Fabrication and Testing of a 30 mm and 90 mm Laminated, High L' Railgun Designed and Built at CEM-UT

By:

J.J. Hahne
J.L. Upshaw
J.H. Herbst
J.H. Price

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Center for Electromechanics
The University of Texas at Austin
BRC, Mail Code 77000
Austin, TX 78712
(512) 471-4496

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Abstract—With the emphasis on moving railgun technology from a laboratory based setting out into the field, a new lighter weight and stiff railgun structure was designed at the Center for Electromechanics at The University of Texas at Austin (CEM-UT). This innovative design takes advantage of stainless steel laminations with a composite overwrap to provide radial and longitudinal support for the rail/insulator package. The goal of this design effort was to build a 90 mm bore gun with a 9 MJ muzzle energy and provide comparable stiffness to the hydraulically pre stressed 90 mm railgun at CEM-UT. The fabrication phase involved building a 90 mm x 7 m long railgun in conjunction with a 30 mm x 3 m subscale version for performance testing up to full design loads. The 30 mm subscale launcher has been successfully tested at CEM-UT up to its full current rating of 1.0 MA. With the outstanding results from the 30 mm subscale gun, the full scale 90 mm gun was completed and sent to the U.S. Army's Armament Research, Development, and Engineering Center (ARDEC) for testing while the skid mounted power supply is completed. A new and improved version of the original 30 mm subscale launcher was also designed and built by CEM upon request by U.S. Army ARDEC. This new design improved fabrication techniques as well as made the gun more durable for laboratory testing. The updated 30 mm railgun was also sent to U.S. Army ARDEC to be fired on their capacitor bank power supply. This paper discusses the problems encountered during the final assembly of the 90 mm skid gun and how these difficulties were overcome. The paper also discusses the successful testing to full load of a 30 mm one-third scale version of the 90 mm gun. The paper concludes with a brief discussion on an additional 30 mm laminated gun which was redesigned based on experience with the previous laminated gun assemblies. This gun was fabricated and sent to U.S. Army ARDEC for testing in their facility.

INTRODUCTION

The conceptual design and structural analysis of nine, sub-scale 30 mm and full scale 90 mm laminated railguns for the 9 MJ Range Gun project have been previously discussed in a paper titled "Design, Analysis, and Fabrication of Two Lightweight, High L' Railguns" [1]. During the fabrication and final assembly of these launchers, several difficulties were encountered which can be addressed in subsequent laminated containment structure designs. Fabrication and successful testing of the 30 mm subscale launcher to currents of 1 MA has been completed and the results are presented in this paper. The 90 mm railgun fabrication and final assembly have also been completed and a test program at the Electric Armaments Research Center at Picatinny Arsenal is currently underway.

Figure 1 shows an isometric view of the final configuration of the 90 mm railgun structure. Although the basic components of the railgun and breech connection match the conceptual design, several modifications have been incorporated into the structure and assembly procedures for the completed launcher. In addition, several important lessons were learned which will be incorporated into subsequent launcher designs.

Figure 1. Laminated steel range gun structure

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The railgun structure consists of a rail/insulator package contained in an axially laminated 301 stainless steel containment structure to react the primary rail repulsion forces. A seamless FEP insulator sleeve surrounds the rail package and provides primary electrical insulation between the rails and stainless steel containment structure. The FEP insulator also provides a pressure boundary for the pressurized cure preloading operation. Longitudinal bending stiffness is provided by an S-glass/epoxy composite overwrap.

The rails are Glidcop AL-60 dispersion strengthened copper extrusions with a pair of high strength brass coolant tubes brazed into the out-bore surface. The rails were extruded to near net shape, then machined to provide slots for the coolant tubes and control tolerances on the inner bore radius. Even though the extruded rails required relatively little post-machining, the machine operations created a significant twist along the 8 m length of the rails. An hydraulically actuated straightening fixture was developed, but it was not possible to eliminate all rail twist, which created problems during subsequent assembly procedures. The sidewall insulators are epoxy reinforced pultrusions combining 45° bi-directional fiberglass cloth and unidirectional fiberglass roving.

