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UCRL-CR-112610
B157379

PULSED POWER SUPPLY FOR NOVA UPGRADE

Final Report

August 1, 1991 to March 31, 1992

Submitted to:

J. Krueger and M. Crowningshield
University of California
Lawrence Livermore National Laboratory
Livermore CA 94551

Subcontract # B157379

Submitted by:

J.L. Bacon, J.P. Kajs, A. Walls, W.F. Weldon, and R.C. Zowarka

RF 115

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

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ACKNOWLEDGMENT

CEM-UT would like to thank Parker Kinetic Design (PKD) for providing us access to their Trailblazer II Experiment proposal, RFP F08635-86-R-0030. In 1986 PKD generated a detailed cost proposal for the design and fabrication of five 260 MJ class homopolar generators (HPGs). This proposal was written shortly after PKD finished the fabrication of the six Balcones HPGs for CEM-UT and therefore reflects insight and experience. We have used this proposal as a template for the HPG cost section of this report because it provides realistic manufacturing hours and materials estimates for machines the size of those required for LLNL Nova Upgrade.

1.0 INTRODUCTION

This report describes work carried out at the Center for Electromechanics at The University of Texas at Austin (CEM-UT), for Lawrence Livermore National Laboratory (LLNL) at the University of California under Subcontract No. B157379, entitled "Study and Design of a Homopolar Generator/Inductor Flashlamp Power Supply for the Nova Upgrade."

A baseline design of the Nova Upgrade has been completed by Lawrence Livermore National Laboratory. The Nova Upgrade is an 18 beamline Nd:glass laser design utilizing fully relayed 4x4 30 cm aperture segmented optical components. The laser thus consists of 288 independent beamlets nominally producing 1.5 to 2.0 MJ of 0.35 μm light in a 3 to 5 ns pulse. The laser design is extremely flexible and will allow a wide range of pulses to irradiate ICF targets. This facility will demonstrate ignition/gain and the scientific feasibility of ICF for energy and defense applications. The pulsed power requirements for the Nova Upgrade are given in table 1-1.

Table 1-1. Flashlamp pump

Electrical pulsed power supply energy (MJ)	200
Electrical pulsed power supply voltage (kV)	20
Flashlamps per module	32
Modules per beamline	17
Bore diameter (cm)	2.3
Length (cm)	170
Explosion fraction	0.2
Gas fill Xenon (torr)	200
Pump pulse length (μs)	500

CEM-UT was contracted to study and develop a design for a homopolar generator/inductor (HPG/inductor) opening switch system which would satisfy the pulsed power supply requirements of the Nova Upgrade. The Nd:glass laser amplifiers used in the Nova Upgrade will be powered by light from xenon flashlamps. The pulsed power supply for the Nova Upgrade powers the xenon flashlamps. This design and study was for a power supply to drive flashlamps.

Historically the pulsed power supply for the laser amplifiers has been based around large capacitor bank technology. CEM-UT performed this study of HPG/inductor technology as an alternative pulsed power source with the potential for significant cost savings. The system designed is very similar to the existing six HPG/inductor system at CEM-UT known as the Balcones power supply. Because of its similarity to an existing power supply, it should perform as designed. HPG/inductor technology is at the heart of pulsed power research worldwide. There are major facilities in Australia, United Kingdom, Netherlands, and the United States. The facility at The Australian National University at Canberra has actually used an HPG/inductor system to drive parallel flashlamp loads. In the U.S. there are large HPG/inductor power supplies performing significant electric gun research at the U.S. Army Armament Research, Development, and Engineering Center (U.S. Army ARDEC) at Picatinny Arsenal; Westinghouse Sunnyvale Division; Air Force Armament Test Laboratory (AFATL) at Eglin Air Force Base; and CEM-UT. The largest of these power supplies is The University of Texas Balcones power supply which consists of six 10 MJ HPGs charging six energy storage inductors each at a peak charging current of 1.25 MA. The power supply is used in concert with opening switches to produce power pulses of 25 GW magnitude for electric gun research.

1.1 Statement of Work

The technical scope of work for this subcontract is described in the following tasks:

Task 1: Design an HPG/inductor opening switch system.

Task 2: Study alternate system switch configuration and submit report on comparisons

Task 3: Perform system trade-off vs. cost study

Task 4: Provide results of studies to LLNL for evaluation of best system design.

Task 5: Publish a final report on system selected including configuration and costs estimate.

1.2 Assumptions

Various assumptions were required to design this HPG/inductor system. The first was that a particular flashlamp system was being designed. The number of amplifiers and their physical placement inside the experimental complex at LLNL was assumed. This layout was developed with assistance of LLNL personnel.

The next assumption was that the power supply should produce a current pulse which was similar to the capacitor power supply current pulse. This requirement arises for two reasons. The first reason is the cost of the HPG/inductor power supply can be easily compared to the cost of the capacitor based system. The second reason is that the effect of a different current pulse shape upon flashlamp lifetime and light wavelength output from the flashlamps is unknown. The flashlamp lifetime data is empirically derived and has all been measured based upon a critically damped RLC circuit pulse shape. The 'natural' pulse shape derived from the HPG/inductor power supply is an RL decay. The critically damped waveform can be approximated by absorbing energy in the opening switches to force a slow current rise and a later crowbar circuit to cut off the tail of the current. The HPG/inductor power supply could be significantly smaller if a current pulse with a steeper current rise were acceptable.

The last assumption was that a minimum of 40 μH of inductance was in series with each flashlamp pair to force current distribution between flashlamps.

1.3 Conclusions

Our preliminary HPG/inductor design meets the pulsed power requirements for the Nova Upgrade. The system has built in fail-safe features. In the event of site power loss the diesel bearing skid will keep oil flow to the HPG hydrostatic bearings and the machines will spin down to a safe stop. The explosives used in the opening switches are class C Prima-cord™ initiated by noise immune bridge wire detonators. Recommended safe disposal of Prima-cord™ and detonators is by burning. For this reason, a fire in the facility does not produce an additional hazard of explosive initiation. The explosive are housed in containment vessels certified for a worst case fault condition. Worst case fault would occur when a switch opened and there was no load in which to commutate the current. In this situation all of the magnetic and explosive energy is dissipated in the containment vessel. The vessel design will be tested at an explosives range with the equivalent deta sheet to simulate the worst case fault energy.

The fixed cost to the system is $27,004,912 (FY 1995). If pre-ionization of the flashlamps is required, an additional cost of $1,152,139 will be incurred for the purchase of switches to isolate the HPG opening switches from the preionization lamp check (PILC) bank. The opening switches are single shot devices that are installed for every test. The cost of the opening switch expendables for a full energy test is $9,731. This cost is linear with the test energy.

The system has been designed to accommodate a test every two hours. To achieve this turnaround 2 engineers and 13 technicians are required. A detailed time motion study is presented in the body of the report. This staffing will drop if the time between tests is increased.

Cost tradeoffs have been investigated in every aspect of the system design and are presented in the report. The HPGs are the cost driver. As the number of machines decreases, the cost comes down. We investigated one-, four-, six-, and nine-generator options and found the four-generator design to be sufficiently conventional and familiar that there will be little doubt that it will perform as designed. If one generator is decommissioned for service, a significant fraction of the pulsed power, 75%, is still available for testing.

An abbreviated schedule is

- design HPGs 10/94-11/95
- manufacture and test first HPG 10/95-8/96
- manufacture and test HPGs two to four 1/96-12/97
- design pulsed power circuitry 12/94-5/95
- manufacture pulsed power circuitry 6/95-5/96

A detailed schedule is presented later in the report.

1.4 Recommendations

Several test programs should be set up to demonstrate feasibility of this approach.

An experimental program should be set up to check the effect of HPG/inductor pulse shape on flashlamp lifetime and light output. It is our understanding from talking to Livermore personnel that large populations of lamps exist with over 100,000 successful discharges. Additionally, we understand that samples of these populations were extracted at low numbers of pulses (100 and 1,000) and the glass was examined for crack sites. To quantify the effect of the inductor pulse shape on lamp life in the near term, a pulse-forming network which reproduces an HPG/inductor pulse should be set up and discharged into a lamp population. Long term life (100,000 tests) can then be predicted by comparing glass samples from the old and new population after 100 and 1,000 tests and use glass appearance to extrapolate lifetimes.

An experimental program should be set up to demonstrate flashlamps driven in parallel from an HPG/inductor power supply. The Balcones power supply is available for these demonstrations. Two test approaches are proposed. First, 32 parallel flashlamps are a good load for the Balcones Inductors to produce a pulse shape similar to the RLC pulse shape. This can be accomplished with the existing opening switches. Second, we are in the process of adding an electrical connection from the Balcones power supply which uses hexapolar cables for another experiment. The electrical connections planned for the Nova Upgrade in this report use these same type cables. It would be convenient to connect one of the amplifiers to the Balcones power supply. An amplifier consists of 16 parallel pairs of series connected flashlamps. The Balcones power supply opening switches have only been demonstrated at 15 kV because the loads placed on the system don't require any more voltage. The amplifier would require about 23 to 24 kV of developed voltage. If the present opening switches would develop this higher voltage we could drive amplifiers with the Balcones power supply. We believe minor modifications to the existing switches should produce additional voltage:

1) Increase the number of series gaps in the switch.

2) Stage the opening of the gaps so that some gaps open at time zero and others open 10s of microseconds later. The first gaps drive the switch current down and the staged gaps open lower currents with subsequently higher recovery voltage.

3) Use a higher grain size Prima-cord™ so that the element is ejected in a shorter time and there is a higher volume of cold explosive gas to starve the arc.

The main goals of this Balcones test program would be:

- demonstrate parallel operation of flashlamps driven by an HPG/inductor power supply
- demonstrate use of flexible cables for amplifier electrical connections
- determine effectiveness of forcing current distribution between flashlamps by varying inductances of flashlamps
- demonstrate acceptability of pulse shape derived from the HPG/inductor system by measuring light output
- Allow LLNL personnel to witness the operation of a system very similar to the one designed in this study and evaluate the feasibility based upon actual performance of such a system

The expected pulse shape for the 32 parallel flashlamp experiment is shown in figure 1-1 along with the reference RLC pulse shape desired for the Nova Upgrade. The calculations for the reference RLC pulse shape are shown in the September 1991 monthly report. The only method we know to evaluate acceptability of a pulse shape is to compare it to the reference RLC pulse shape. This test would only require about 35% of the capacity of one of the six generators.

If the present opening switches can develop higher than 15 kV then the operation of an amplifier from the Balcones power supply is feasible. Driving a single amplifier should produce a pulse shape similar to that shown in figure 1-2. Driving three amplifiers rather than one would produce a less peaky pulse as shown in figure 1-3.

An additional study and cost report on a compulsator based system to provide the pulsed power for the Nova Upgrade should be considered. A preliminary examination of compulsators for this application is presented in Appendix A.

We are very interested in conducting this test program for LLNL, and would be pleased to propose this work.

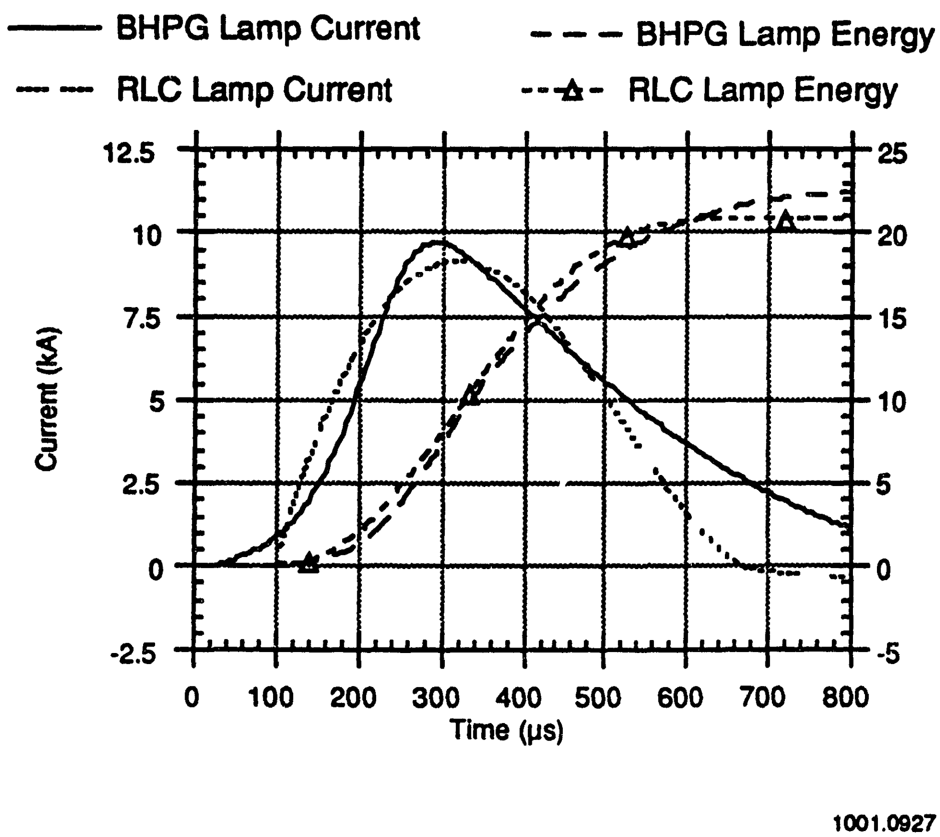


Figure 1-1. BHPG driving 32 parallel flashlamps

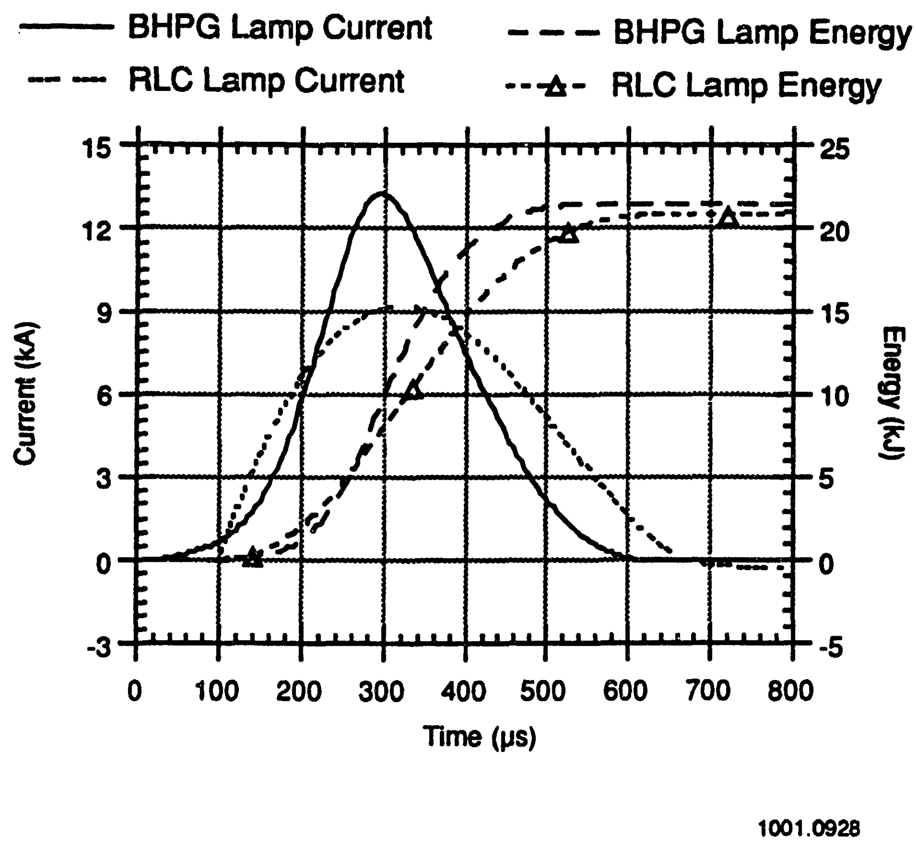


Figure 1-2. BHPG driving one amplifier

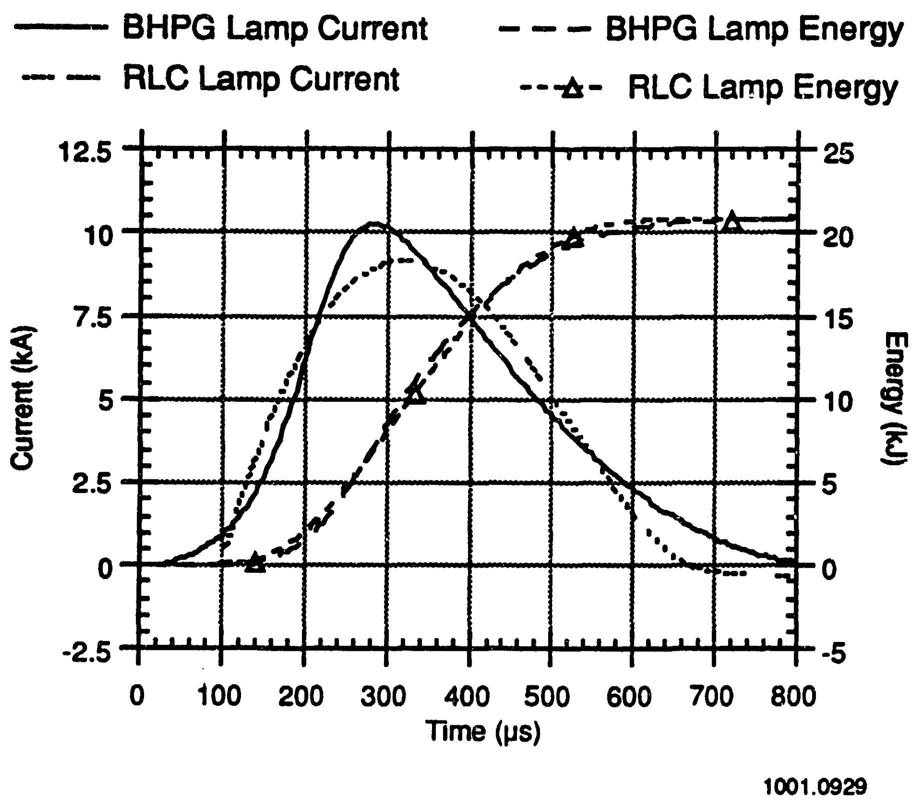


Figure 1-3. BHPG driving three amplifiers

2.0 TASK 1 HPG/INDUCTOR OPENING SWITCH SYSTEM DESIGN

2.1 Overall System Design

The pulsed power supply is required to supply 200 MJ of electrical energy to the flashlamps in a 500-μs pulse. There is some concern about the flashlamp lifetime if a pulse shape other than that provided by the capacitor power supply is used to drive the flashlamps. The reasons for choosing the particular HPG/inductor/opening switch system are covered in Appendix B.

An overall circuit schematic for the system is shown in figure 2-1. The circuit schematic shows two HPGs with three storage inductors per HPG. The full system has four HPGs with six inductors per HPG for a total of 24 inductors and opening switches. Figure 2-2 shows the HPGs, inductors, and containment vessels. The major components of the pulse power supply are the HPGs, storage inductors, charging bus, opening switches, explosive containment vessels, collection bus, distribution bus, and common bus. The abort, crowbar, and isolation switches are optional and will also be discussed.

