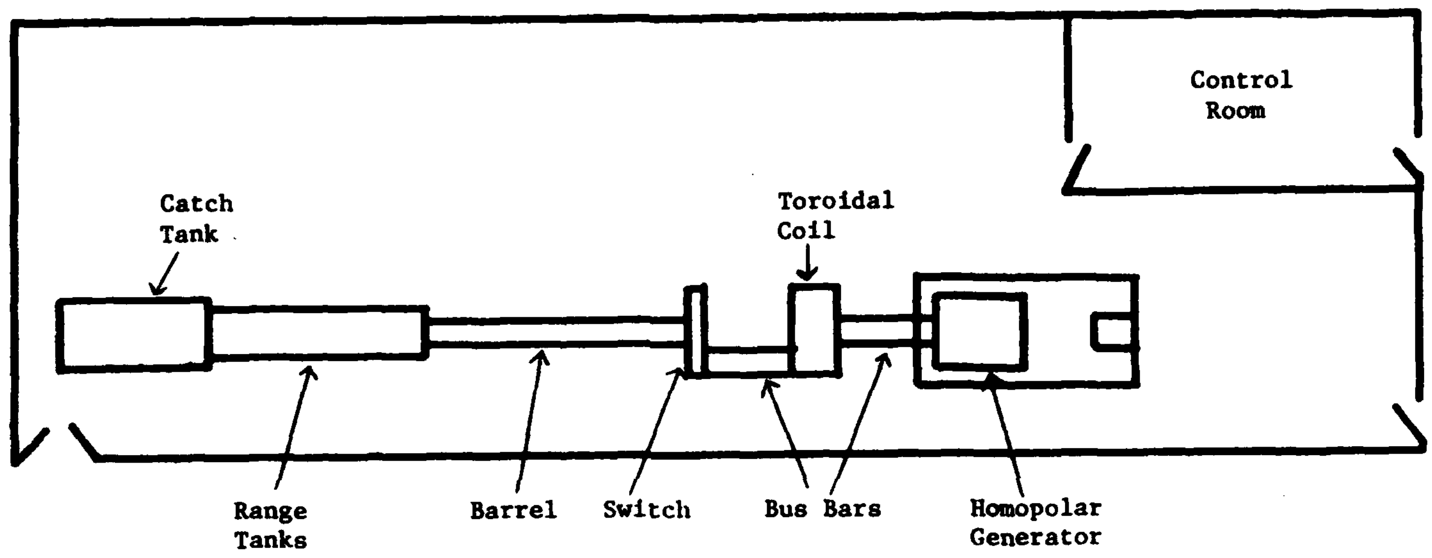

Figure 3. Laboratory layout for the EMACK system. The control room and laboratory walls are 10 inch concrete block, sand filled. All doors and the control room roof are armored and all high impact strength windows have steel cover plates.

APPENDIX I

TEST SEQUENCE CHECKLIST

TEST SEQUENCE CHECKLIST

Safety Engineer ____________________ Test Date-Time ______________

Test Type ____

____

Preshot Phase

______ 1. Repair and modify system as needed
______ 2. Assemble barrel
______ 3. Refurbish range and catch tanks
______ 4. Reset railswitch
______ 5. Load package into barrel
______ 6. Install barrel on system
______ 7. Load cameras with film
______ 8. Engage drive system circuit breaker
______ 9. Engage coil excitation system circuit breaker
______ 10. Turn on oil lube water
______ 11. Turn on coil cooling water
______ 12. Turn on cover gas
______ 13. Turn on seal gas
______ 14. Turn on oil lube system
______ 15. Verify HPG inspection plugs are seated
______ 16. Move crane to either extreme end of lab
______ 17. Verify brush and excitation systems are connected for remote operation
______ 18. Verify all foreign objects have been removed from generator, coil, bus bars, switch, barrel, and range tank area
______ 19. Verify oil is flowing through HPG return lines
______ 20. Verify muzzle resistors are cool enough for shot (50°C or less)
______ 21. Verify that shock absorber on range tank is in place
______ 22. Verify that rail switch is loaded and system is cocked
______ 23. Lock all doors to experiment bay - verify from outside
______ 24. Verify all window screens are locked

Safety Engineer ______________________

Test Date-Time ______________________

Preshot Phase (Cont.)

______ 25. Post warning signs

______ 26. Post monitors at high bay entrances

______ 27. Turn on warning lights

______ 28. Computer and console power switch on

______ 29. Video monitor and recorder on

______ 30. Load computer for preshot checks

______ 31. Cycle brush system and switch release mechanism

______ 32. Set coil excitation current

______ 33. Set maximum HPG drive speed

______ 34. Verify that experiment leader has completed preshot checks

______ 35. Load computer for test

______ 36. Verify that experiment leader is satisfied with operation state and settings for data acquisition system and system control programs

______ 37. Verify that experiment leader is satisfied with condition of instrumentation on EML

Experimental Phase

______ 1. Verify brush system parameters are correctly set

______ 2. Turn on laser camera system

______ 3. Turn on Hall velocity station

______ 4. Verify switch position sensors are in place

______ 5. Turn on flash x-ray system

______ 6. Turn on vacuum pumps

______ 7. Set H.V. level on laser

______ 8. Set active triggers

______ 9. Turn on isolation and instrument amplifiers

______ 10. Set delay unit timers

______ 11. Start HPG drive

______ 12. Turn on x-ray H.V.

______ 13. Verify all personnel are out of lab

______ 14. Verify correct maximum speed of HPG on console

Test Date-Time ______________________

Experimental Phase (Cont.)

______ 15. Sound horn to verify lab clear

______ 16. Close control room door

______ 17. Inspect lab using video system

______ 18. Post monitor at control room door

______ 19. Arm system

______ 20. Put on sound barriers

______ 21. Blow horn as warning

______ 22. Fire system

Post Shot Phase

______ 1. Inspect lab using video monitor

______ 2. Verify laser H.V. off

______ 3. Verify x-ray H.V. off

______ 4. Safety engineer enter lab

______ 5. Verify HPG drive off

______ 6. Verify field coil current off

______ 7. Experiment leader verifies data transfer to tape

______ 8. Safety engineer allows access to lab

______ 9. Turn off power to coils

______ 10. Turn off power to drive

______ 11. Lift brushes

______ 12. Retrieve film for processing

Comments:

REFERENCES

1. "DC Electromagnetic Launcher Development: Phase I," Final Report ARPA Order 3732, ARRADCOM Contract DAAK-10-79-C-0110, Nov. 16, 1979.

2. Safety standards for magnetic fields recommended by the Stanford Linear Accelerator Center.