The laminated containment structure is constructed of 16 gauge half-hard 301 stainless steel sheet with an American Cyanamid FM-123 sheet adhesive providing the interlaminar bonds. Approximately 5 cm thick subassemblies were fabricated and machined and then bonded into 1 m sections which were then assembled over a full length internal mandrel. Assembly and bonding in 1 m sections allowed removal of excess adhesive after the elevated temperature curing operations. After final bonding of the 8 m containment structure assembly on the internal mandrel, the composite overwrap was installed.

Final Assembly of 90 mm Laminated Launcher

Several complications and obstacles were encountered and overcome while completing the assembly of the 90 mm railgun. The remaining discussion concerning the 90 mm gun will briefly detail these problems and how they were solved so future gun designs may avoid similar complications.

The laminated containment assembly was installed in the CEM-UT five axis filament winding machine for application of the S-glass/epoxy composite overwrap. The overwrap consists of primarily axially oriented 3.5° fibers to provide longitudinal bending stiffness along with 90° hoop layers to provide radial compaction and maintain proper location of the axial fibers during the winding process. The non-uniform, low bending stiffness of the laminated containment structure created significant problems during the filament winding procedure. Alternating deflections of the containment structure during rotation in the filament winding machine caused buckling of the axially oriented fibers, compromising the required bending modulus. In addition, the

large deflections failed several of the interlaminar bonds, which further increased the bending deflections. The non-circular cross section of the laminations also made it extremely difficult to maintain uniform tension and spacing of the fiber tows around the laminations circumference. After removing the initial 3.5° fiber layers, several layers of $\pm 45^\circ$ fibers were applied to reduce the bending deflections. A wet layup of axial roving was also applied to the overwrap to preferentially build up the minor diameter and speed development of a more circular cross section. The final diameter of the composite overwrap was approximately 12.75 in.

Fabrication of composite overwrap structures for subsequent launchers can be simplified by incorporating more uniform lamination outer profiles, with a circular cross section being preferred. Construction of the composite overwrap on a separate mandrel designed to minimize longitudinal bending deflections, or utilizing vertical axis filament winding equipment will improve the quality of the composite structure and allow parallel fabrication of the containment and overwrap structures.

After assembly of the rails and insulators around the Teflon™ coated bore mandrel, a seamless FEP shrink tube was installed around the bore package. Shell Epon 828 resin was applied to the outer surfaces of the bore package to bond the FEP insulator in place during the elevated temperature shrink of the FEP. The non-circular cross section of the bore package make it difficult to insure uniform contraction of the FEP, resulting in wrinkles in the insulator. The epoxy collected in these loose wrinkled regions and, after curing, created rigid high spots which resulted in damage to the FEP insulator during installation of the rail package into the containment structure. The epoxy also collected in the rail/insulator interfaces, preventing proper positioning of the bore components during the pressurized cure. The loosely woven fiberglass sleeve used to provide reinforcement to the pressurized cure epoxy also tended to wrinkle and contributed to the problems during the insertion of the bore package into the containment structure. After the first and unsuccessful assembly attempt, several modifications were developed to address these issues.

The rail/insulator seams were masked during application of the FEP bonding epoxy to prevent migration into the rail/insulator interface. The thickness of the bonding epoxy was also carefully controlled to prevent collection of excess resin in loose regions of the FEP insulator. Using experience developed during rotor fabrication, axial tension was applied to the FEP insulator during the high temperature contraction process, minimizing wrinkles and reducing high spots on the insulator. Fiberglass prepreg "bore riders" were bonded around the perimeter of the insulator to prevent contact between the FEP and the laminations bore. Finally, the braided fiberglass sleeve was eliminated and a glass filled epoxy resin was used during the pressurized cure procedure.

This eliminated a source of problems during insertion and provided more uniform reinforcement of the potting epoxy.

The containment structure was oriented vertically and an external fixture was used to axially preload the laminations during the pressurized cure procedure. The axial preload also provided compression of the elastomeric seals used to seal between the containment structure and FEP insulator in the breech and muzzle regions. This seal configuration was developed and tested to full pressure using a 0.5 m section of the actual bore package and containment structure components. The elastomeric seals must track the deflections experienced by the bore package components during the pressurized cure. Custom bore mandrels were installed in the seal locations to reduce the radial deflection in these regions and simplify seal requirements. The seal components immediately adjacent to the FEP insulator were constructed of G-10 composite to minimize the risk of insulation system breakdown in the event of damage to the FEP insulator. Examination of the breech and muzzle seal regions after the pressurized cure indicate that these seal configurations performed as designed.