The system was designed by a fairly straightforward process. First, the flashlamp behavior was modeled. The entire system of flashlamps was assumed to be 18 beamlines with 17 multi-segment amplifiers per beamline. Each amplifier was assumed to consist of 32 flashlamps which supplied light energy to a 4x4 Nd:glass laser amplifier array. The 32 flashlamps are electrically connected as 16 pairs of series lamps inside each amplifier. Each flashlamp pair should have minimum of 40 μH of series inductance to aid in forcing current distribution between flashlamps. The flashlamps used in the design were assumed to be 2.3 cm diameter, 170 cm long, and filled to 200 torr with xenon. After ionization the individual flashlamp electrical behavior was assumed to follow the equation

$$V = K_0 \sqrt{I}$$

V = flashlamp voltage
K_o = flashlamp constant
I = current in flashlamp

K_o was calculated as

$$K_0 = 1.27\left(\frac{P}{450}\right)^{.2}\frac{l}{d} = 1.27\left(\frac{200}{450}\right)^{.2}\frac{170}{2.3} = 80\ V/A^{.5}$$

P = xenon fill pressure in torr
l = flashlamp length
d = flashlamp diameter

Within an individual amplifier, there are four rows of Nd:glass plates with flashlamps on the outside edges and between all of the rows of plates. With the present design there are eight lamps between each row of plates and four lamps on each of the outside edges. The lamps located between rows illuminate the plates on both sides of their locations so a row of plates is illuminated by eight flashlamps per

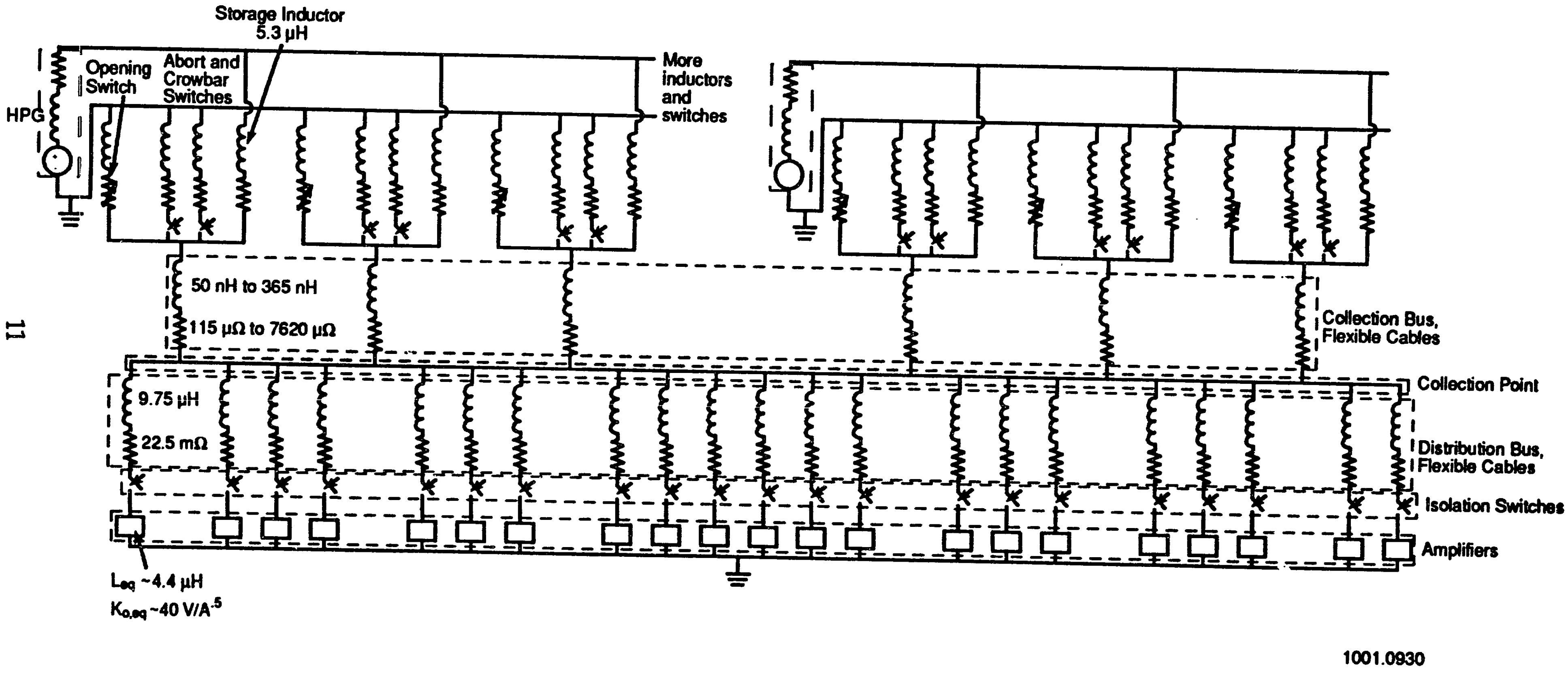


Figure 2-1. System circuit schematic

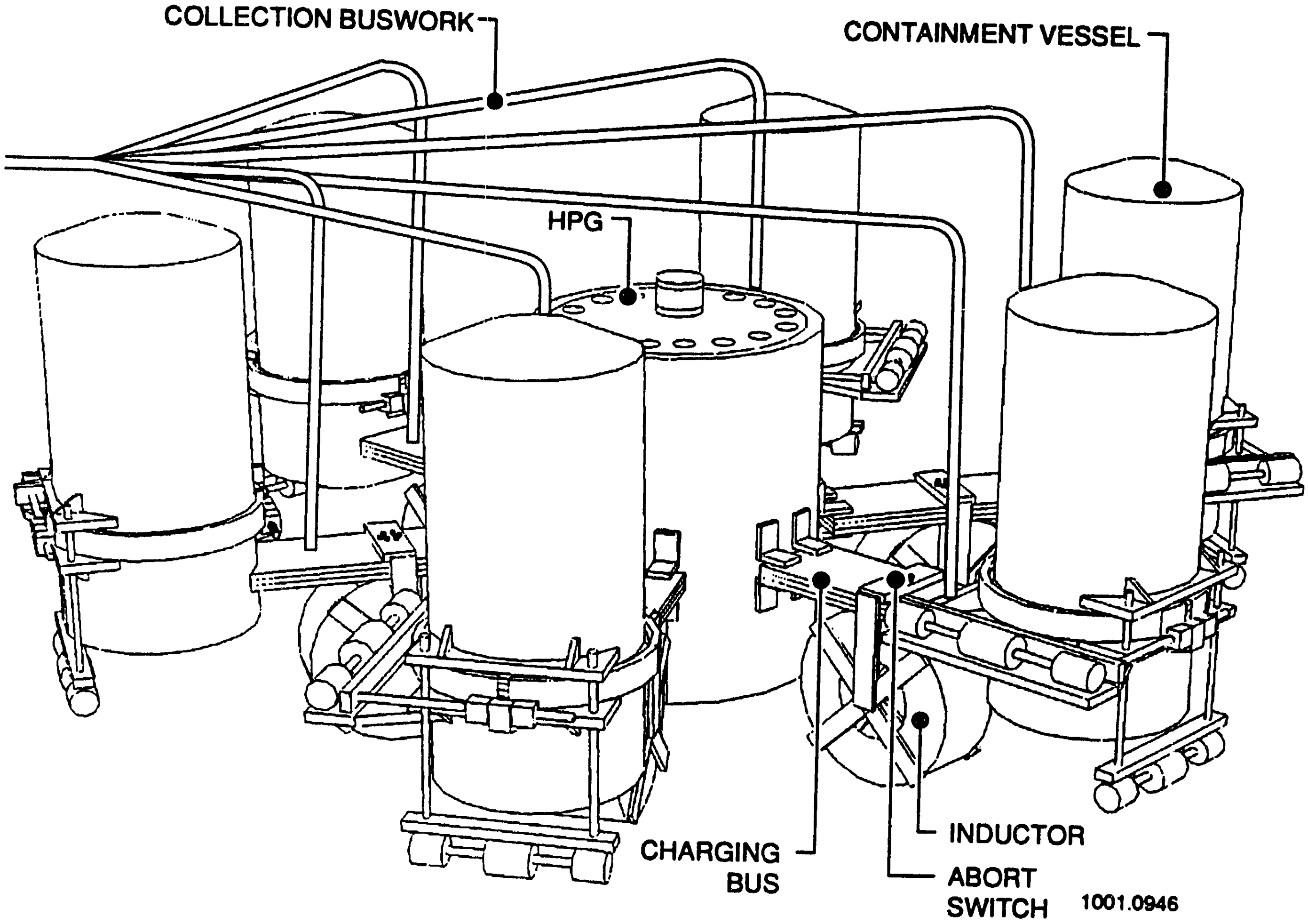


Figure 2-2. Overall isometric

side. The outside rows of plates are illuminated by eight flashlamps on the inside edge and four flashlamps on the outside edge. To compensate for having only four flashlamps on the outside edge, a reflector is placed on the outer edge of the outside flashlamps to return the light going out from the flashlamp to the plates. This reflector isn't quite as effective as a second flashlamp. As a result the flashlamps on the outside edge will require higher light output to provide equal light energy to all of the plates. How much higher this energy needs to be is somewhere around 5 to 10% additional energy input. Simulations were done for the HPG/inductor power supply with different series inductances connected to the inside flashlamps compared to the outside flashlamps to see if this difference in energy could be forced. By keeping the series inductance of the outside flashlamps at 40 μH and increasing the series inductance of the interior flashlamps up to 100 μH, a difference in energy delivered to the flashlamps of up to 15% could be obtained. An approximate equivalent inductance per flashlamp for this 15% difference in energy is 70 μH.

The buswork impedance between the amplifiers and power supply was calculated based upon a physical amplifier layout. From various conversations with Lawrence Livermore personnel and drawings sent to CEM-UT, the amplifier arrangement shown in figure 2-3 was assumed.

The distribution bus is the buswork from the common bus to the amplifiers. This bus is designed as flexible hexapolar cables. Each amplifier will have its own cable from the common bus. After the distribution bus impedance was calculated, numerical simulations were performed to determine a combination of initial inductor current and inductor energy which would provide a pulse shape similar to the capacitor based power supply. Details of the calculation of the capacitor reference waveforms are presented in the September 1991 monthly report. The HPG voltage changes very little during the flashlamp pulse and is relatively small (<100 V) so a simple inductor-only simulation is a fairly good model to determine the required system current and inductive energy. These simulations indicated that the inductors should store 70 MA and 520 MJ prior to the opening switches being opened. A significant portion of this magnetic energy is dissipated to create the slow rising capacitor pulse shape. A flashlamp pulse shape with a steeper current rise would dissipate less energy in the opening switches and require less initial current and energy in the inductors.

Once the required peak current and stored magnetic energy were obtained, the HPGs were designed. An HPG design spreadsheet was devised which required initial rotor kinetic energy and peak current. A transfer efficiency of 50% between HPG rotational energy and stored inductor magnetic energy was assumed. After trying various numbers of HPGs, it was determined that a practical current limit of around 15 to 18 MA per machine should be used to stay within demonstrated HPG parameters. The 70 MA peak system current implies a minimum of four HPGs. The spreadsheet helps determine the dimensions of the machines, number of brushes, etc. which effect cost of the machines. Outputs from the spreadsheet include electrical performance parameters such as resistance, inductance, voltage per rpm, initial speed, and generator inertia.

System reliability for a given number of generators is difficult to analyze for the chosen system. The cost of the generators goes up with increasing numbers of generators, therefore the system was designed using four HPGs. If one of the

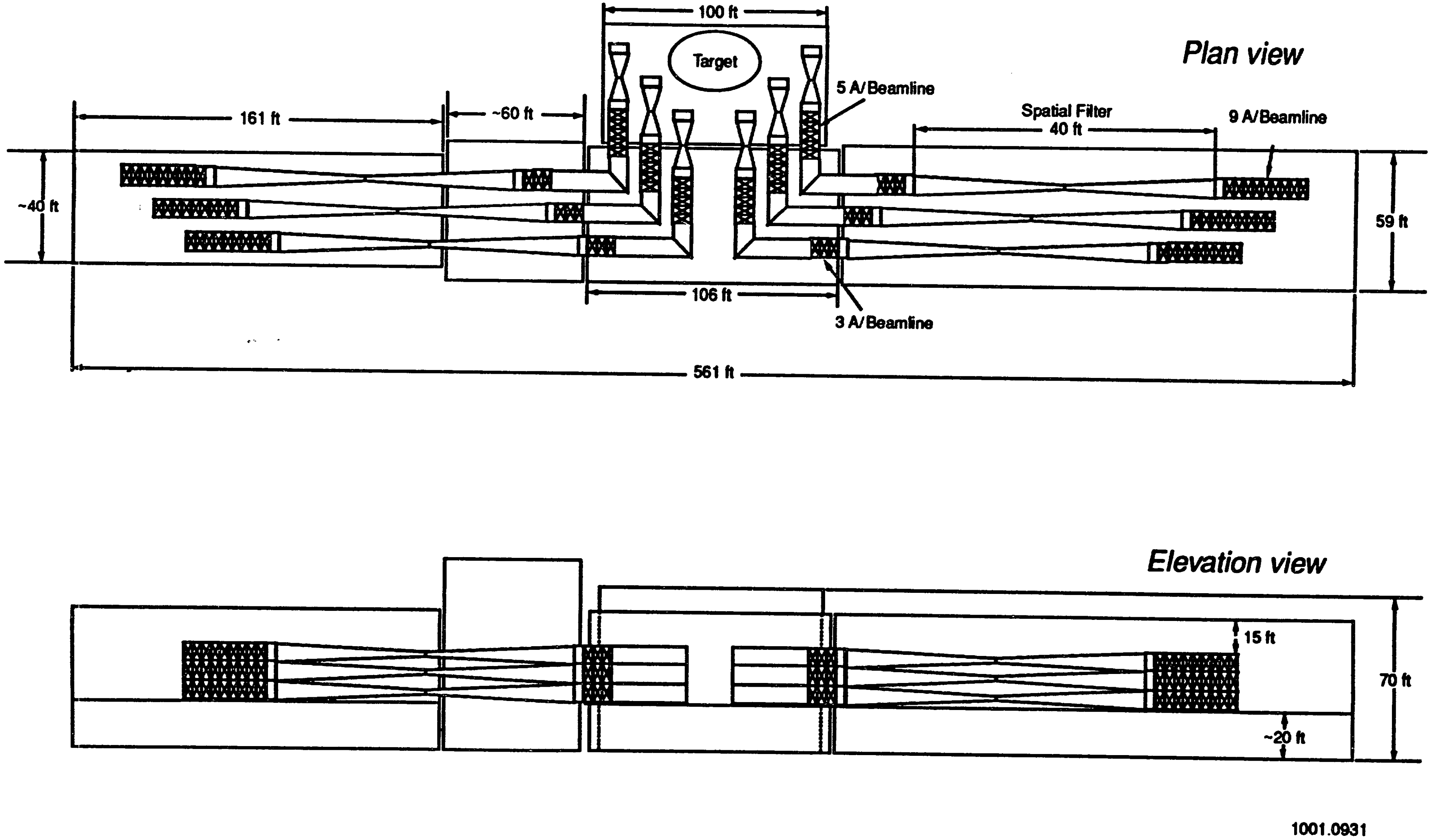


Figure 2-3. Physical amplifier layout

generators is down for some reason the power supply is still available at 75% capacity. This 75% capacity can be split among the amplifiers in whatever method is desired, either using any 75% of the amplifiers at 100% power or using 100% of the amplifiers at 75% power.

If part of the amplifiers are unavailable, another possibility occurs. If 33% of the amplifiers are not available it would be possible to either use three of the four generators and save the expense of using four generators, or to use all four generators at 100% of capacity and increase the power delivered to each amplifier by 50% so that the same total energy is delivered to the amplifiers, though at higher energy levels per amplifier.

After the HPGs were designed, a simulation was performed using the required energy storage inductance as a load to determine the maximum resistance of the rest of the charging circuit. This simulation used empirical brush voltage and friction models as well as the resistance, inductance, etc. calculated by the spreadsheet. The charging buswork, opening switches, and inductors were then designed to stay below this total load resistance. A minimum of six Brooks coil type inductors per generator was chosen to give a reasonable containment of the magnetic flux. The inductors will be arranged in a circle around each HPG oriented such that they couple each others flux and approximate a toroid. The number of inductors was set at six because the cost goes up for each additional inductor and the current per opening switch was within acceptable limits.

After the HPGs, charging buswork, switches, and inductors were designed and the physical layout determined, physical locations for the generators and inductors inside the experimental complex were chosen. This allowed collection buswork to be designed from the opening switches to the common bus. This collection buswork uses the same type cables as the distribution buswork because of ease of insulation, installation, and force management. After all of the parts were designed, a final simulation was performed using an empirical opening switch model, all of the generator and buswork parameters as designed, and the previously described flashlamp model. This simulation included both charging the inductors to peak current and discharging the current into the flashlamps.

The main question at this point in the design concerned what an acceptable pulse shape was. A pulse shape very close to that supplied by the capacitor system can be obtained from the system designed if a crowbar circuit is added across the opening switches. This crowbar is shown schematically in figure 2-1. The system can be built without the crowbar which will then supply a longer pulse and deliver additional energy to the flashlamps after the 500-μs period. The current for both the crowbar and noncrowbar system are shown in figure 2-4, along with the pulse which would be supplied by a capacitor system. The energy for these same three systems are shown in figure 2-5. The method for deriving the reference capacitor pulse shape is covered in the September 1991 monthly report. The crowbar switches are currently designed as high current, high coulomb arc gap switches. This will facilitate rapid turnaround between tests of these closing switches. The costs for installing and using these crowbar switches are non-trivial and may not be worth the difference in pulse shape from the non-crowbarred pulse. Because CEM-UT personnel aren't qualified to determine whether the crowbar is necessary the crowbar components are priced as a separate item.

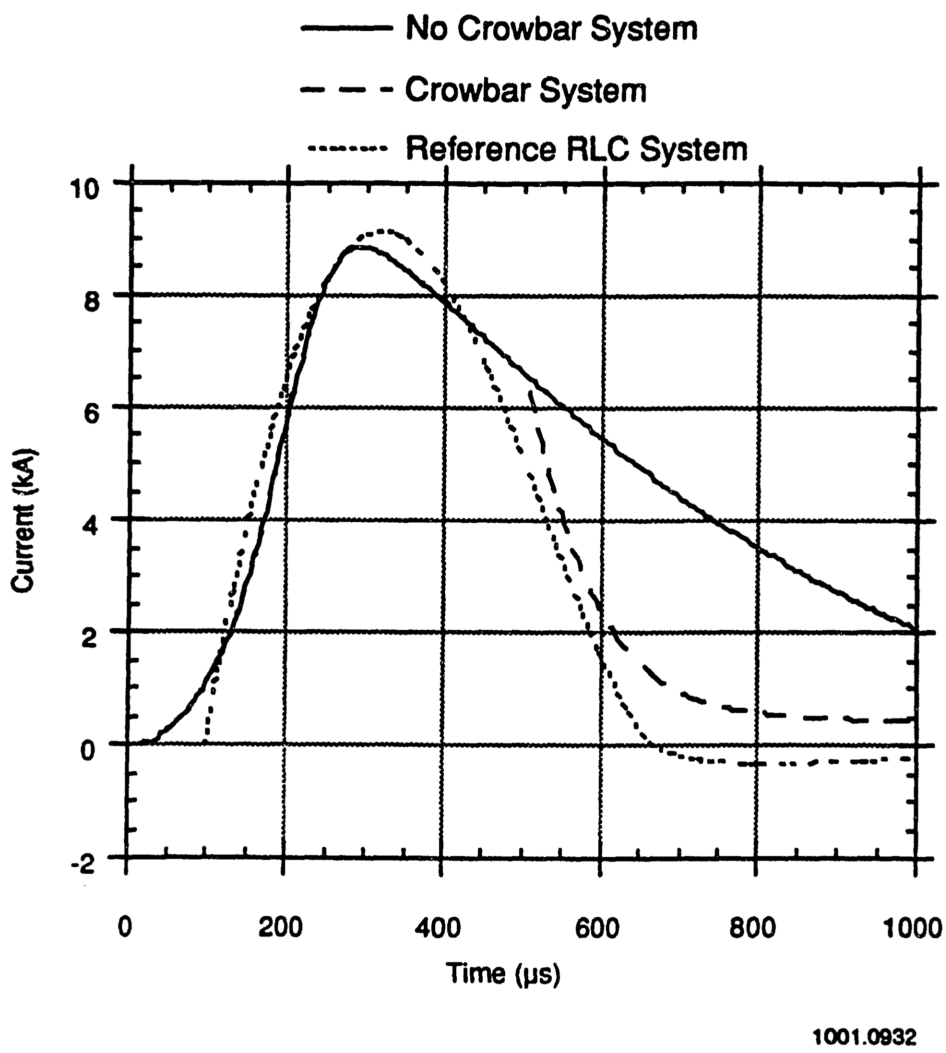


Figure 2-4. Flashlamp currents

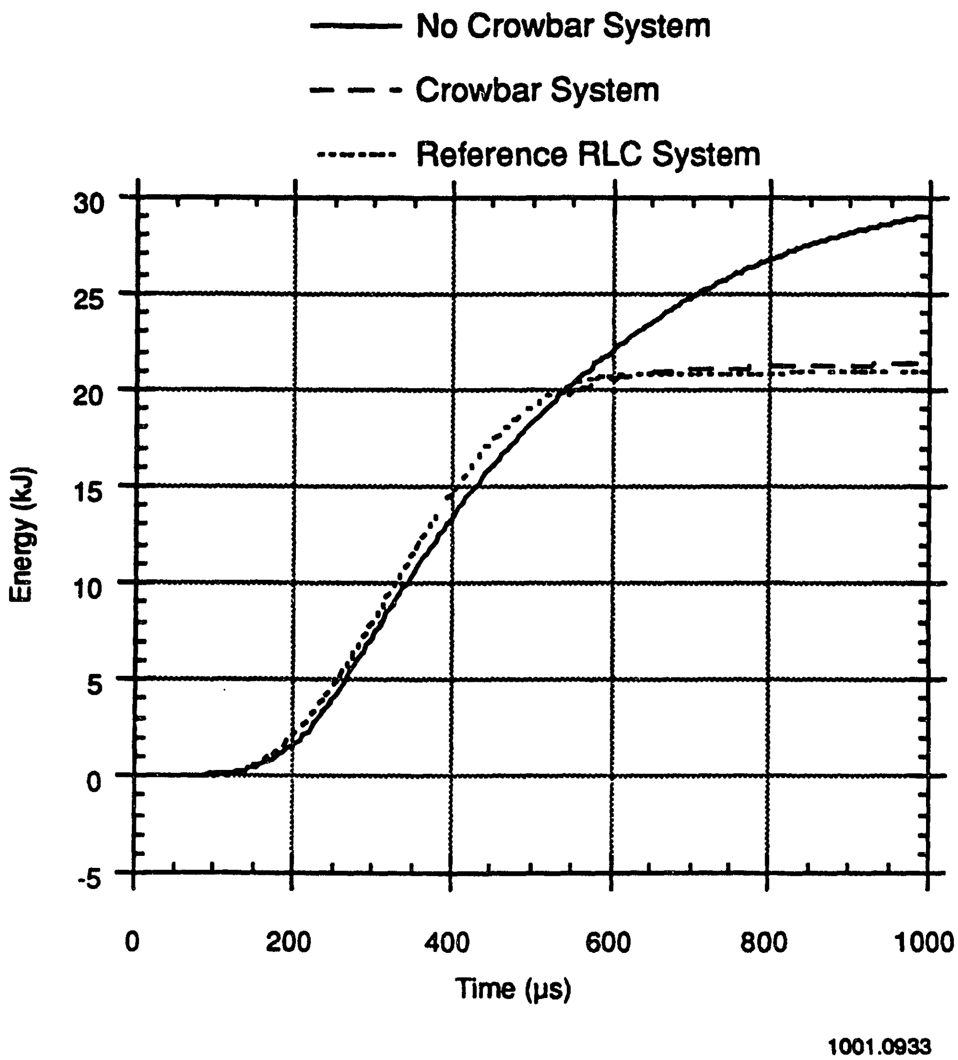


Figure 2-5. Flashlamp energies

Also shown in figure 2-1 is an abort switch. The abort switches are explosive closing switches which are triggered by the ionization circuitry. The signal for the abort switch originates external to the CEM-UT designed power supply. As discussed earlier with Livermore personnel, the system should go into an abort sequence and not deliver current to the flashlamps if the abort signal is received. The initial idea was to monitor individual flashlamp currents flowing during the ionization and use this as a basis for the decision to perform the experiment. If the ionization controller decides that something is wrong and no experiment should occur it signals the HPG controller to close the abort switches. The abort switches are designed as explosive closing switches because they are less expensive to install than arc-gap or ignitron switches for very high coulomb transfers. The main difficulty with using explosive closing switches is that they are fairly time consuming to reload prior to the next test. Reloading of the explosives between tests shouldn't be a problem since these switches should normally be used only during emergencies. The coulomb and current requirements for the abort switches are well above the values which can be provided by currently available ignitron and arc-gap switches.

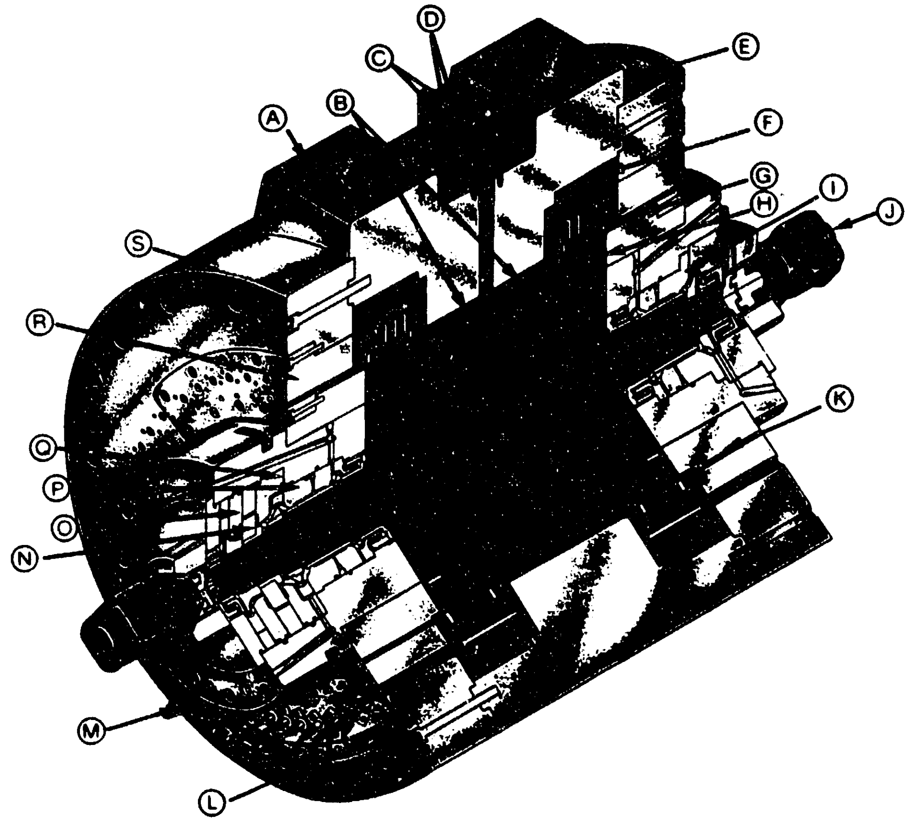
2.2 Engineering Design Description

2.2.1 HPG Design

In an earlier study disk and drum type HPGs were compared and it was shown that the drum HPG is the lighter and more efficient machine in the application of charging inductive stores.[1]

The topology of the drum machine is shown in figure 2-6. The design of the HPG is an iterative process involving the system simulation, a generalized HPG spreadsheet design algorithm, and a detailed HPG charged inductor simulation. The process begins by assuming inductors discharging into a flashlamp load. Once the inductance and peak current are established to meet the desired flashlamp performance, these values are entered into a generalized drum HPG design algorithm and a first pass machine option is produced. The HPG parameters are then input to a detailed HPG charged inductor simulation to include nonlinearities such as armature reaction, brush frictional loss, and sliding contact interface voltage. Parameters of brush friction energy, brush interface electrical dissipation, and total circuit electrical action are returned to the spreadsheet algorithm and iterations are performed until a convergence is achieved.

The results of the design algorithm are presented in table 2-1. The input parameters are the output of the system simulation. The simulation results are the output of the detailed HPG charged inductor simulation. HPG requirements are an output of the HPG design algorithm. HPG design assumptions are engineering limits which have been established through brush test research programs, operation of four generations of homopolar generators, and the basic laws of electromechanical conversion. The HPG sizing evolves from the inputs and the critical parameters are outputs that are inspected to insure an operational design. The electrical parameters are calculated from machine dimensions and material specifications and in turn they are input into the detailed HPG charged inductor simulation to update design algorithm inputs for the next iteration.



A Stator
B Compensating conductor
C Output terminal
D Output terminal cooling tubes
E Stator end cap (Non thrust end)
F Field coil
G Brush assembly
H Rotor/shaft assembly
I Radial bearing (Non thrust end)
J Hydraulic motor
K Brush dust collection
L Brush actuation manifold
M Field coil termination
N Thrust rotor
O Outer thrust bearing
P Radial bearing (Thrust end)
Q Inner thrust bearing
R Brush access plug
S Stator end cap (Thrust end)

Figure 2-6. Drum HPG topology

Table 2-1. HPG designs

Input Parameters	Units							
Total Peak Current	A	7.00E+07	7.00E+07	7.00E+07	7.00E+07	7.00E+07	7.00E+07	7.00E+07
Total Inductor Energy	J	5.20E+08	5.20E+08	5.20E+08	5.20E+08	5.20E+08	5.20E+08	5.20E+08
Number of HPGs		**4**	**4**	**4**	**6**	**6**	**9**	**9**
SIMULATION RESULTS								
Charging Efficiency		0.5	0.5	0.5	0.5	0.5	0.5	0.5
Action per HPG	A^2*s	2.18E+13	2.18E+13	2.18E+13	1.07E+13	1.07E+13	5.19E+12	5.19E+12
Brush Friction Energy	J	1857	1857	1857	1952	1952	1542	1542
Brush Drop Energy	J	303	303	303	338	338	367	367
HPG REQUIREMENTS								
Energy per HPG	*J*	*2.60E+08*	*2.60E+08*	*2.60E+08*	*1.73E+08*	*1.73E+08*	*1.16E+08*	*1.16E+08*
Current per HPG	*A*	*1.75E+07*	*1.75E+07*	*1.75E+07*	*1.17E+07*	*1.17E+07*	*7.78E+06*	*7.78E+06*
HPG DESIGN ASSUMPTIONS								
Slip Ring Current Density	A/in^2	3200	3200	3200	3200	3200	3200	3200
Slip Ring Current Density	A/m^2	4.96E+06	4.96E+06	4.96E+06	4.96E+06	4.96E+06	4.96E+06	4.96E+06
Rotor Radius	m	0.9	0.8	0.7	0.7	0.61	0.64	0.56
Max Rotor Tip Speed	**m/s**	**160**	**170**	**180**	**160**	**180**	**160**	**180**
Slip Ring Thickness	m	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254
Flux Density	T	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Air Gap	m	0.00254	0.00254	0.00254	0.00254	0.00254	0.00254	0.00254
Comp Turn Thickness	m	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254
Brush Mech Radial Ht.	m	0.0762	0.0762	0.0762	0.0762	0.0762	0.0762	0.0762
Field Coil Thickness	m	0.0762	0.0762	0.0762	0.0762	0.0762	0.0762	0.0762
Brush Strap x-section	m^2	0.000121	0.000121	0.000121	0.000121	0.000121	0.000121	0.000121
Brush Strap Free Length	m	0.0508	0.0508	0.0508	0.0508	0.0508	0.0508	0.0508
Number of Output Pairs		6	9	9	6	6	4	4
Output Thickness	m	0.0381	0.0381	0.0381	0.0381	0.0381	0.0381	0.0381
Output Width	m	0.7112	0.2032	0.2032	0.2032	0.2032	0.2032	0.2032
Brush Strap Resistivity	IACS	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Brush Pad Resistivity	IACS	0.096	0.096	0.096	0.096	0.096	0.096	0.096
Conductors Resistivity	IACS	0.8	0.8	0.8	0.8	0.8	0.8	0.8
HPG SIZING CALCULATIONS								
Shaft Radius	m	0.18	0.16	0.14	0.14	0.122	0.128	0.112
Flux Area	m^2	4.27	3.38	2.58	2.58	1.96	2.16	1.65
Flux Length	m	0.7560	0.6720	0.5880	0.5880	0.5124	0.5376	0.4704
Rotor Speed	r/s	177.78	212.50	257.14	228.57	295.08	250.00	321.43
Brush Length	m	0.6245	0.7025	0.8029	0.5351	0.6140	0.3902	0.4459
Rotor Length	m	2.0049	2.0771	2.1938	1.6581	1.7404	1.3179	1.3622
Rotor Inertia	kg-m^2	14400.78	9178.96	5576.97	4215.28	2495.13	2308.15	1365.65
Shaft Inertia	kg-m^2	33.63	21.58	13.20	10.67	6.38	6.33	3.80
Slip Ring Inertia	kg-m^2	1979.16	1432.39	1006.60	760.83	524.21	459.80	315.66
Total Inertia	kg-m^2	16413.56	10632.93	6596.77	4986.77	3025.72	2774.28	1685.11
Energy Stored	*J*	*2.59E+08*	*2.40E+08*	*2.18E+08*	*1.30E+08*	*1.32E+08*	*8.67E+07*	*8.70E+07*
Stator Outer Radius	m	1.36	1.22	1.09	1.09	0.97	1.01	0.90

Table 2-1. HPG designs (continued)

HPG CRITICAL PARAMETERS								
Rotor L/D		1.11	1.30	1.57	1.18	1.43	1.03	1.22
Air Gap Flux Density	T	3.89	4.38	5.00	3.33	3.83	2.43	2.78
Air Gap Magnetic Pressure	Pa	6.02E+06	7.62E+06	9.95E+06	4.42E+06	5.82E+06	2.35E+06	3.07E+06
Air Gap Magnetic Pressure	psi	873.1666992	1105.102	1443.398	641.5102	844.7729	341.0807	445.4932
Axial Force per Brush	N	592.6666667	666.75	762	508	582.9508	370.4167	423.3333
Axial Force per Brush	lb	133.1835206	149.8315	171.236	114.1573	131.0002	83.2397	95.13109
HPG ELECTRICAL PARAMETERS								
Voltage	v	193.536	182.784	169.344	150.528	147.5712	137.6256	135.4752
Drum Inductance	H	1.47024E-08	1.73E-08	2.1E-08	1.56E-08	1.89E-08	1.33E-08	1.58E-08
Output Bus Inductance	H	3.29603E-09	7.1E-09	6.52E-09	9.78E-09	9E-09	1.39E-08	1.28E-08
Total Inductance	*H*	*1.79984E-08*	*2.4E-08*	*2.8E-08*	*2.5E-08*	*2.8E-08*	*2.7E-08*	*2.9E-08*
Number of Brushes		5833.333333	5833.333	5833.333	3888.889	3888.889	2592.593	2592.593
Brush Strap Resistance	ohm	6.18956E-09	6.19E-09	6.19E-09	9.28E-09	9.28E-09	1.39E-08	1.39E-08
Brush Pad Resistance	ohm	1.93406E-09	1.93E-09	1.93E-09	2.9E-09	2.9E-09	4.35E-09	4.35E-09
Voltage Drop Resistance	ohm	1.71429E-07	1.71E-07	1.71E-07	2.57E-07	2.57E-07	3.86E-07	3.86E-07
Brush Ring Resistance	ohm	8.97234E-08	1.13E-07	1.47E-07	9.77E-08	1.28E-07	7.76E-08	1E-07
Compensating Turn Resistance	ohm	1.11335E-07	1.11E-07	1.11E-07	1.11E-07	1.1E-07	1.11E-07	1.1E-07
Slip Ring Resistance	ohm	4.19402E-07	2.35E-07	2.73E-07	2.2E-07	2.54E-07	1.99E-07	2.26E-07
Output Resistance	ohm	1.21462E-07	2.62E-07	2.4E-07	3.6E-07	3.31E-07	5.12E-07	4.73E-07
Total Resistance	*ohm*	*9.21E-07*	*9.01E-07*	*9.50E-07*	*1.1E-06*	*1.1E-06*	*1.3E-06*	*1.3E-06*
COMPONENT MASSES								
Shaft	kg	2,080	1,689	1,350	1,091	859	775	607
Rotor	kg	36,201	29,408	23,549	17,799	14,023	11,738	9,175
Slip Ring	kg	795	730	673	509	464	369	333
Brush rings	kg	1,744	1,763	1,788	1,192	1,212	803	817
Compensating Turns	kg	977	773	594	594	452	497	382
Brush Straps (2 sets)	kg	635	635	635	423	423	282	282
Brush Pads	kg	185	185	185	123	123	82	82
Field Coils	kg	1,408	1,436	1,471	980	1,008	665	685
Stator Iron	kg	70,519	54,582	41,391	36,025	26,936	26,494	19,799
Bearings	kg	863	606	406	406	269	310	208
Output Conductors	kg	624	246	224	150	137	94	86
Total HPG Mass	kg	115,406	91,807	72,040	59,142	45,769	42,016	32,369
CONDUCTOR THERMAL MASSES								
Rotor Slip Ring	J/°C	7.79E+05	7.16E+05	6.60E+05	4.99E+05	4.55E+05	3.62E+05	3.26E+05
Brush Straps (2 sets)	J/°C	2.43E+05	2.43E+05	2.43E+05	1.62E+05	1.62E+05	1.08E+05	1.08E+05
Comp Turns & Brush Rings	J/°C	1.04E+06	9.71E+05	9.12E+05	6.84E+05	6.37E+05	4.98E+05	4.59E+05
Output Conductors	J/°C	2.39E+05	9.42E+04	8.59E+04	5.73E+04	5.24E+04	3.60E+04	3.31E+04
Brush Pads	J/°C	5.55E+04	5.55E+04	5.55E+04	3.70E+04	3.70E+04	2.46E+04	2.46E+04

Table 2-1. HPG designs (concluded)

CONDUCTOR TEMPERATURE RISES								
Rotor Slip Ring	°C	11.7198361	7.153716	8.993193	4.745133	6.003607	2.859121	3.589077
Brush Straps	°C	0.55406538	0.554065	0.554065	0.615732	0.615732	0.669044	0.669044
Comp Turns & Brush Rings	°C	4.198998832	5.019048	6.139703	3.277	4.016385	1.960822	2.381565
Output Conductors	°C	11.05450979	60.47814	60.82533	67.59511	68.00895	73.73868	74.18385
Brush Pads	°C	137.0477796	137.0478	137.0478	145.3871	145.3871	121.4117	121.4117
MATERIAL COST ESTIMATES								
Rotor Forging	$	159,285	129,395	103,614	78,315	61,700	51,649	40,369
Shaft	$	11,442	9,291	7,424	6,000	4,723	4,260	3,337
Slip Ring	$	13,984	12,854	11,852	8,958	8,172	6,499	5,860
Brush Rings	$	11,507	11,637	11,803	7,866	7,997	5,299	5,392
Comp turns and outputs	$	10,567	6,727	5,399	4,906	3,888	3,903	3,092
Field Coils	$	15,492	15,793	16,179	10,782	11,085	7,317	7,531
Stator Iron	$	320,285	120,080	91,059	79,256	59,260	58,287	43,557
Bearings	$	6,898	6,333	5,893	5,893	5,591	5,682	5,457

Upon convergence the component masses of the machine are available and the heating of the individual discharge circuit parameters are checked for proper performance. The design algorithm provides material cost estimates for some of the important components. But in the case of this study these values have been incorporated into a more detailed cost analysis.

2.2.2 Energy Storage Inductors

The inductor specifications as determined from the simulation were

Inductance	5.33 μH
Resistance	3.26 μΩ
Peak Current	2.91 MA

The inductors were designed as Brooks coil inductors. Aluminum was chosen as the conductor material because a copper Brooks coil requires approximately 60% more weight of conductor than an aluminum Brooks coil for the same resistance and inductance. A high conductivity aluminum such as 1350 aluminum which has a resistivity of 2.8 μΩ-cm was used for the calculations. A cross-section of a Brooks coil inductor is shown in figure 2-7.

Nomex paper is used fairly extensively for electrical insulation in windings in motors and generators. 30 mil Nomex paper is resistant to ripping and tearing and is good for insulation up to approximately 7 kV. Assuming we use three layers of Nomex between turns this will provide about 18 to 20 kV insulation between turns. Since there will be multiple turns the required voltage standoff between turns will be less than the developed voltage of approximately 20 to 25 kV. Insulation thickness between turns will be close to 100 mil (0.1 in.).

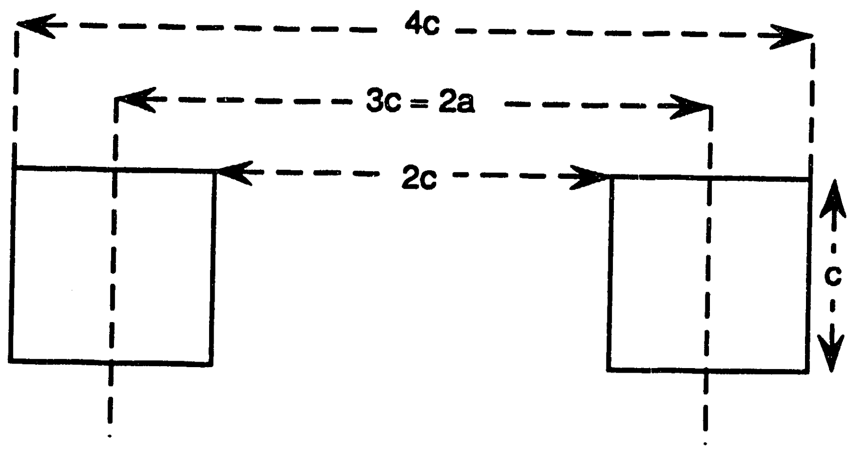


Figure 2-7. Cross section of Brooks coil

A high strength glass filament winding can withstand 300 ksi tensile stresses. Using 0.1 in. insulation space between conductors, 2.8 μΩ-cm resistivity aluminum and a hoop winding of 300 ksi strength, an inductor was designed which meets the required electrical characteristics. The calculations required for the inductor resistance, inductance and bursting force were included in an appendix to the December 1991 monthly report and will not be included here. The inductor physical specifications can be described as

c = 16.7 in.
N = 2.25 turns
resistance = 3.23 μΩ
inductance = 5.33 μH
winding thickness = 0.43 in. required for strength, 0.75 in. to be used for safety

The inductors will be made with four current feeds or starts 90° apart. Each start will be 1.75 in. thick and 16.75 in. wide and have 2.25 turns. The current which goes in at a current feed will come out next to the current feed 1/4 of a turn away. The inside diameter of the inductors will be 33.5 in. The outside diameter of the inductors will be 67 in. A sketch of a side view of the inductor showing the buswork feeding into one side of an inductor are shown in figure 2-8.

The conductors for the turns will be fabricated and then bent to the correct shape. A company has been identified which has given an estimate on how much they would charge for bending these thick conductors. After the conductors have been bent the inductors will be assembled with insulation. Prior to bolting on the connecting buswork, the filament wound overwraps will be installed. All of the overwraps will be wound at one time as a tube on a mandrel. After winding the fiberglass tube of the right strength and dimensions, the individual overwraps will be sliced off of the tube and installed over the inductors. Filament winding is very effective in producing strong structures except at the ends where it is difficult to maintain a uniform winding density and pattern. By winding all of the overwraps at once and only using the central section of the winding for the overwraps the strength of the overwrap can be predicted fairly accurately. Once the overwraps have been installed the connecting buswork can be installed along with the clamping.

2.2.3 Charging Bus

The charging bus is the buswork which connects the HPG, inductor, opening switch and collection buswork cables. These are mainly large flat parallel copper conductors. The buswork will have a urethane coating in all areas except where other buswork is connected to aid in insulation. The charging bus will be located above the inductors as shown in figure 2-2. There will also be some G-10 insulation between the plates as well. The buswork will be clamped together using an insulated through-bolt scheme which has proven very successful in many applications at CEM-UT.