Even with the improvements to the FEP insulator sleeve and use of the fiber/epoxy "bore riders", the twist present in the rail/insulator package resulted in damage to the FEP insulator during the subsequent assembly procedure. After approximately 6.5 m of the bore package had been inserted, the FEP insulator was breached. In order to avoid removal of the bore package for FEP sleeve replacement, a procedure was developed and tested to allow repair of the FEP sleeve. Again, examination of the launcher bore after the pressurized cure indicates that the FEP insulator repair was successful.

After the FEP sleeve repair, the bore package was fully inserted into the containment structure and the breech and muzzle seals were installed. The assembly was axially preloaded with the external support fixture and the pressurized cure procedure was initiated. The elimination of the braided reinforcing sleeve simplified insertion of the bore package into the containment structure, but required a room temperature cure, glass filled epoxy to provide the required mechanical properties of the epoxy layer. Room temperature cure, filled epoxies typically exhibit higher viscosity than elevated temperature cure or unfilled resins, which increases the pressure required to fill the annulus between the FEP insulator and the stainless laminations. Typically, these resin systems also have relatively short working lives. After an extensive product search, a low viscosity, filled resin system manufactured by Emerson & Cuming was identified. The 2651-40/Catalyst 23LV resin system has a rated working life of 60 to 90 minutes (in small masses) and fully cures in 24 hours.

To prevent acceleration of the cure reaction, the resin was measured out in small batches and mixed in stages as the annulus was filled. An hydraulic accumulator was used to transfer the resin into the railgun, with a second cylinder and valve manifold used to refill the primary transfer cylinder.

After filling the annulus and observing epoxy flow at the breech end of the railgun, the bleed valve was closed and the annulus pressurized. At approximately 2300 psi, epoxy leakage was observed from the breech end of the structure. Heat was applied to accelerate the resin cure in the region of the leak and a final pressure of 2600 psi was obtained before the resin cure cycle and resulting viscosity increase prevented further attempts to increase the annulus pressure. Examination of the seal regions after the pressurized cure indicate that the leak path was radially through the laminations and then axially along the laminations/overlap interface, bypassing the bore package seal assemblies.

After assembly of the breech connection and initial honing of the railgun bore, the railgun was mounted in the linear bearing system of the recoil mechanism.

Testing of the launcher is scheduled to begin in early 1994 on the capacitor bank power supply at the Electric Armament Research Center at Picatinny Arsenal. The initial test program is designed to work to full 9 MJ muzzle energy over a 10 shot sequence.

30 mm Subscale Task C Gun

With the new and innovative barrel design proposed for the Task C skid mounted gun system, it was important to verify the electromagnetic and mechanical analysis done on the gun structure and verify assembly procedures for the 90 mm gun. CEM-UT proposed and built a one-third scale version of the Task C gun. The subscale gun was a 30 mm x 3 m long launcher with an L' of 0.48 $\mu\text{H/m}$ and a peak current rating of 1.0 MA. The rails were fabricated from Glidcop Al-60® copper and the sidewalls were pultruded vinyl ester/S-glass composite. The gun was tested to full design loads with a series of 12 shots on the 60 MJ Balcones HPG power supply. Specific details of the design which were tested as part of the shot sequence were the ability of the laminated structure to retain the rail repulsion and prohibit eddy current formation in the gun structure. Another important design detail tested was the prestress induced on the rail/insulator package during the epoxy injection operation. The new light weight gun design used pressurized epoxy injection between the rail/insulator package and the laminated gun containment to prestress the rail package in compression. This epoxy was maintained at pressure until fully cured; thus leaving the rail/insulator package in compression. It was very important to verify the pre stress level was adequate to keep gaps from opening at the rail insulator seams at full firing loads.

The rail/insulator package was also an important design feature to be tested. The rail package successfully tested in the Task B 90 mm round bore gun used 90° rail segments. The design of the Task C gun utilized 75° rail segments to more efficiently fit the rail package in the laminated gun containment. Electromagnetic and thermal analysis had shown

the 75° segments were adequate to fire a solid armature to full current with no melting of the rail surface. It was very important to fire the subscale gun at full current and verify the rail surface integrity.