2.2.4 Switch Design

A modular opening switch which can be rapidly installed and inexpensively fabricated is shown in figure 2-9. This switch design is basically the same as the one used in the Balcones power supply. Alterations to the Balcones design allow the switch to be installed simply by lowering it into position and then activating the

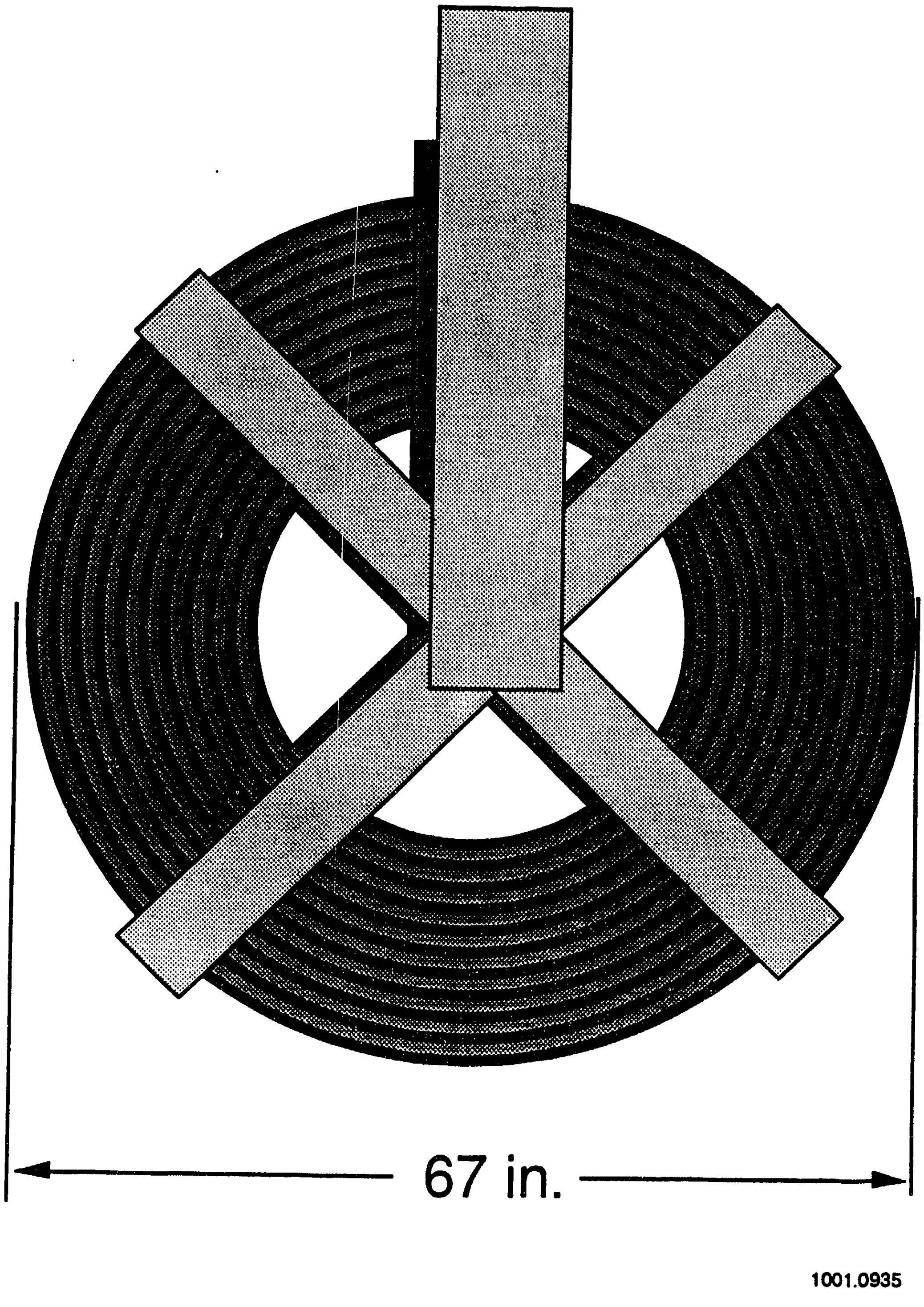


Figure 2-8. Side view of inductor

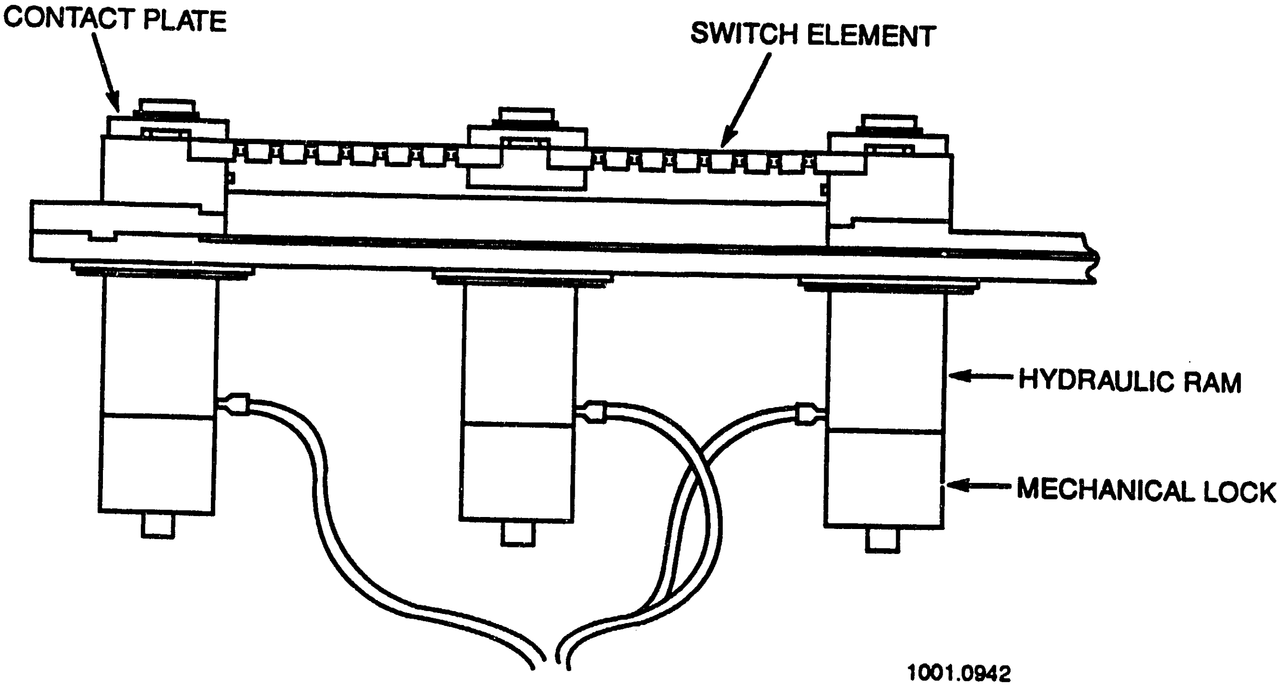


Figure 2-9. Opening switch installed in buswork

hydraulic rams which provide the necessary contact pressure at the electrical joints. The switch is comprised of six elements (fig. 2-10) four of which open explosively (upon detonation of explosives) and two of which open thermally (due to ohmic heating). A combination of explosive and thermal switch elements allows flexibility in tailoring the nature and length of the switching event. The thermal opening switch is used on the Balcones power supply to aid in pulse shaping. The thermal opening switch may not be required for pulse shaping in which case the switch will be reduced to two series elements. Both switch types are made of aluminum and are extruded with a cross-sectional shape (fig. 2-11), eliminating a great deal of machining. Written quotes for the explosive switch elements have been obtained from both Alcoa Aluminum and Spectrulite Consortium.

Notice the seven dovetail regions in the switch's cross section shown in figure 2-11. Prima-cord™ is lain inside these dovetail regions and extruded polyethylene bars are slid into place behind the cord. The Prima-cord™ either runs up and over the thermal element or terminates at the inside boundary of the explosive element. All fourteen ends of the Prima-cord™ are pig-tailed together at the outside boundary of the explosive elements and a length of Prima-cord™ run from this union to a detonator bolt. Upon detonation the metal slats above the dovetails are blown up and out of the element, leaving seven air gaps. Since there are two pairs of such elements in series, a total of 14 air gaps are created which together can hold off a total electrical potential of 28 kV (CEM-UT uses a switch design with seven gaps which holds off 14 kV).

Mechanically, there are several factors governing the geometry. First, the slat must be thin enough to be reliably blown out of the element and the thicker the slat the greater the quantity of explosives needed. Second, the region between the slats must be wide enough to allow bolting to a G10 foundation and wide enough to limit crack propagation from one region to the next. Third, the slat length effects the way the slat is blown out of the switch element. Too long of lengths would peel the slat up in one place while it is still firmly attached in others, causing slat fragmentation and increasing the possibility of leaving a piece in place.

While charging, the thickness and the length of these metal slats determine a cross section normal to the current's direction, creating 14 higher resistance regions across the switch. These high resistance regions dominate the switch resistance which contributes to the total resistance of the charging circuit. While it is desirable to reduce the switch resistance by increasing the conducting area and/or its width, the mechanical factors discussed above must also be considered. The width of the cross section, or the gap once the slat is blown out, must be sufficient to hold off 1/14 of the maximum switch voltage, plus some for safety. The design gap width of 0.188 in. has experimentally been shown to hold off 2 kV.

As mentioned above, the primary issues which governed the switch design (besides functionality) were switch turnaround time and cost. Switch turnaround time is the total amount of time needed to remove one switch and install another in its place within the explosive containment structure. The switch assembly occurs in an assembly style fashion in a location designed and delegated for that purpose. The assembly of the switches in this fashion plus the fact that the amount of machining on the elements is drastically reduced combine to greatly reduce the total cost of the switch. To install the switch; the mechanical lock on the hydraulic preload rod is

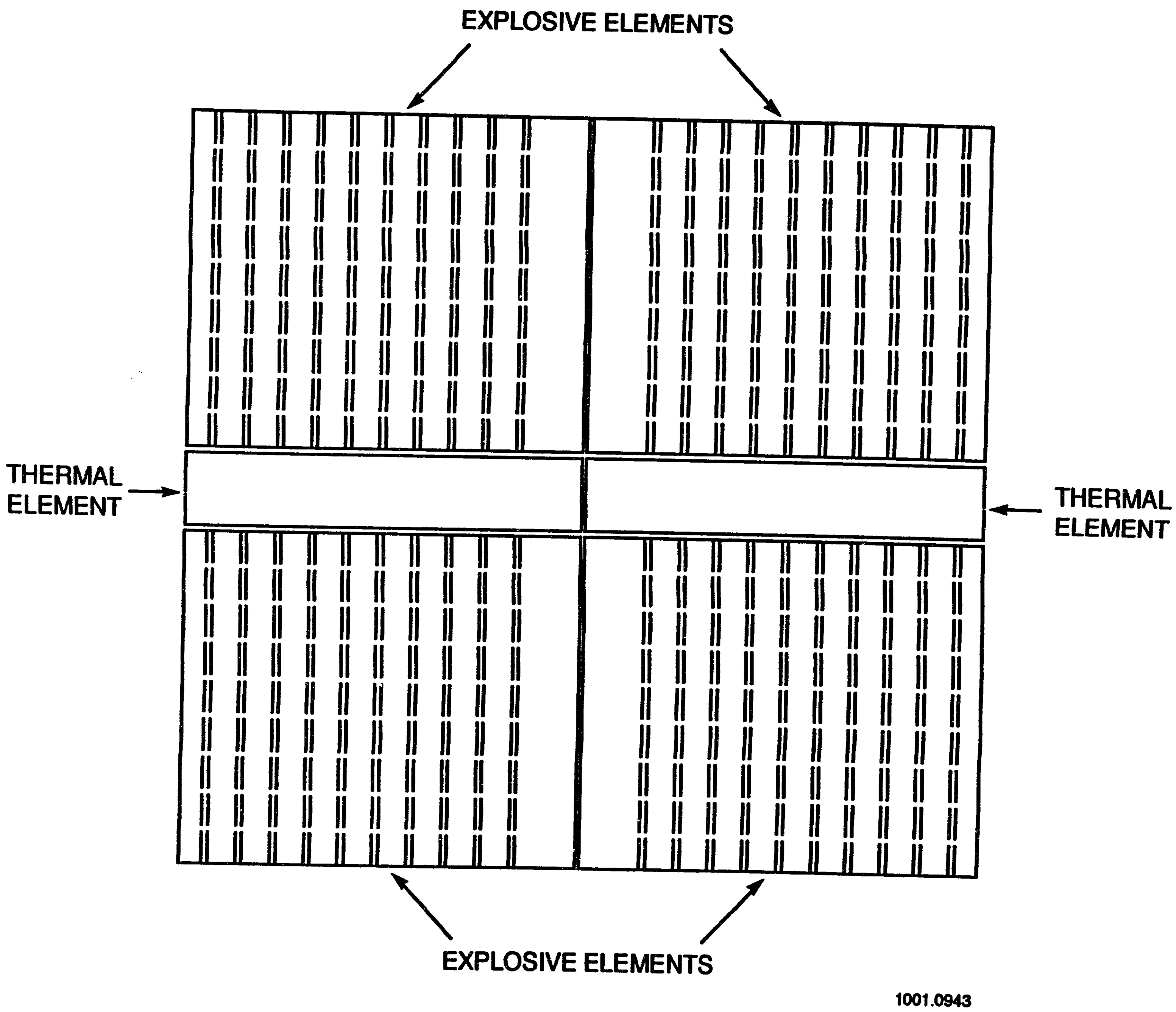


Figure 2-10. Top view of opening switch

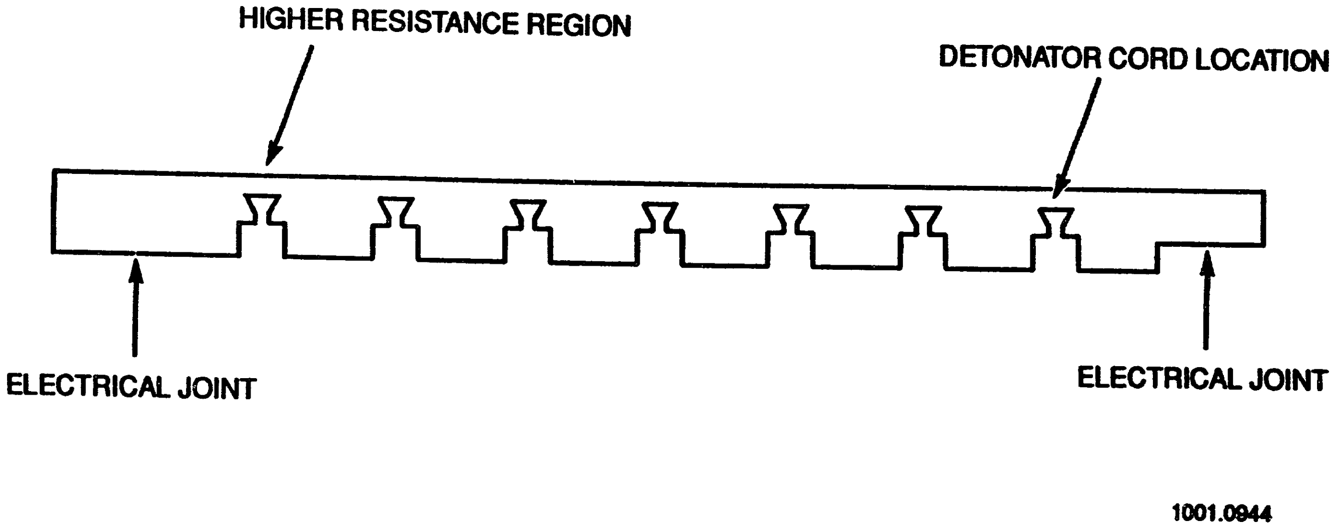


Figure 2-11. Side view of fixtured switch element

deactivated, the old switch is removed, the area cleaned, the new switch laid in place, the hydraulic pump is turned on, providing power to the hydraulic ram which develops the needed contact pressure at the electrical joints, the mechanical lock on the hydraulic preload arm is activated and the pump is turned off.

2.2.5. Containment Vessels

The function of this vessel is to contain the shock wave and quasistatic pressure generated from the explosive and magnetic energy release during commutation of current to the flashlamp load. For normal energy release associated with successful commutation, the vessel operates in the elastic regime and completely contains the blast. In the rare event of a worst-case fault where no current is commutated to the load and the total explosive and magnetic energy are absorbed in the vessel, the vessels are designed to avoid a catastrophic failure of the vessel by allowing plastic deformation. To insure proper design, a prototype vessel will be constructed and loaded with detasheet of a quantity equivalent to the worst case fault energy and tested at an explosives range. We have worked with Wilfred Baker Engineering of San Antonio, Texas in the design of similar vessels figure 2-12, and the budget includes a subcontract to have Baker Engineering certify the containment design. The vessels will be made of aluminum so that they do not experience undo forces associated with the fringing fields from the toroidal configured Brooks coil inductors.

For ease of operation, the vessels are clamped at their girth with an automated clamp (fig. 2-13). These clamps are routinely used to seal pressure vessels and are ideal for our application. After the test, a switch in the control room will start the motor drive that separates the Marmon type clamp. After the clamp expands clear of the vessel flange, a second motor is started that raises the containment shell by means of a screw type jack. A screw type jack was selected so that there was a positive location of the raised vessel with no chance of personnel injury due to cylinder bleed down or some other non positive actuation. The top is raised to a height to allow ease of access to the switch loading area. The process is then reversed to lower the containment top and secure the pressure seal for the next test. This is shown in figures 2-14a, 2-14b, and 2-14c.

The preliminary design of the vessel starts with the specification of the explosive and magnetic energy that need be contained. The system simulation is run with an empirical switch model that has traceability to experimental results. An output of the simulation is the magnetic energy dissipated as the switch arc commutates current to the flashlamps. This energy is then added to the energy released by the Prima-cord™ used to open the switch gaps. For the preliminary design these values were calculated as

8.3 MJ magnetic energy
1.6 MJ explosive energy.

Next, an equivalent mass of TNT and the independent blast loading parameter are calculated to determine the magnitude and time history of the internal blast pressure.

$$W = \frac{9.9\ \text{MJ}}{4.52\frac{\text{MJ}}{\text{kg}}} = 2.19\ \text{kg}\frac{2.2\ \text{lb}_m}{\text{kg}} = 4.82\ \text{lb}_m$$

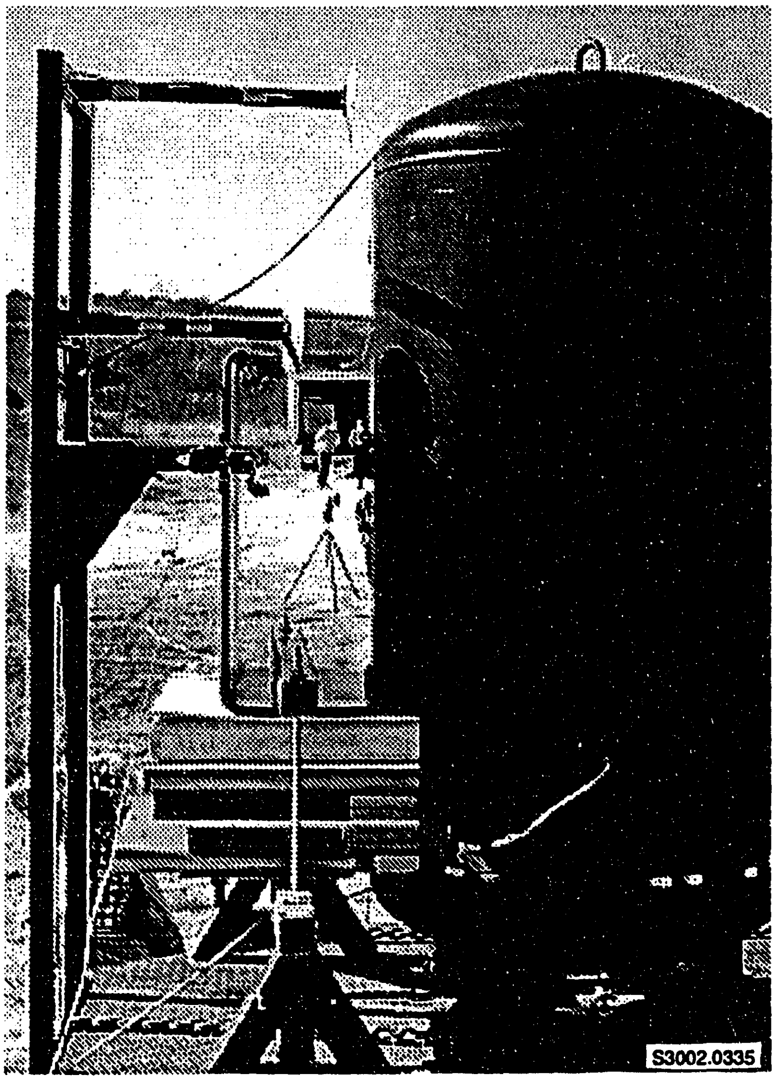


Figure 2-12. Containment test at APD explosives range

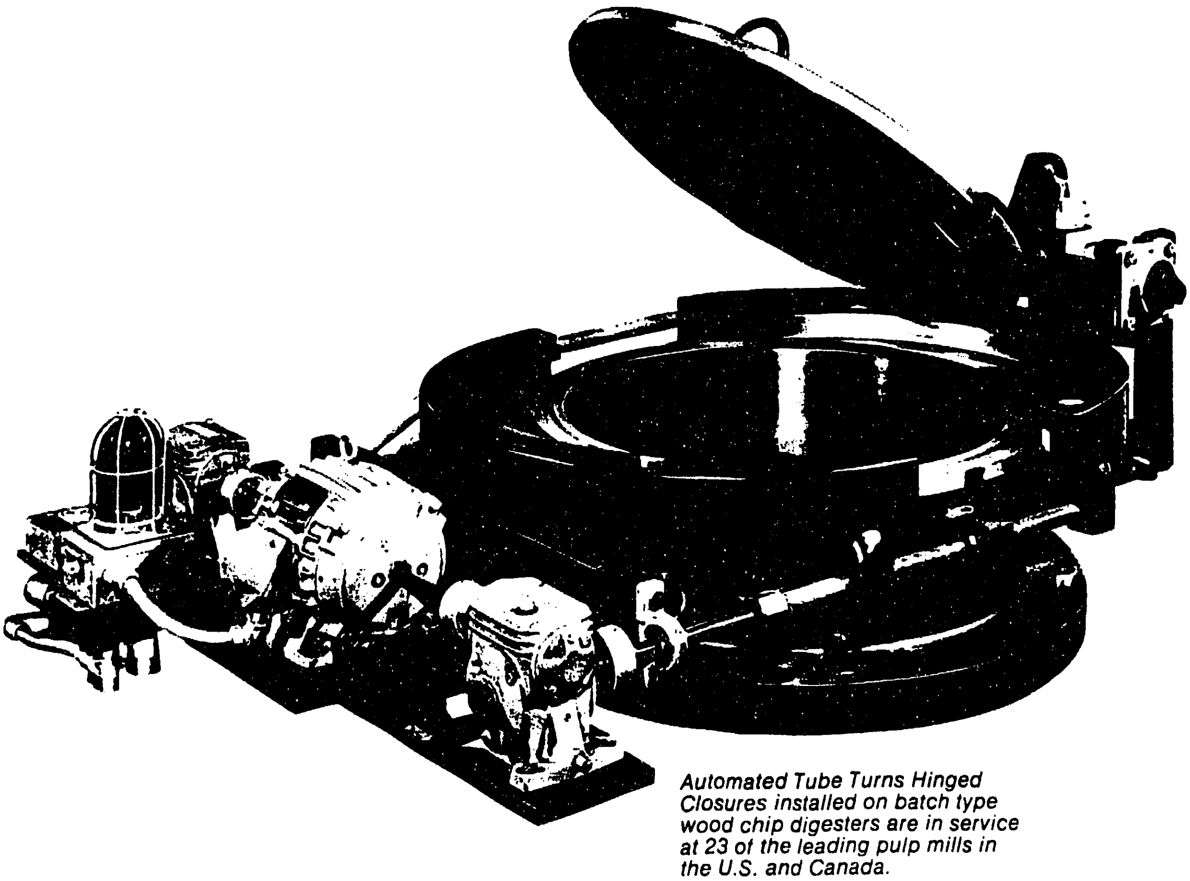


Figure 2-13. Automated Marmon flange

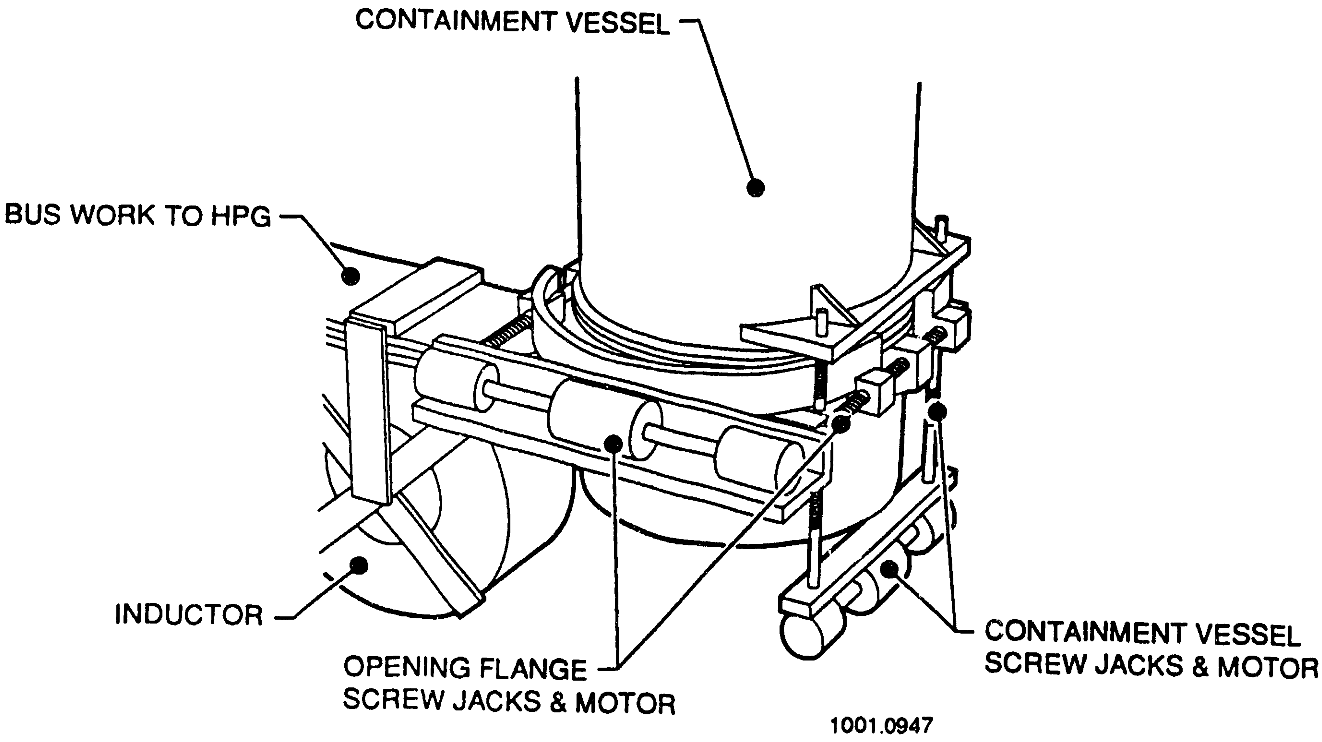


Figure 2-14a. Close-up of containment vessel with flange open

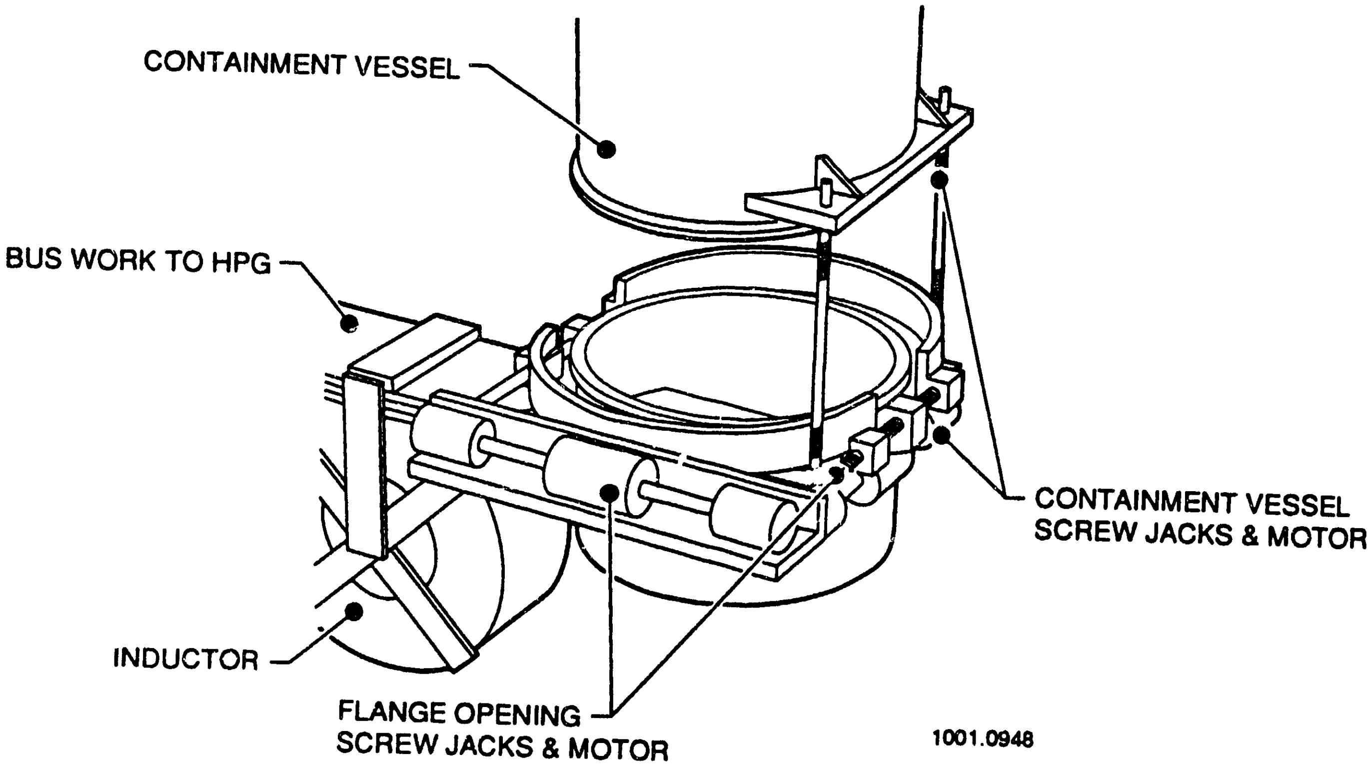


Figure 2-14b. Close-up of containment vessel with screw jacks up

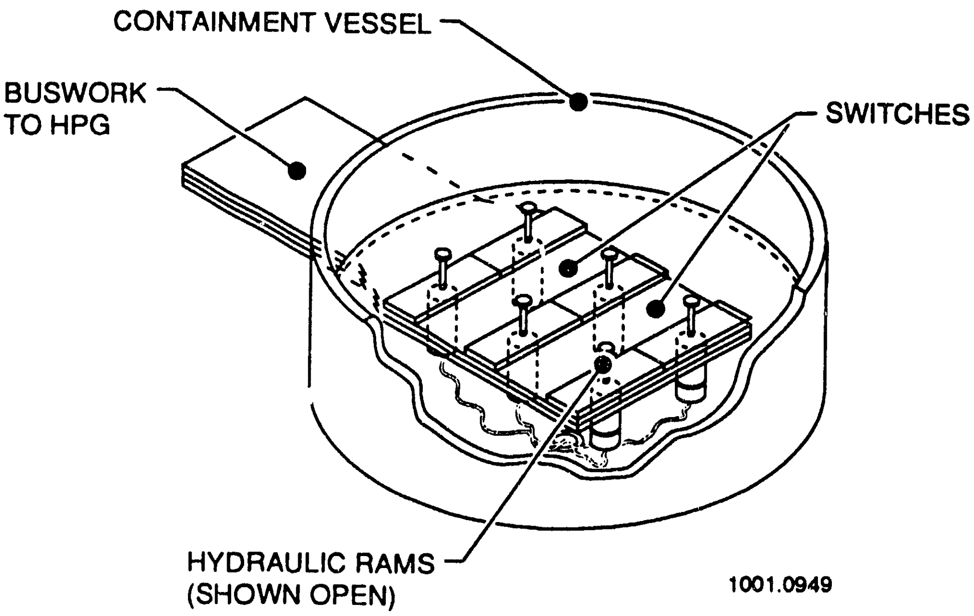


Figure 2-14c. Inside containment vessel hydraulic ram, cutaway view

where

W = equivalent weight of TNT
= 4.52 MJ/kg - TNT heat of explosion

$$\frac{R}{W^{\frac{1}{3}}} = 2.37\frac{ft}{lb_m^{\frac{1}{3}}}$$

where

R = is the distance from the explosion to the containment wall in feet

The TNT blast loading curves are then used to find the peak reflected overpressure and the reflected positive impulse (fig. 2-15). The reflected shocks can be represented as a simplified internal blast pressure as shown in figure 2-16. A further simplification expresses the blast loading as $P_r' = 1.75\ P_r$ to represent the individual reflected shocks as one equivalent pressure front. A summary of blast parameters is presented in table 2-2.

Table 2-2. Blast parameters

Value	Unit	Number
Charge	lb_m	4.82
$\frac{R}{W^{\frac{1}{3}}}$	$\frac{ft}{lb_m^{\frac{1}{3}}}$	2.37
P_r	psi	950
$\frac{I_r}{W^{\frac{1}{3}}}$	$\frac{psi-s}{lb^{\frac{1}{3}}}$	0.065
1.75 P_r	psi	1,663
1.75 I_r	psi - s	0.19
T_d	s	2.31 x 1^{-4}

The time duration of the blast front is then

$$T_d = \frac{2I_r'}{P_r'}$$

To complete the information for the blast loading curve (fig. 2-17) the quasi-static pressure must be determined. Table 2-3 presents the dependent parameters and the value for the quasi-static pressure determined from the graphical relation in figure 2-18.

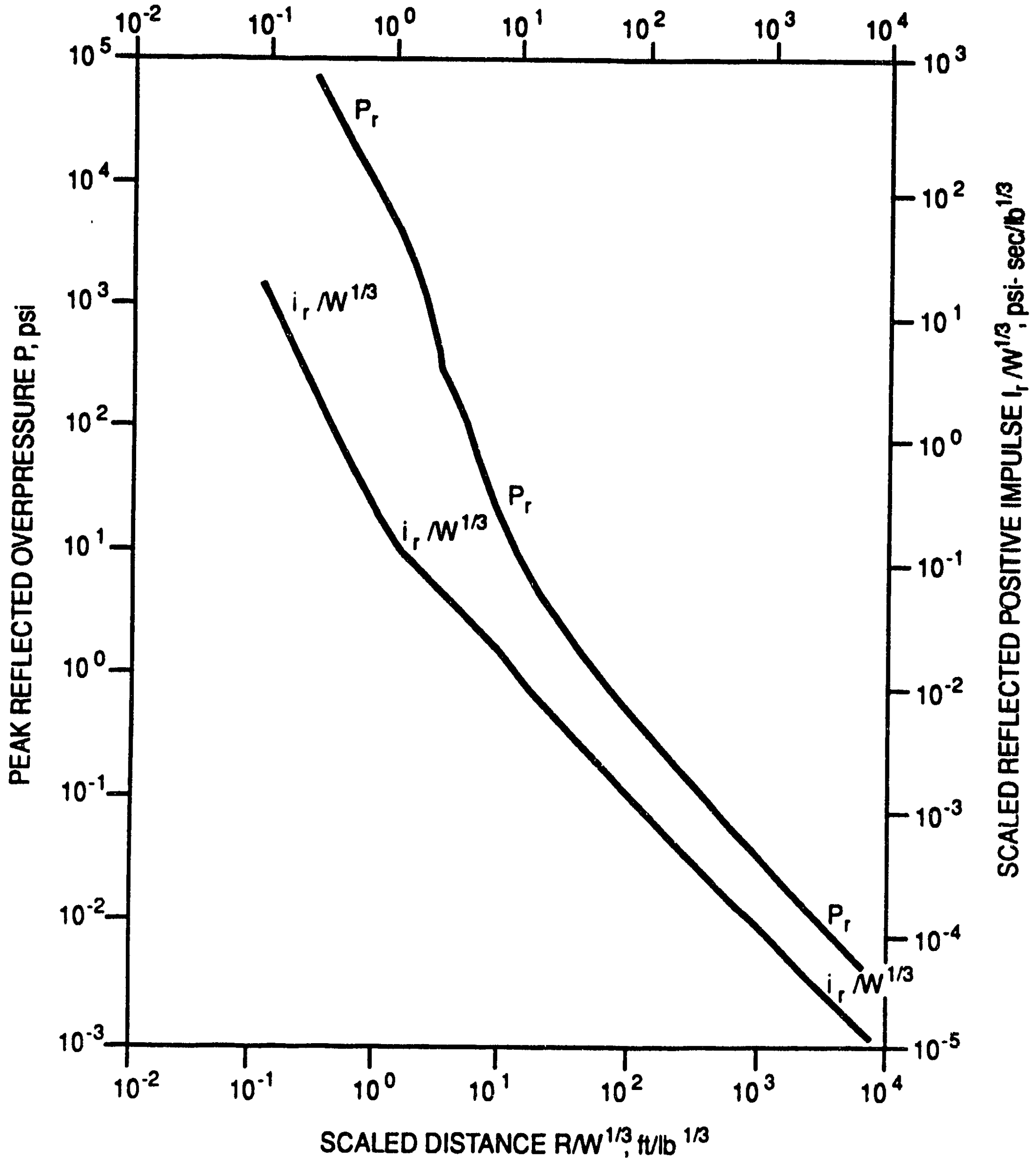


Figure 2-15. Normally reflected blast wave properties for bare spherical TNT at sea level

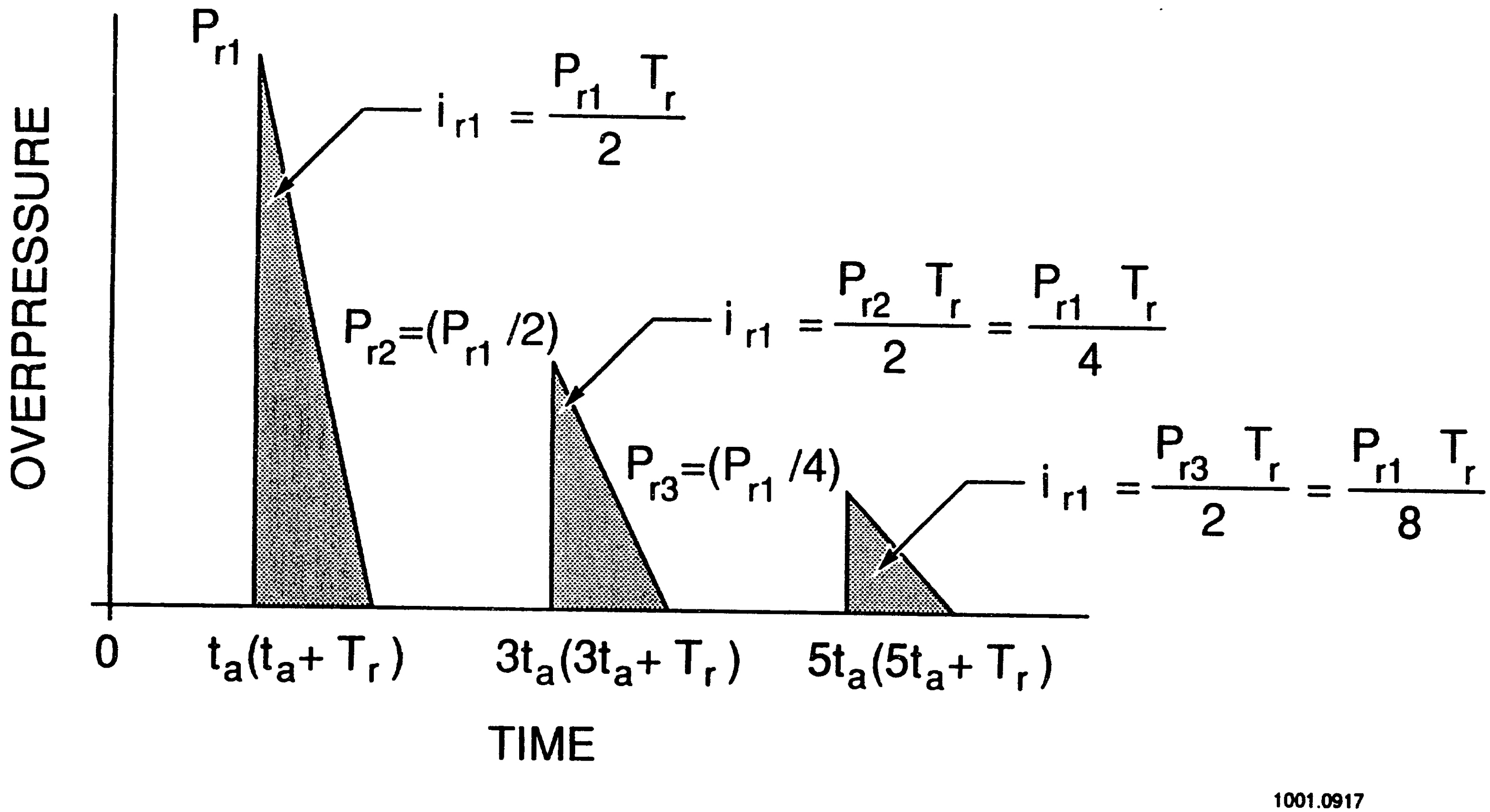


Figure 2-16. Simplified internal blast pressure

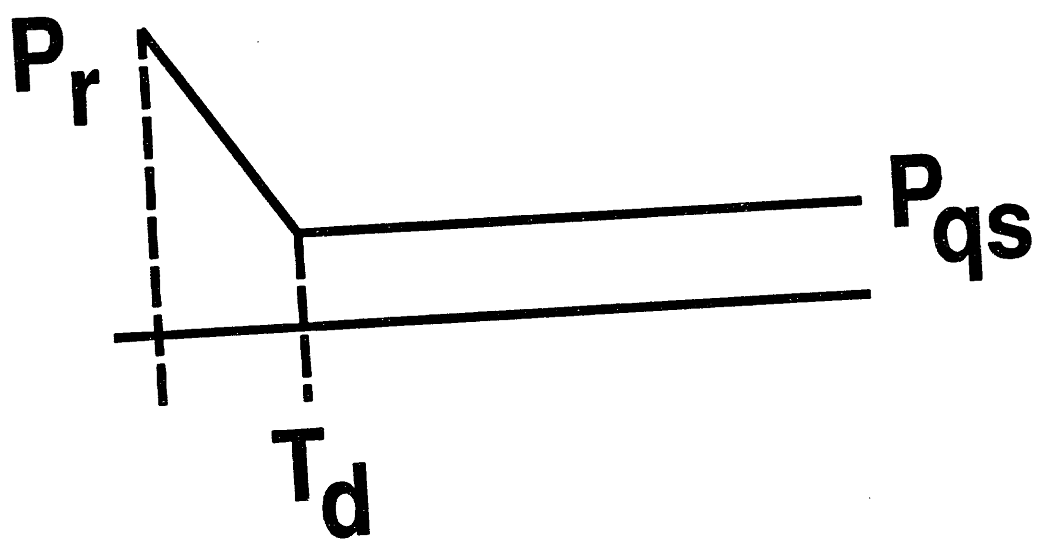


Figure 2-17. Peak and quasi-static pressure

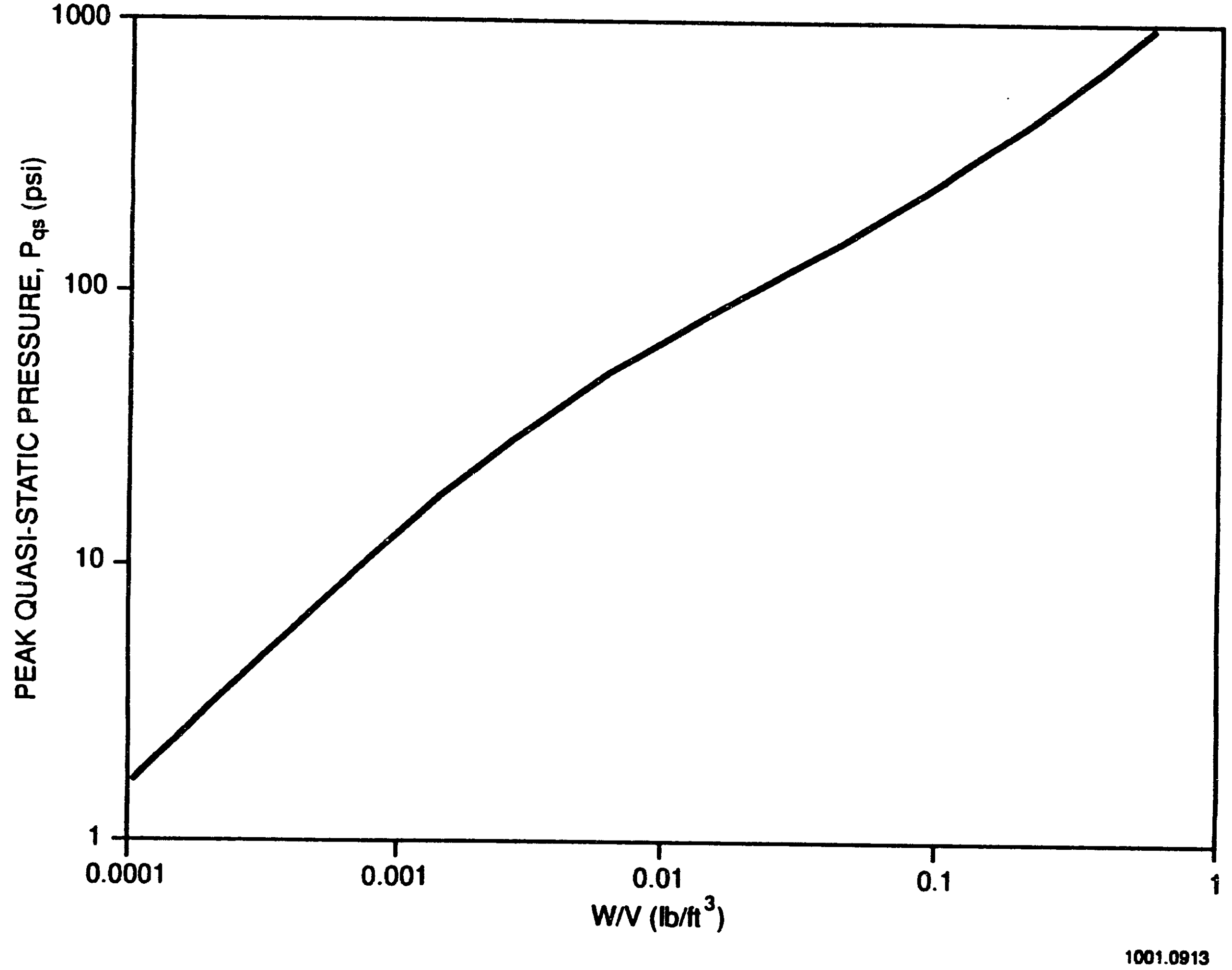


Figure 2-18. Peak quasi-static pressure (Southwest Research Institute)

Table 2-3. Quasi-static pressure

Value	Unit	Number
Charge	lb_m	4.82
Volume	ft^3	301.6
W/V	$\frac{lb_m}{ft^3}$	0.016
P_{qs}	psi	92

Loads are applied to the containment vessel as depicted in figure 2-19. The spring mass representation of the vessel and the differential equation describing the deflection are presented in figure 2-20. The solution to the differential equation using the forcing function described in figure 2-17 is presented in figure 2-21. It can be seen that the response satisfies the elastic criteria. Load time pairs were then calculated for the vessel fault condition where a total magnetic and explosive energy of 25.8 MJ is deposited in the containment. This loading was then analyzed with the elastic-plastic analytical capability of the dynamics code and a total deflection of 0.205 in. was calculated. This gives a U_{max}/U_y ratio of $2.44 << 15$, the one time safe operating elongation for the 6061-T6 aluminum selected for this design. Typical dimensional values for this vessel design are:

a = 4 ft
h = 1.5 in.
l = 6 ft

The vendor (American Tank Fabricating Company) was contacted and they submitted written bids and schedule times for hemispherical end cap rolling and rolling and welding the tube structure for the vessel.