The shot sequence was setup such that the gun was initially fired at low current levels and worked to full current over a series of ten shots. The last two shots on the gun were done as primarily solid armature development work for the TASK C, SLEKE and CCEML programs. Table 1 summarizes the 12 shots done in the 30 mm launcher. The active gun length changed from shot to shot because the armatures were loaded past minor rail damage incurred during several shots and past insulator damage caused by later shots. The tests in the 30 mm gun revealed several interesting items.

The first of these is the higher muzzle volt transition velocities observed during the shots. Previous solid armature work in the 90 mm Task B gun had reached transition velocities of 800 to 1200 m/s [2]. It was observed during the 30 mm solid armature tests the muzzle volts transitioned at a much higher velocity. Throughout the railgun community, there is a wide ranging definition of armature transition. Some consider transition as the point when true metal-to-metal sliding ceases and the muzzle voltage rises above several volts. CEM-UT considers an armature to be in good sliding contact if it has an efficient muzzle volt drop of 20 to 50 V. In this voltage range, a projectile is accelerated extremely well with little power lost in the armature/rail interface and little to no damage to the bore. In this text, muzzle volt transition is defined as the point at which the muzzle voltage sees a "step" increase above this 20 to 50 V range and there is a significant increase in power lost across the armature. The higher transition velocities in the 30 mm gun have been attributed to the ability of the Balcones power supply to keep the current up in the smaller bore gun [2]. Keeping the current up close to peak for a longer duration retains the electromagnetic loading on the compliant armature and keeps the contacts in a lower voltage sliding contact. The large bore Task B gun has such a voracious appetite for energy, it is difficult to keep the current elevated for an extended duration. The current rapidly drops during acceleration and the electromagnetic loading on the armature is reduced. The combined effect of armature wear and reduced magnetic loading does not allow the armature to keep a good sliding contact and the muzzle voltage rises. The increased transition velocities are very encouraging and demonstrate the need for more "flat top" current pulses into EM guns.

Another interesting observation taken from these shots was the performance of the gun without honing between shots. Prior to shots 2 through 11, cleaning the bore involved running a ScotchBrite® pad through the gun on the end of a rod several times to remove the loose soot and lightly buff the rail/insulator surfaces. The minimal amount of cleaning performed was necessary for viewing the bore with a small 0.5 in. CCD color camera. This camera was very useful for

inspecting the bore for possible insulator damage or arc damage on the rails. The gun performed very well and no obvious effects of not honing were observed. The original bore diameter was 1.211 in. A polyethylene plug was machined precisely to this diameter and prior to shots 2 through 11 the plug was run through the gun to see if the bore had changed diameter. Throughout the series of shots, there was no obvious build up of bore deposits or bore erosion. Prior to shot #12 the gun was lightly honed with a total of 0.007 in. removed from the diameter. This was a duplicate of shot #8 to see if a refurbished gun bore and a slightly different current input would increase the muzzle volt transition velocity seen on shot #8. As seen in Table 1, shot 12 had comparable performance, but no real advantage was gained by honing the gun.

Table 1. Summary of test on 30 mm subscale Task C gun

Shot #	Projectile Mass (g)	Active Gun Length (m)	Muzzle Velocity (m/s)	Muzzle Energy (kJ)	Peak Current (kA)	Transition Velocity (m/s)
1	140.5	2.27	195	2.7	220	NA
2	140.5	2.27	644	29	400	NA
3	77.5	2.27	1335	69	573	NA
4	75.7	2.27	1666	105	NA	NA
5	115.5	1.89	1014	59	598	NA
6	76.2	1.89	1838	129	830	1381
7	74.3	1.89	1848	126	839	1473
8	77	1.89	2080	167	717	1868
9	77.6	1.78	1773	121	845	1371
10	76.8	1.63	2111	172	1025	1705
11	76.7	1.85	2309	204	972	1930
12	78.5	1.85	1919	145	804	1611