The vessel will be equipped with the special detonator bolt fixture shown in figure 2-22. This allows the switches to be loaded, vessels sealed, and (right before the test) the detonator bolts installed external to the vessel to allow safe and simple operation.

2.2.6 Collection Bus

The buswork from the charging bus to the common bus will be flexible hexapolar cables. This cable has an impedance of 87 μΩ and 38 nH per foot. This six conductor cable is rated for 250 kA per cable and >25 kV voltage stand-off conductor to conductor. This cable and terminations have been tested at these ratings for other programs at CEM-UT. The terminations collect the two polarities of three conductors each into two studs. These studs then have a wedge inside which is expanded with a bolt to attain electrical contact. A drawing and picture of one of the connector and cable assemblies are shown in figures 2-23 and 2-24. With this design the connectors easily connect to a parallel bus with simple holes drilled to the correct diameter.

The design of the collection bus is fairly simple since both the charging bus and the common bus are essentially flat parallel plates. By keeping all of the cable lengths from one charging bus to the common bus equal in length, a fairly good current distribution should be attained. Each of the inductors carries a maximum of 2.9 MA

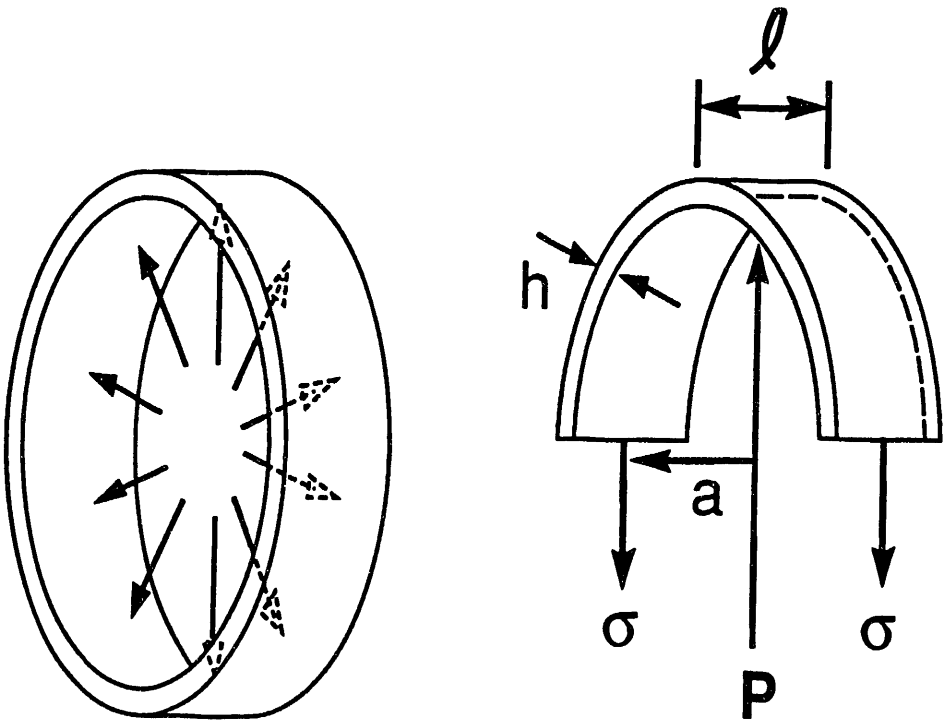
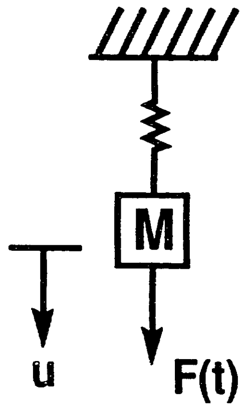
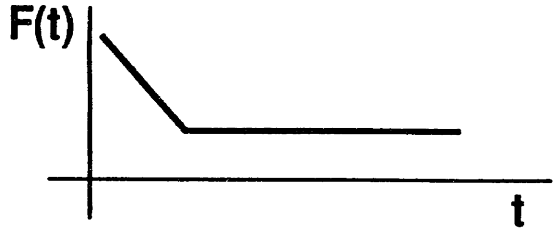


Figure 2-19. Hoop section out of cylinder



$$F(t) - ku - M\ddot{u} = 0$$



1001.0915

Mass

$$M = 2\pi a h \rho_m$$

Resistive Force

$$R_m = 2\sigma_y h \ell$$

Strain

$$\varepsilon = \frac{u}{a}$$

Hooke's Law

$$\sigma_y = E \varepsilon_y$$

Elastic Limit

$$U_y = \frac{a \sigma_y}{E}$$

Load-time Pairs

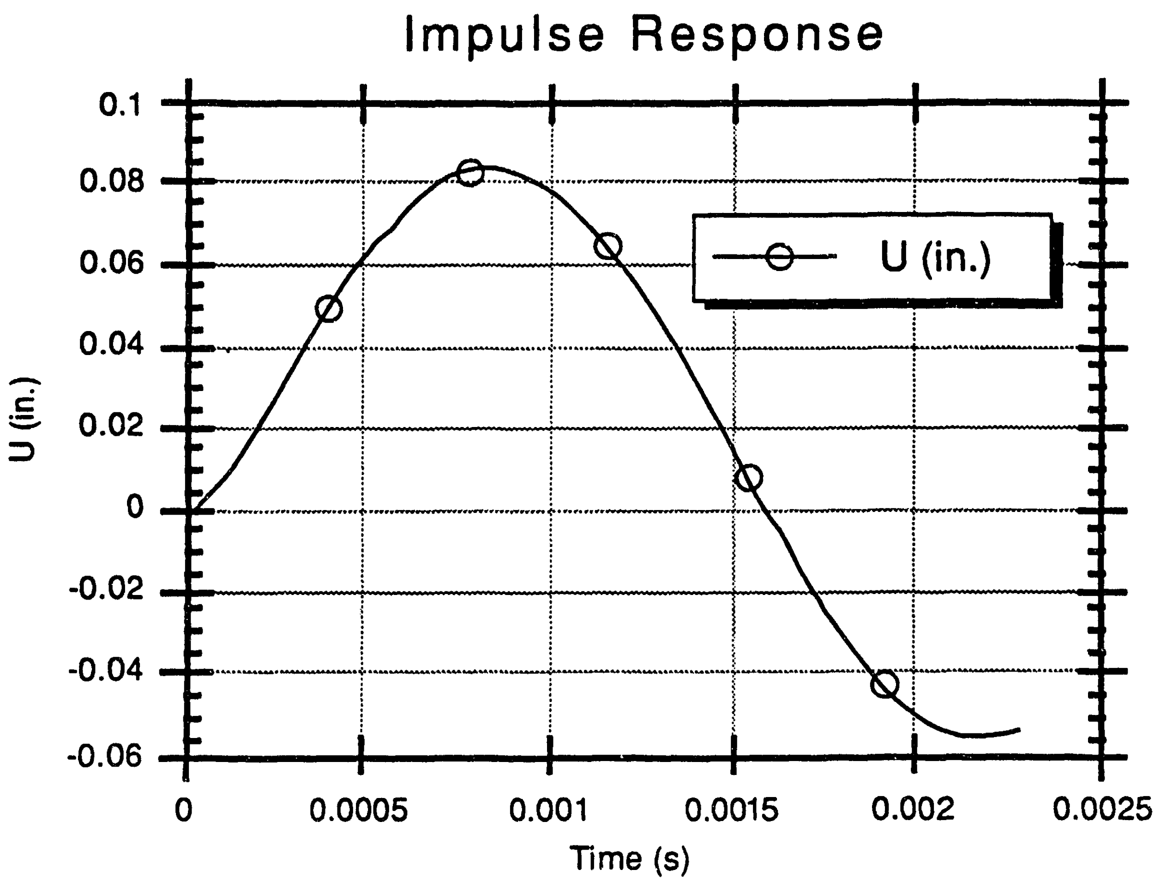
$$F_r = P_i \, 2a\ell$$

Spring Constant

$$k = \frac{R_m}{U_y} = \frac{2\sigma_y h \ell E}{a \sigma_y} = \frac{2Eh\ell}{a}$$

1001.0916

Figure 2-20. Dynamic system



$\frac{U}{U_y} < 1$

1001.0920

$U_y = 0.084$ in.

Figure 2-21. Elastic criterion satisfied

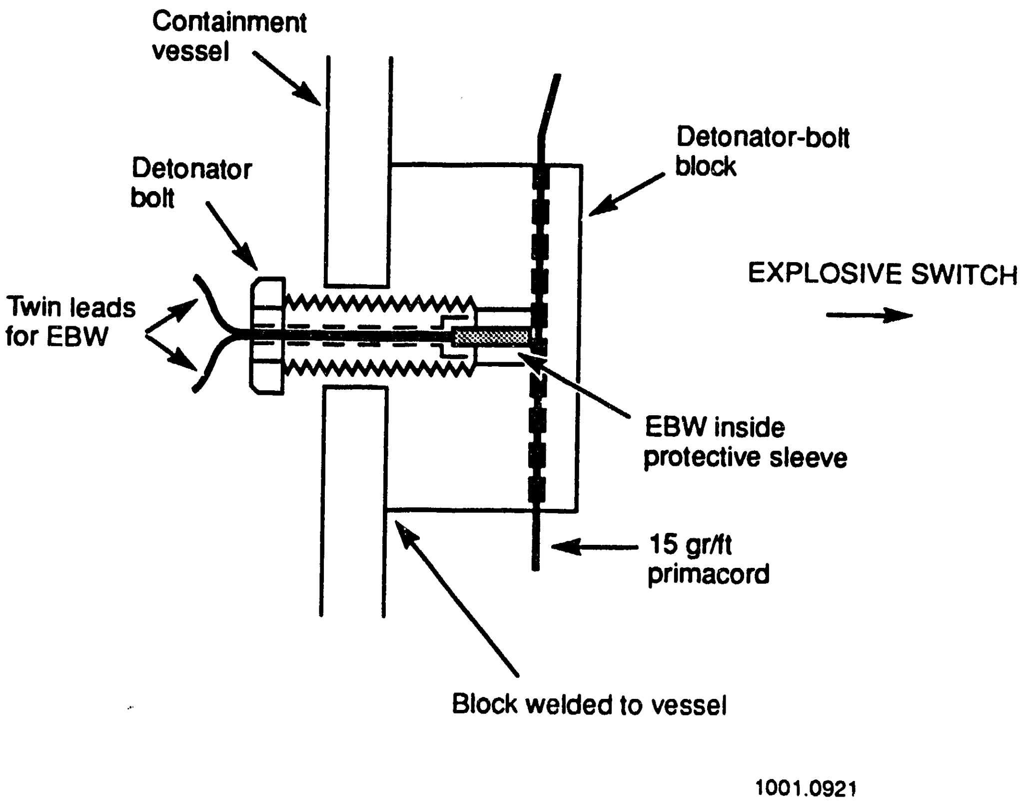


Figure 2-22. Detonator bolt block

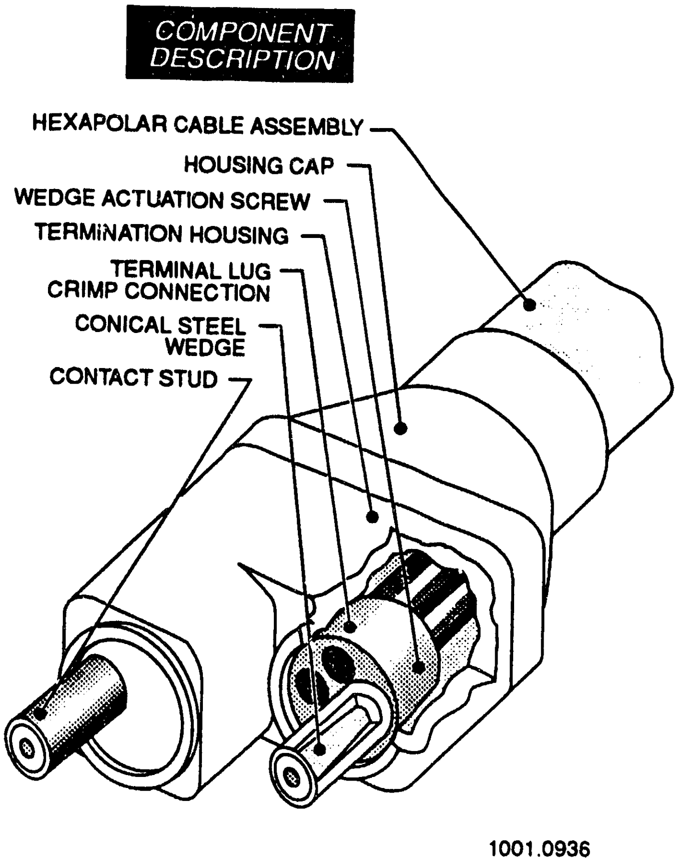


Figure 2-23. Standardized modular termination

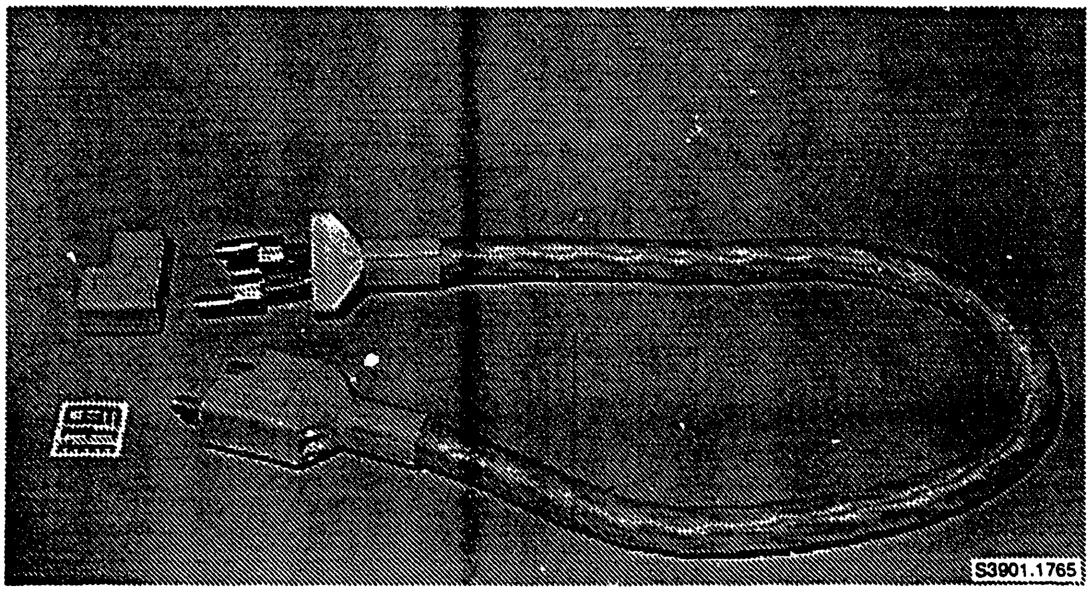


Figure 2-24. Completed prototype cable and termination assembly

initial current. The maximum simulated current which flows through the collection bus from an individual inductor is 1.8 MA because of switching losses. The collection bus has been designed to have 12 of the cables per inductor. This should handle the maximum expected current (1.8 MA) at 60% of the cable rating and fault current of 2.9 MA just below the cable rating. The cables have been tested up to 250 kA where some fraying of the Kevlar™ overbraid occurred at a very tight bend. No problems were observed in the cable connectors.

Other options were examined for this bus and the distribution bus other than the hexapolar cables. The possibility of building parallel plate buswork at first seems attractive until the fabrication problems were considered for the distribution bus where there would be 306 individual buses of 150 kA and 25 kV voltage standoff. A coaxial cable which is being used at the Air Force Advanced Tactical Laboratory (AFATL) at Eglin Air Force Base was also considered. This coaxial cable costs $56 per foot compared to $25 per foot for the hexapolar cable. The terminations for the hexapolar cable are more expensive than the coaxial cable terminations, but the savings on terminations are more than made up by the difference in cable cost per foot. The coaxial cable does not have as high ratings as the hexapolar cable. The coaxial cable has a current limit of 200 kA and impedance of 152 μΩ/ft and 55 nH/ft, compared to the hexapolar cable ratings of 250 kA, 87 μΩ/ft, and 38 nH/ft. The coaxial cable option was abandoned because it was more expensive, had a higher impedance, and was less flexible than the hexapolar cables. The parallel plate bus was abandoned because installation, force management, insulation, and reconfiguration is vastly simplified with the flexible buswork.

2.2.7 Distribution Bus

The buswork from the common to the amplifiers will be the same flexible hexapolar cables used for the collection bus. One of these cables will be used for each amplifier. The peak current simulated per amplifier is 145 kA which is approximately 60% of the rated current of this cable. Using the assumed amplifier locations shown in figure 2-3, the longest distance between an amplifier and the center of the experimental complex was taken to be 260 ft. The distribution bus impedance per amplifier is 22.5 mΩ and 9.75 μH using the hexapolar cable. This impedance is shown in figure 2-1. The impedance of the distribution bus for each amplifier will be kept identical to force equal current distribution between amplifiers. The amplifiers located toward the outside of the complex will all have the same length of cables with the excess cable for the shorter runs coiled up as service loops in the basement. The amplifiers located near the center of the complex will have a second, shorter cable length. An impedance matching device to account for the lower impedance of the shorter cable length will be added. Because the cable is fairly flexible, it will be possible to change the amplifier locations in the future without much difficulty. The cost of this cable was strongly driven by the amplifier locations.

2.2.8 Common Bus

The common bus is a fairly large buswork to connect all of the collection bus and distribution bus cables. There are 594 cables terminated on this bus, 288 collection bus cables and 306 distribution bus cables. This bus was designed to withstand the forces for 70 MA which is the maximum system current. The design consists of two large coaxial rings of diameter 16 ft and width of 2 ft with the void between the rings filled with urethane for voltage standoff and mechanical stability. These coaxial rings will be placed in the center of the experimental complex. The 12 cables from each inductor will be distributed symmetrically around the circumference of the rings to insure even current distribution. The cable resistance between common bus and amplifiers should dominate any differences in the common bus impedance because of the relatively short path lengths and wide cross-sections of the common bus. The current plan is to cast the rings of aluminum and use a high strength easily machinable aluminum alloy. Originally the idea of rolling and welding the rings from high strength aluminum bars was considered. This option was dropped because the aluminum must withstand substantial magnetic forces under the 70 MA fault condition. This fault condition would require approximately 1 in. thick 7071 aluminum to withstand the magnetic forces. The welds would become the weak point in the structure and would force an even thicker structure. Instead the plan is to cast the rings and inspect the final castings to check for voids.

2.2.9 Isolation Switches

The isolation switches are an option which may or may not be necessary. These switches are used solely to isolate the PILC circuitry from the opening switches. If there is a pre-ioni ation pulse without isolating the opening switches, the opening switches will appea. as a short circuit across the pair of flashlamps with only the cable impedance isolating the opening switches. If ignitron switches are installed immediately prior to the amplifier, a rather elegant method of triggering the ignitrons would be to use the voltage which the opening switches develop to drive the ignitors. In this manner an active ignitron firing mechanism would not be needed and the closing would be passive. According to conversations with Livermore personnel, the current ignitrons being developed should be capable of 200 kA discharges which is adequate for one ignitron per amplifier. If the ignitrons are closed using an active triggering method it would be possible to not close the ignitrons during an abort sequence and thus isolate the inductor power supply from the flashlamps completely. Because the inductor current must be dissipated to stop rotor reverse rotation there will still be a voltage of approximately 1,000 V across the abort resistors and flashlamps if they are not isolated.

2.2.10 Abort Switches

The abort switches divert the current away from the flashlamps in the case of a fault. In the case of a fault the current in the inductors still must be dissipated to avoid spinning the HPGs backward. An HPG can be modeled electrically as a very large capacitance capacitor with voltage proportional to rotor speed. The RLC circuit with the HPG (capacitor) and inductor is an underdamped circuit so that the maximum transfer from rotor kinetic energy to inductor energy can be attained. In an underdamped RLC circuit with initial starting conditions of zero current and an initial capacitor voltage, capacitor voltage reverses shortly after peak current. For the HPG/inductor circuit this means that the HPG rotor will reverse direction. The brush mechanisms which are in the HPGs aren't designed to handle reverse rotation.