The full scale Task C launcher was designed and built with pultruded sidewall insulators. The full scale sidewalls were fabricated with a 70% fiber fraction, including both roving (filaments) and cloth. The roving was pulled axially in the direction of projectile motion and the cloth was oriented 45° to projectile motion. The manufacturer of these sidewalls advised CEM-UT that making one-third scale sidewalls was prohibitively expensive. At this point CEM-UT purchased a set of subscale insulators that were strictly axial fiber pultrusions with no cloth woven into the sidewall. During assembly and initial bore honing, the bottom insulator was slightly damaged in the breech area of the gun. Over the first five shots, this damaged area became worse. Approximately a one foot length of the insulator had split along its axial centerline and one side of the insulator was loose and slightly bowed up into the bore. Loading or firing over the loose sidewall was deemed unacceptable. A small amount of Epon® epoxy was applied under and around the damaged area and a Teflon™ mandrel was used to hold the insulator down while the epoxy cured. This repair worked well and the testing continued. As an armature was being loaded prior to shot #10, the armature bound on the bottom insulator and buckled the previously damaged sidewall, bowing it into the bore. Pushing the armature further into the gun would have severely damaged the bore and pushing the armature back-

wards out the breech may have caused the high pressure contacts to dig into the copper rails and "broach" the rail material. The armature was drilled out of the bore and the damaged insulator material was drilled out of the gun with a spade drill. The void left by the removed insulator was potted with epoxy and to prevent further propagation of cracks in the insulators, Superglue® was dripped in the bore and allowed to run down each insulator. The goal was to get the Superglue® to run into any cracks in the insulators and bond them shut before they could be opened during a shot. The insulator repair and the Superglue bonding were very successful and the remaining three tests were done in the gun with no further insulator damage or repairs. A conclusion from the 30 mm gun shots is that pultruded insulators without the 45° woven cloth may have been extremely risky in the full scale gun. Based on the 30 mm testing, there is guarded optimism for the survivability of the insulators in the Task C gun.

30 mm Laminated Gun Redesign

U.S. Army ARDEC hired CEM-UT to construct a one-third scale railgun of the 90 mm bore 7 m long railgun being built for the Task C program. This 30 mm round bore simple railgun was built and tested over the past two years. U.S. Army ARDEC also contracted CEM-UT to build a second 30 mm railgun for use by the Army at Picatinny Arsenal, NJ.

The second 30 mm gun was to be identical to the first, but the first gun experienced sidewall damage during early testing and though it was successfully repaired, a decision was made to investigate design alternatives for the second 30 mm launcher. Also the question of building a simple vs. an augmented gun to better model the full-scale Task C gun was considered. There were a number of issues to be considered as follows:

1) Power Supply To Be Used

On examining the possible performance of gun types with the EARC (capacitor bank) or EMACK (homopolar/inductor) power supplies at the Picatinny Arsenal facility, it was apparent that a simple gun configuration could be fired off either supply. An augmented gun would be limited to the capacitor bank unless a developmental opening switch program resulted in a successful means to commutate sufficient energy to an augmented gun load.

Given the U.S. Army ARDEC decision to primarily test the scale gun on the EMACK homopolar power supply, the near term solution was to build a simple gun configuration.

2) Issues of Scaling

Experience to date did not allow CEM-UT to make definite correlations as to the scaling of armature/rail heating, stress and wear in one style gun over another as compared to the full-scale Task C gun. To be able to refine the modeling techniques to accurately represent of 90 mm gun tests at the

subscale level would require a substantial amount of work over and above the effort budgeted to construct a second 30 mm gun.

3) Experience

CEM-UT had built both simple and augmented guns of the 30 mm and 15 mm bore size. The scaling of the 15 mm augmented gun (tested to 320 kA) to a 30 mm size could have been done, but the design and construction techniques required to build it would have required a significant design effort. It was not clear that such a gun could be built for the money budgeted, and as mentioned, it was not clear to CEM-UT that the resulting subscale augmented gun would accurately model a simple full-scale Task C gun.

CEM-UT's recommendation was to proceed with a 30 mm simple rail configuration gun very similar to the one already built and tested. The design alternatives were limited to varying bore component materials or the dimensions of the cross sections of these components. An investigation for an improved sidewall design that would replace the pultruded fiberglass insulators with continuous alumina ceramic sidewalls was carried out. Vendors were contacted and price and delivery quotes were obtained. Preliminary calculations were also done to determine what initial preload would be necessary on the bore components to maintain the ceramic in a compressive state during the actual full energy gun shot event. These loads were calculated to be on the order of tens of thousand psi and would require new gun manufacturing techniques to be developed to apply such a large preload. Therefore to keep the preload assembly pressures at levels that had been previously achieved, an improved pultruded sidewall was selected.