Due to the explosive propagation delay, the opening switches must be opened at the approximate time when the flashlamps are ionized even if the flashlamps cannot be used as the load. During an abort sequence the opening switches are opened so that the rotors will not spin backward. At the same time the abort switches are closed to supply a current path other than the flashlamps. This type of explosive closing switch has been used successfully in several experiments at CEM-UT. Similar switches to the ones for Nova which are in use at CEM-UT are shown in figure 2-25 and 2-26. These switches are used as the closing switches for the Balcones HPG system to provide more accurate closing time of the electrical circuits than the brushes provide. In this experiment these switches are used to initiate current flow in a 9 MA magnet driven by the HPGs. In a second experiment using the Balcones HPGs, they are used to isolate the six inductive stores charged from the HPGs so that the inductors can have their opening switches opened in stages to provide pulse shaping for a railgun experiment.

The main design parameters for these switches are their peak current, voltage standoff, coulomb, and electrical action ratings. Action is an electrical parameter based upon adiabatic heating. The action of a circuit element can be calculated as

$$\text{Action} = \int I^2 dt$$

The demonstrated current for these switches is 1.5 MA, the estimated current rating for these switches based upon demonstrated currents for smaller switches is approximately 6 MA. The required current per switch during operation is less than 3 MA per switch. The demonstrated voltage stand-off of these switches has been 15 kV. Testing will be performed to insure adequate current capacity and voltage standoff.

The abort switches don't have sufficient resistance by themselves to dissipate the inductor current because they are very low impedance devices. An additional resistor made of parallel stainless steel plates has been designed to be placed in series with the abort switches. The planned location for these abort switches is flat on top of the charging bus parallel to the charging bus.

2.2.11 Crowbar Switches

It was seen in figures 2-4 and 2-5 that a crowbar switch was required to duplicate the capacitor pulse. This switch would need to be used every test. Because the explosive closing switches require a significant time for replacement between tests other switches are planned for this operation. Data published by Physics International about the ratings for their Arc Gap Switches indicate they should be capable of this type of duty. Multiple switches will be used for each inductor. Each switch will have a substantial crowbar resistor in series to dissipate the magnetic energy, to force current distribution between switches, and to keep the action and coulomb requirements of the switches within demonstrated values. The crowbar resistors will also be parallel stainless steel plates similar to the abort resistors and located immediately above the abort resistors. These switches with their associated triggering circuitry are rather expensive and it may be possible to use ignitrons for a substantial cost savings. At this time an ignitron with a sufficient rating has not been identified.

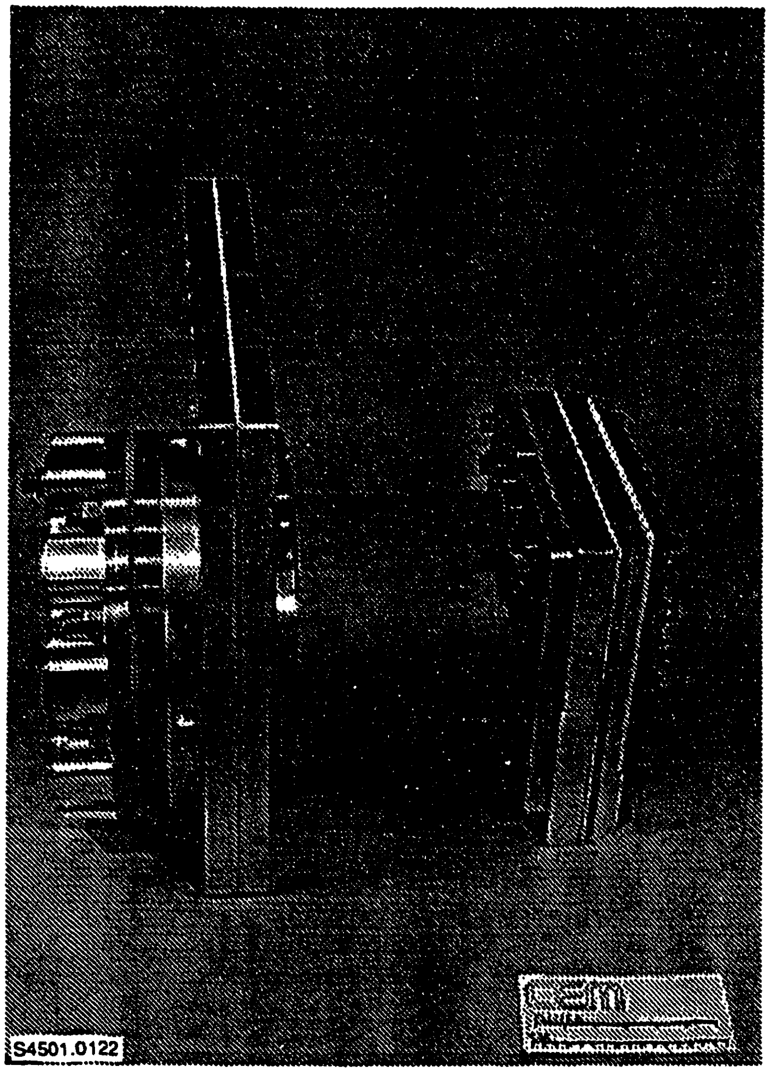


Figure 2-25. Balcones HPG closing switches

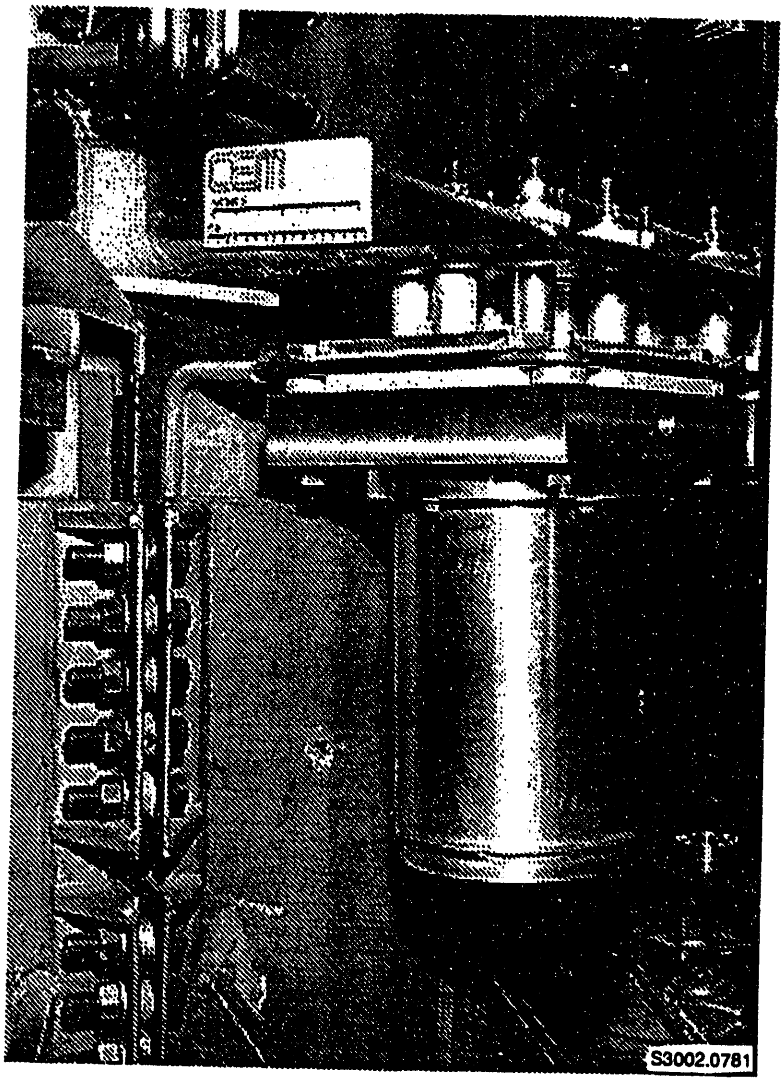


Figure 2-26. Balcones HPG isolation switches

2.3 Time Motion Study for Operation of System

Figures 2-27 and 2-28 show the various tasks which will need to be performed between tests. In order to obtain a two hour turnaround time, four crews of three technicians will be required to reload the explosive opening switches. Besides these switch crews one additional technician and two engineers will be required to run the power supply. One of the engineers will oversee the switches and buswork while the other engineer will be the HPG operator. The additional technician will be an assistant to the HPG operator and aid in the testing of the explosive firing boxes. This is very similar to the manpower requirements for the six Balcones HPGs except for the switch crews. The Balcones system operates with one engineer for the HPG operator, one technician for an operator assistant, one engineer in charge of the switches and a crew of two for changing switches. More manpower will be required for switch replacement for this system because there are four times as many switches and there is a shorter required turnaround time. Additional time will be required in the event that an abort is performed. The abort will only be performed during an emergency because of some problem in the ionization of the flashlamps at the time of the test.

Starting immediately after the previous test the tasks performed are:

Lock-Out HPG Power: This is basically the final shutdown of the generators. The explosive firing box power supplies are disabled to inhibit any additional explosives from being accidentally detonated. The field coil currents are all turned off. After all of the rotors have been assured of no more rotation the hydraulics for the bearings are turned off.

Perform Visual Inspection: Immediately after the test the engineers in charge of the power supply will do a quick visual inspection of the area around the containment vessels and buswork to insure no damage has occurred during the test. After this inspection has been done the switches for the opening of all of the containment vessels are flipped and the automatic flanges start opening.

Open All Containment Vessels: The process for opening the vessels will not be instantaneous. The motors priced for opening the vessels should take approximately 5 minutes to perform this task.

Check HPGs: The HPG operator and the HPG assistant will do a close inspection of the HPGs to insure no problems occurred during the test. Such things as checking for oil leaks, checking instrumentation connections etc. will be performed during this period.

Check Generator Data: This will involve downloading and checking the generator data from the previous test to check for anomalies. All of the inductor currents and switch currents should be checked to insure adequate switch performance and charging performance. Data such as bearing pressures and generator speeds during spin-up will also be examined to insure proper operation.

Check Firing Boxes: After the generator data has been checked the firing boxes will be tested. To enhance system reliability, all of the explosives are detonated from two ends and each end is detonated from two different firing boxes. In this manner three different firing boxes detonate an opening switch. It would require a failure of all three firing boxes to cause a misfire. At CEM-UT these boxes are used

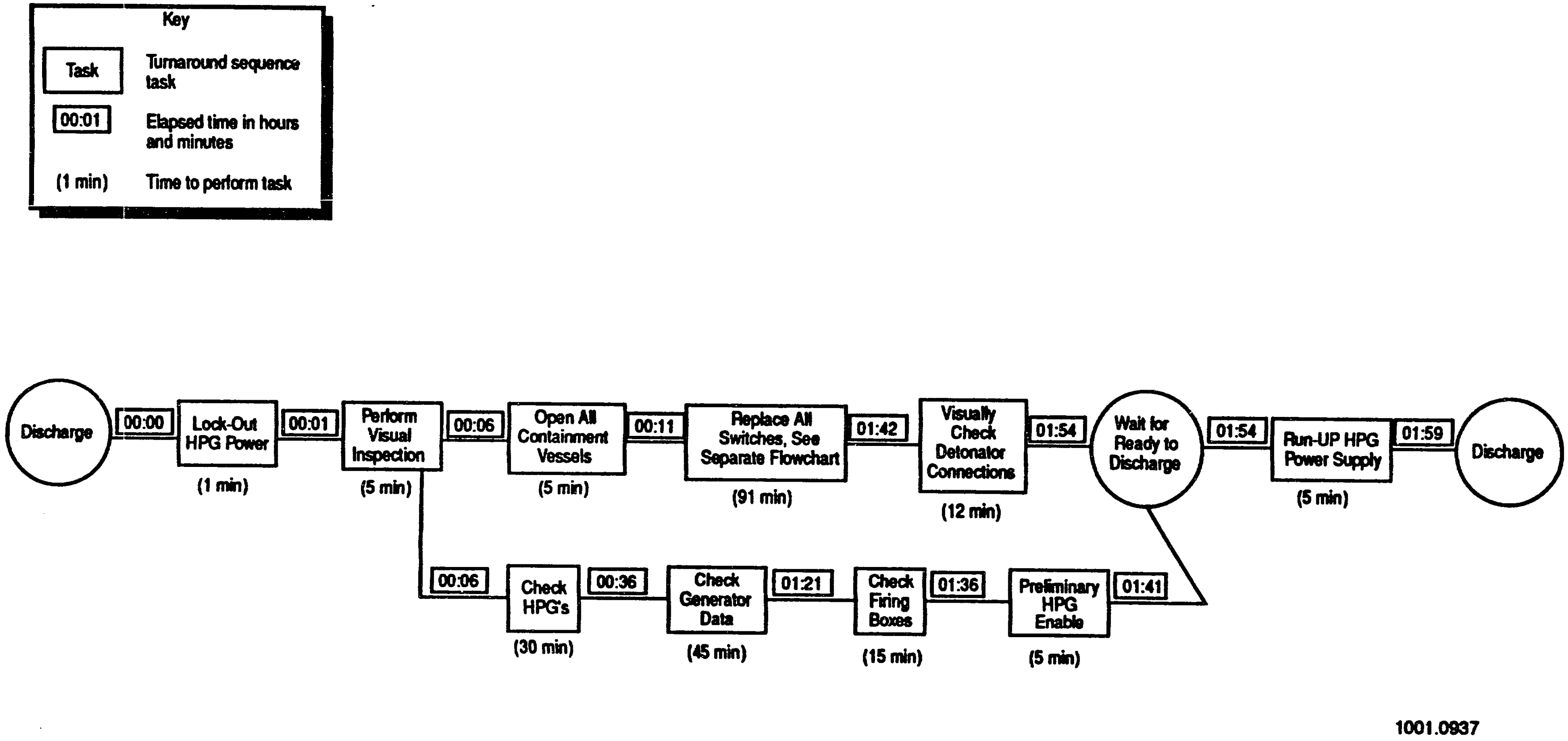


Figure 2-27. Overall time motion

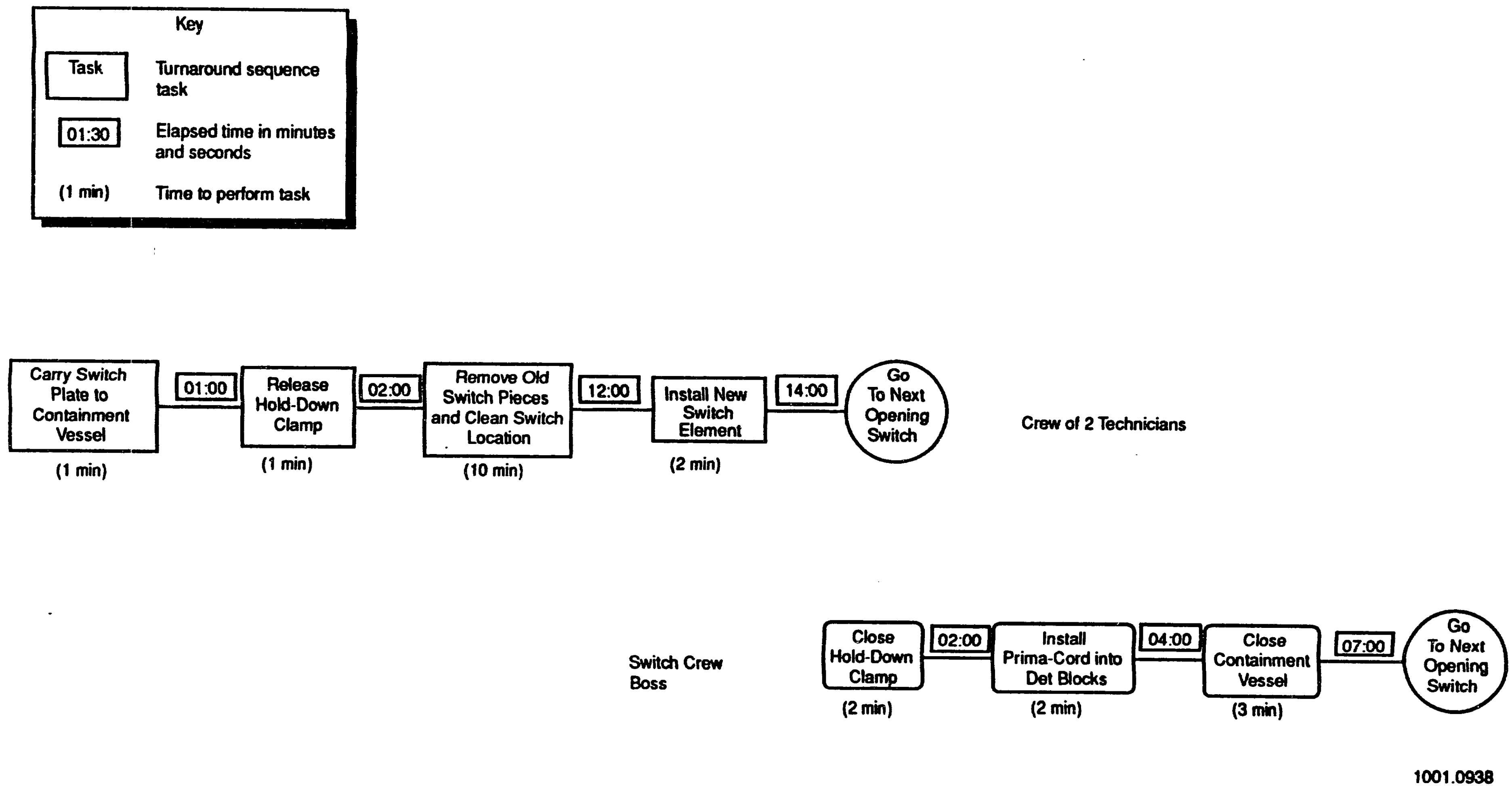


Figure 2-28. Switch replacement time motion

without backups to fire parallel opening switches without problems. By checking data to insure that defective boxes are promptly replaced, the possibility of a switch not opening should be very remote.

Replace Switches: There is a separate chart for this operation since it involves specific tasks and requires significant manpower. During the time when the visual inspection and containment vessels are being opened the switch crews should be carrying the assembled switches from the explosives room or building to the containment vessels to get ready to replace the old switches. After the containment vessels have been opened the automatic hold-down clamp can be released. The old switch debris can be picked up and the smaller debris vacuumed out by the switch crew. Next the switch element can be put into place by the entire switch crew. As soon as the switch element is in place two of the switch crew can move on to the next containment vessel. The switch crew boss then closes the automatic hold-down clamp, installs the Prima-cord into the detonator blocks on the inside of the containment vessel, and closes that containment vessel. After this is done the switch crew boss can go on to the next opening switch and help the other two with replacing the next switch.

Visually Check Detonator Connections: After the switches have been installed and the switch crews have left the area, the last duty of the switch crew bosses is to properly install the explosive bridgewire (EBW) detonators. The engineer in charge of switches will verify connections and initial the checklist.

Preliminary HPG Enable: Various generator pre-test operations such as turning bearings on, setting speeds, etc. are performed. A detailed description of these operations are covered in section 6.1.

Run-Up HPGs: After the basement has been cleared of all personnel and the lasers are ready to be fired, the generators can be brought up to speed. The motors should be capable of bringing the generators up to speed in approximately 5 minutes.

Discharge: After the generators have all reach full speed for the experiment the firing boxes are energized and checked: this check should take approximately 3 s. Next the field coil currents are turned on to create the generator voltages. Finally the generator brushes are actuated to initiate the current rise in the inductors. The rise to peak current should take approximately 200 ms at which time the flashlamps should be ionized. Immediately after ionization the explosives in the opening switches will be detonated. If there are crowbar switches they will be closed at the appropriate time interval.

Abort: If the HPG controller receives an abort at any time the explosives will be detonated to close the explosive closing switches on the abort switches. This will supply a much lower impedance path for the inductor currents than the flashlamps will provide. The estimated time to replace the abort switches is about one hour for one person per switch. This means that it would take all of the switch crews an additional two hours to replace the 24 abort switches each time they were used. The additional expendables for replacing all of the abort switches is $2,567 per use.

3.0 TASK 3 FIXED COSTS

The cost of the HPG, inductor, opening switch system to provide pulsed power for the Nova Upgrade is presented in four separate budgets. Detailed budgets are presented in Appendix C.

Task	Total
I) HPG Design	$1,333,391
II) HPG Manufacture	$19,336,858
III) Pulsed Power Design	$404,118
IV) Pulsed Power Manufacture	$5,930,545
Total	$27,004,912

Cost realism has been achieved in this report in the following manner:

- Task I - Manpower costing for this task closely follows the level of effort required to design the Balcones HPGs. CEM-UT performed the conceptual and detail design producing the machine and auxiliary systems layout, and Parker Kinetic Design (PKD) produced the detailed manufacturing drawings.
- Task II - In 1986 after completing the construction of the six 10 MJ HPGs for the Balcones system, PKD produced the detailed cost for manufacturing five 260 MJ HPGs. This analysis was part of a response to the Trailblazer II Experiment proposal (RFP F08635-86-R-0030) for the Air Force. We have taken that detailed cost proposal and scaled the manufacturing time and materials to the requirements for the four 260 MJ HPGs required for the Nova Upgrade.
- Task III - CEM-UT has designed Brooks coil inductors, explosive opening switches, and explosive containment vessels. We have also sized cables, ignitrons, and dissipate resistors for pulsed power applications. The cost of the pulsed power design effort is based on that experience.
- Task IV - To properly cost the manufacturing of the pulsed power circuitry, we produced preliminary designs and then used existing purchase orders, written quotations, and phone quotations to arrive at the final cost.

We felt the fabrication time estimates in Task II were very accurate because at the time PKD had just fabricated six 10 MJ machines and should have had good scaled estimates of the fabrication time for the larger 260 MJ machines. For actual pricing realism for a fiscal year 1995 start date we consulted with Mr. Will Williams of Victoria Machine Works. Mr. Williams indicated that his company had completed large jobs for Lawrence Livermore in the past. We discussed part sizes with Mr. Williams and he gave us hourly rates for the size machine tool required to perform the machining. This rate combined with the PKD manufacturing hours estimate led to the final price. Because the rates at Victoria have been constant over the last 10 years we felt no further inflation burden need be placed on the estimate to account for the FY 95 start date.