The resulting design doubled the insulator sidewall thickness and increased the width of the rails to accommodate the sidewall. Also the cooling channels were eliminated from the rails. Minor changes to the shape of the structure laminations were also incorporated to shorten, improve or eliminate various fabrication steps that proved unnecessary or exceedingly difficult during the fabrication of the first 30 mm gun. These changes are seen in figures 2 and 3. Component materials were left the same, but the fiber pattern in the pultruded fiberglass sidewall was different in the second gun. The sidewalls were pultruded to finished shape where the first gun's set had been machined from pultruded round stock rod. This original round stock contained only axial fibers and with the second gun a layer of 90° weaved ribbon cloth was placed about the perimeter of the insulator during the pultruding process.

Both guns' rails were machined from dispersion strengthen copper stock. The rails for the second gun were Glidcop® C15760 manufactured by SCM Metal Products, Inc. The extruded material was purchased as 1 in. x 3 in. x 105 in. rectangular bar. The over sized cross section was purchased to permit the rail and the rail's breech termination to be

machined from a continuous piece of material and there by eliminate any difficult electrical joint between a two piece design. The rail breech termination was dimensioned to match up to the already existing buswork at the Army's facility. To terminate the 30 mm gun rails in such a manner caused design concerns because the rails in this region are not supported by the gun laminated steel structure and depend on the buswork structure for support. Complete dimensional information and a materials list for the existing buswork were obtained, and a 2-D finite element method (FEM) analysis was done to verify that the rails' loading in the breech region would not result in stresses that could lead to material failure.

Figure 2. The cross section of the original 30 mm Task C simple railgun

Figure 3. Cross section for the redesigned 30 mm simple railgun -- sidewalls increased in thickness and made of pultruded fiberglass, cooling channels eliminated and laminations produced with a circular outer profile to aid in fabrication and assembly

Upon completion of the fabrication, inductance measurements verified an inductance gradient of $.48 \mu\text{H/m}$ for this 30 mm gun. These measurements were done at 100 kHz using a programmable frequency LCR meter, model Video Bridge 2150, manufactured by Electro Scientific Industries, Inc. Measured values were plotted and the Least Squares Curve Fit method with a regression coefficient of 0.99977 was used to determine a L' value of $0.513 \mu\text{H/m}$ for the new 30 mm gun.

Other gun parameters measured were the gun's, length, weight, straightness, and the voltage standoff between rails. The gun bore length is 2.3 m, and its weight including breech tabs is 255 lb. The gun's straightness was measured by observing deviations in positions of a cross hair mounted on a tight fitting bore plug that was pushed through the gun. These deviations from center were determined using a precision machinists telescope. The deviations increase gradually as one moves down the gun and near the middle reach a maximum of 0.022 in. from the centerline of the bore. Deviations then gradually become smaller as one nears the muzzle end of the gun. The gun's insulation to voltage breakdown was checked by placing a 2.0 kV, 0.1 mA power supply source across the rails and the leakage current was measured at $5.0 \times 10^{-8} \text{ A}$ (i.e. 40 GW). The gun was packaged and delivered to U.S. Army ARDEC for firing on the EMACK power supply.

CONCLUSIONS

CEM-UT has successfully fabricated three light weight, high performance railgun launchers to help move railgun technology from the laboratory setting to mobile platforms. The 90 mm Task C gun assembly has been completed and the gun delivered to U.S. Army ARDEC to begin characterization of its performance. The design and analysis of the full scale 90 mm gun was verified with the successful testing of a one-third scale version at CEM-UT. This 30 mm x 3 m long launcher was fired during a series of twelve shots with several at full current tests to test the guns structural integrity. Valuable lessons learned during the assembly of the 30 mm gun and its subsequent testing were used to complete fabrication of the 90 mm gun as well as build an additional 30 mm gun for delivery to U.S. Army ARDEC for firing on the EMACK power supply.

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