Because the HPG raw material quotes were from 1986, we inflated all materials by 37%, 4% a year from 1986 to the anticipated FY 1995 start date. For large expensive pieces like rotor forgings we actually got written quotations. The LLNL machines, of a higher current rating than the Trailblazer machines, have more brushes, and hence, more rotor and machine length to accommodate the brush gear. All of these scaling considerations were accounted for in the cost.

In Task IV we took the preliminary pulsed power circuit design presented in this report and sent sketches to vendors, cross referenced prices to old purchase orders, and solicited bids over the telephone. The budgets associated with the pulsed power circuit manufacturing list a code which refers to the source of the price validation. Table 3-1 is an identification of code abbreviations.

Table 3-1. Identification of code abbreviations

Abbreviation	Meaning
VQ	verbal quotation
VQ/S	verbal quotation scaled
PO	purchase order
PO/RA	purchase order RARDE contract
PO/F	purchase order fusion contract
WQ	written quotation
WQ/S	written quotation scaled
VPL	vendors price list
EE	engineering estimate

All material quotations collected during this contract have been escalated by 8% to reflect a 4% a year inflation rate between now and the anticipated start date of FY 95. All salaries and wages have been adjusted in a like manner to account for inflation. To get an idea of the cost of the project in today's dollars the cost listed above can be divided by 1.08, resulting in a total predicted cost of $25,004,548.

There are unknowns in the current flashlamp design. There might be a requirement to crowbar the flashlamp pulse if some lamp lifetime issue is uncovered while testing with the inductive store pulse shape. Additionally, if it is determined that lamp pre-ionization is required, the explosive opening switches, shorted across the load prior to pulse initiation, must be isolated from the PILC pulse. A budget for the required number of arc gap switches for lamp crowbar and the ignitrons for PILC isolation is presented in table 3-2.

A very useful facility modification would be to install two 100 ton bridge cranes for HPG assembly and maintenance. The estimated cost of cranes is $400,000.

Table 3-2. LLNL crowbar and PILC isolation circuitry

Labor:			
Hours	RATE/HR		
0			
Total Labor			0
Purchase Parts:	CODE		
Isolation Ignitrons	EE/LARSON	$612,000	
Crowbar Arc Gaps Switch	VQ	$288,000	
Trigger Generator	WQ	$148,000	
Crowbar Resistor:			
1/8" Stainless Plate	VQ	$7,155	
G-10	VPL	$8,640	
Clamps	PO	$3,000	
Total Parts			$1,152,139
Total			$1,152,139

4.0 OPERATING SCENARIO

The system operation mirrors the time motion analysis. The HPGs are motored to speed using dc motors over several minutes. Once the HPGs are at speed, the field coil currents are turned on which causes the HPGs to develop voltage. All of the HPG brushes are brought down to the rotors to close the electric circuits after the field coil currents have been turned on. The rise time to peak current is approximately 200 ms. After the inductors reach peak current, the flashlamps are ionized from a separate circuit. After the flashlamps are ionized, the explosive opening switches on all of the inductors are opened. The inductor current is diverted from the initially low impedance opening switches to the high impedance flashlamps. If there is a crowbar then it is also closed at its appropriate time.

Once the discharge event is over the switch replacement can be performed. All of the required tasks for this are covered in the motion study.

When an abort sequence is called for by the flashlamp controller a slightly different operating scenario occurs. The abort scenario is exactly the same as the normal operating scenario until the flashlamps are ionized. At the time when the flashlamps are ionized the flashlamp controller signals the HPG controller that an abort should occur instead of a normal discharge. The opening switches still must be opened to avoid reverse rotor rotation. At this point the abort switches and crowbar switches are immediately closed. The crowbar switches are closed because they actuate in 1 μs and divert the initial inductor current from the flashlamps. The abort switches will take approximately 70 μs to close. Once the abort switches close the current will flow through them rather than the crowbar path because they are a much lower impedance. If an abort does occur, an additional two hours will be required for replacing these elements as discussed in the engineering design description of the abort switches.

4.1 Manpower Requirements

To maintain a two hour turnaround, the following manpower is required

- Two engineers, one for HPG, one for switches
- Four switch crews, three technicians each, total of 12 technicians
- One HPG assistant (technician)

In addition if the switch elements are reloaded on sight, then for each full energy test 24 switch elements will need to be assembled with their aluminum plates, backing plates, insulation pieces, explosives etc. These elements can be assembled in advance and kept in stacks to be used later. The assembly of one switch element should take approximately 30 minutes by one technician. Two hours should be reserved at the end of the day for the technicians to prepare switch plates for the next day.

5.0 COST OF EXPENDABLES

Because the power conditioning is based around explosive opening switches, there is an expendable cost associated with each full energy test of the system. The expendable budget is presented in table 5-1. Because this cost is linear with the amount of energy on any given test, the expendables cost will scale directly with the energy.

Table 5-1. Opening switch expendables

Labor:			
Hours	RATE/HR		
54	$35	$1,890	
Total Labor			$1,890
Purchase Parts:	CODE		
Switch Elements	WQ/S	$5,501	
Thermal Switch Elements	WQ	$432	
Polyethylene Plugs	VQ	$175	
Polyethylene Backing Plate	VQ	$444	
50 Gr. Detonation Cord	PO/RA	$195	
Detonators	PO/F	$1,090	
Det Holders	PO/F	$4	
Total Parts			$7,841
Total			$9,731

6.0 RELIABILITY

Rotating machines are at the heart of every power generation center in the United States. We depend on these machines to run reliably day in and day out with very slight maintenance requirements. The homopolar generators are actually simpler than this technology in that they use a much smaller L/D ratio in the rotor for dynamic stability and they have no rotor windings. The only moving parts on the HPG outside the rotor and shaft are the discharge brush mechanisms that are pneumatically actuated through very small deflections. A history of a prototype HPG operating over the last 18 years is presented in Appendix D. In that report it can be seen that the machine has been reliable and 2,460 discharges have been made over the last six years.

The Balcones system of six HPGs is demonstrating similar reliability in supporting electric gun and fusion research over the past six years. Important to the success and reliability of the HPG system is a carefully designed and implemented control system.

6.1 Control System

6.1.1 Architecture

The preferred control architecture for the LLNL power supply is a two level, distributed system. Level I provides primary sequence control of all noncritical generator functions and auxiliary electrical and mechanical equipment. Level II affords fail-safe protection of all critical system parameters.

The sequence supervisory control (Level I) coordinates the operation of the four generators in the start-up or motoring phase, and allows for operator interface, i.e., input from LLNL personnel. Routine sequencing is performed by the system control center (SCC), which brings the power supply to a predischarge energy level specified by the operator. Once the desired energy level has been reached with all four generators running at a given speed, control is passed to Level II, the critical fault monitor system (CFM), which takes over to control the discharge. Level II provides stand alone monitoring of, and intervening control over, this critical stage in the power generation process, while at the same time handling all generator or life safety faults.

Discreet handling of critical and noncritical control functions is made possible by this two level approach, as shown in figure 6-1. The system is equipped at both levels with distinct and separate digital and/or analog field transducers to accomplish the control task. Information is shared by the two levels only to the extent that the SCC indicates readiness for the CFM to activate critical support systems; or conversely, when the CFM informs the SCC that an emergency situation has occurred and immediate shut down action was taken. Moreover, the stand alone, independent nature of the CFM allows for the SCC to be deactivated (e.g., during a CPU fault) during generator operation without damage to the generators.

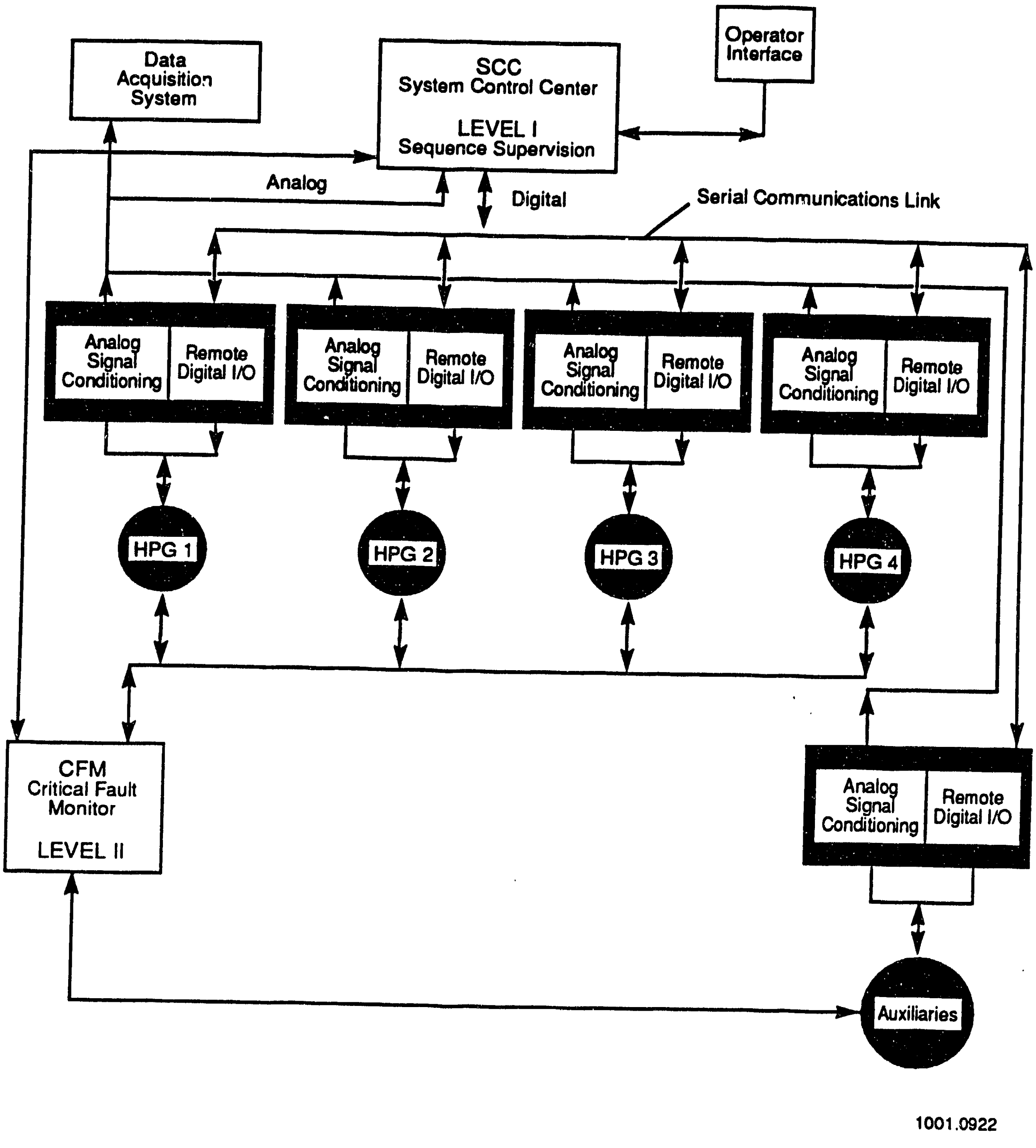


Figure 6-1. Control system architecture

6.1.2 Control Functions

The pulse power supply and its control system operate as a cyclical duty system with operational tasks performed in the following sequence:

1) start-up,
2) discharge,
3) normal shut down, or
4) emergency shut down

As indicated in the previous section on control architecture, these tasks are delegated to the SCC and the CFM. Figure 6-2 shows the typical control timing sequence for the Balcones system during power supply operation.

Generator and auxiliary electrical and mechanical systems controlled by each of the two levels are as follows:

Level I -- System Control Center

- cooling water supply
- brush nitrogen supply
- motoring oil supply and regulation
- motoring oil circuit flushing supply
- field coil ac primary power supply

Level II -- Critical Fault Monitor

- main and backup bearing oil supplies
- bearing oil scavenger system
- field coil dc secondary power supply
- brush actuation
- rotor over speed
- rotor orbit
- rotor motion

1. Start up. The SCC performs the automatic startup sequencing of appropriate support systems in response to input (i.e., performance parameters for an individual experiment) from the LLNL operator. At this stage 1 control of the power supply is occurring at the Level I in the control system architecture. The operator simply indicates a desired rotor speed and generator field coil current. Upon operator command, the SCC executes a prescribed sequence that automatically coordinates the startup of generator support systems. This includes the coordination of inrush current control by sequencing the motor starting loads, the coordination of all warm-up functions, and the monitoring of selected temperatures and pressures for operation of the power supply within tolerable limits. The SCC brings the power supply to the ready-to-motor state, at which time it stands by to receive an operator command that will initiate rotor spin up.

After the command is given by the operator to initiate rotor spin up, the SCC actively regulates the rotor speeds of the four generators, bringing them to a full speed, steady state setpoint. Rotor speeds are regulated by the SCC to within a maximum of 2% difference between generators. In about 5 minutes, all four generators will reach the setpoint inside the 2% window, at which point an "at speed"

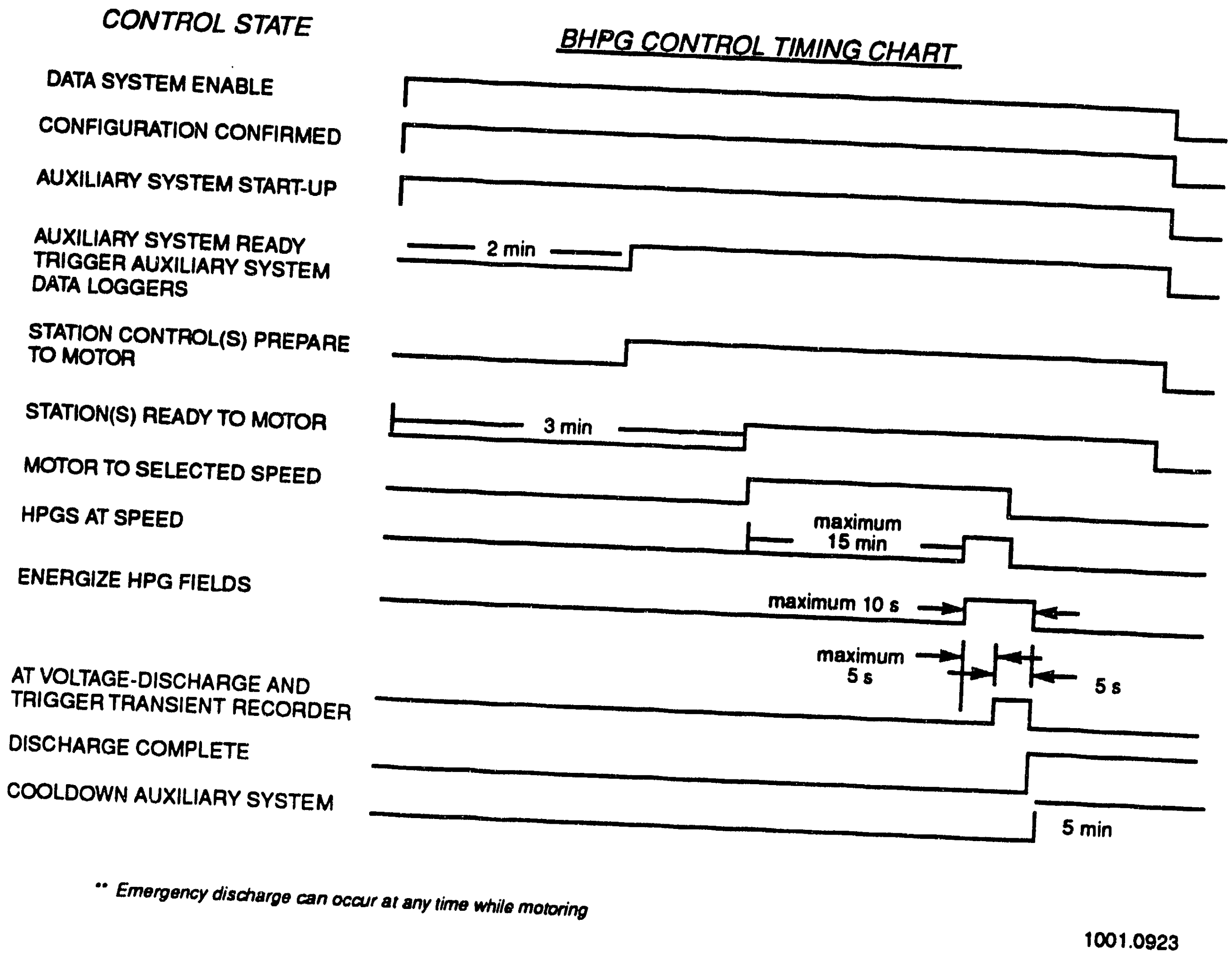


Figure 6-2. Power supply operating process

signal is indicated by the SCC. This then automatically sends a signal to Level II in the system architecture directing the CFM to assume control and initiate the discharge sequence.

*2. **Discharge.*** The CFM responds to the SCC command for discharge by energizing the dc field coil power supplies. Field coil current will rise to a demand setpoint, while the generator open circuit voltage is being measured and compared with the setpoint by the SCC. As soon as the voltage in all four generators matches within 2% of the demand setpoint, the SCC requests brush drop. In response, the CFM energizes the main discharge brushes, which completes the discharge circuit to the load.

*3. **Shutdown.*** Post-discharge cooldown and sequential shutdown is coordinated by the SCC. A rotor stopped indication initiates the cooldown process. The hydraulic and pneumatic support facilities remain ready for subsequent rotor spin up, at which point the operator can either continue with the next start-up or initiate the shutdown sequence.

*4. **Emergency Shutdown.*** The CFM can initiate an emergency shutdown if something goes wrong in the power supply system. This action would be taken automatically if the power supply were to ever enter into an "off normal state." The problem might be either noncritical or critical. Responses to noncritical faults are controlled by the SCC, while many critical faults are handled by the CFM. Depending on whether an "off normal state" is critical or noncritical, the control system will initiate one or both the following responses:

a) hydrodynamic rotor braking and/or
b) discharge of rotor energy.

6.1.3 Control Interlocks

To insure proper performance and protect against "out of sequence" operation, the control system includes software and hardware interlocks. These are as follows:

Software Interlocks

- rotor spinning is prohibited until the ready-to-motor state has been achieved
- normal discharging is prohibited if the rotor voltage is not within tolerance of the demand setpoint
- repetitive motoring cycles are conditional upon cooldown

Hardware Interlocks

- rotor spinning is prohibited until the generator bearing lube oil pump is running and the bearings are pressurized
- dc field coil excitation is prohibited until the generator bearing lube oil pump is running and the bearings are pressurized
- the generator lube oil supply system is prohibited from starting until the bearing oil scavenger system is running

- shutdown of the generator lube oil system is not possible until the rotor has stopped
- shutdown of the generator lube oil system is not possible while the motoring supply is active
- shutdown of the bearing oil scavenge system is not possible while the bearing oil supply is running

6.1.4 Controls Philosophy

Experience has shown that the preferred control system architecture can be implemented most economically and reliably using an industrially proven programmable logic controller (PLC) integrated with a hard wired CFM system. This architecture is preferred because it incorporates the control flexibility afforded by the software driven PLC, while maintaining a high degree of security, EMI noise immunity, and operational integrity afforded by the use of a hard wired, CMOS based, fault tolerant emergency shutdown CFM.

System Control Center. Ample analog and digital I/O capacity is provided to accommodate the control requirements of the SCC. A General Electric Series Six PLC is the preferred unit, programmable in ladder logic and with an interface to a remote I/O system. Its programmable features include proportional/integral/derivative (PID) loop capability; subroutine calling; and matrix, timer, counter, and comparison capabilities. Programming can be done form an off-line station (convenient for program development and documentation purposes). The PLC facilitates on-line monitoring of I/O status and is capable of overriding I/O states.

The distributed architecture incorporates remote I/O, with system blocks located in the vicinity of each generator and auxiliary system. This design minimized both cost and maintenance associated with direct wiring from the field to the SCC. The status of the field transducers is sensed at the remote location and transmitted back to the SCC through a shielded, twisted pair cable to a serial data link. A remote I/O local area network (LAN) conforms to the following minimum requirements:

noise immunity	1,500 V common mode rejection (CMR)
baud rate	153.6 kB
maximum LAN length	7,500 ft
galvanic isolation	1,500 V

In addition, the remote I/O includes the number of diagnostic features: open wire, shorted wire, failed switch, over temperature, no load, over load, short circuit, and pulse test.

Operator/Control Interface. The control terminal (i.e., computer keyboard, screen, and other manually operated controls at Level I in the system architecture) accommodates the operator's commands, directions, and inputs; prompts the operator for start up information; and visually displays alarm/fault and system status information. The recommended control terminal, or PLC, is a General Electric Opti Basic operator interface unit. An additional manual interface panel accompanies this unit. The panel consists of industrial grade selector switches capable of discreetly enabling or disabling the control circuitry for components of the auxiliary system. A layout of the control pane for the conceptual LLNL system is shown in figure 6-3.

Bar graph meters of the LED type provide visual indication of selected power supply parameters. These meters include visible, high/low set points with alarm outputs for the SCC. The following power supply parameters are metered:

- field coil current
- rotor speed
- rotor voltage
- field coil temperature -- thrust end
- field coil temperature -- non thrust end
- bearing oil supply temperature
- bearing oil return temperature
- bearing oil supply pressure
- rotor axial position
- rotor radial position

Critical Fault Monitor. Hardware in Level II of the system architecture provides a high degree of noise immunity and is a stand alone, hard wired control system. The preferred hardware employs discreet logic CMOS rather than programmable software, and offers the following inherent features:

- dual redundant power, logic, and trip paths (random failure protection)
- redundant hard wired logic (systematic failure reduction)
- field input sensing of state, open wire, shorted wire, and grounded wire
- input contact bounce filtering
- maximum response time to fault of 5 ms

In the event of field wiring faults, an alarm is triggered but no automatic control action will result. An emergency shut down system known by the proprietary "PRETECT" is the recommended CFM hardware, and is used to control the Balcones 60 MJ HPG power supply.

Control Reliability and Availability. The power supply can be damaged as a result of both random hardware failures and systematic software errors. The two level control architecture minimizes the chance of damage from either type of fault by separating normal control functions from critical fault monitoring/control functions. The following four principles or guidelines are the predominate design considerations reflected in the control system architecture:

- the control system must maintain the power supply in a safe state or bring the power supply to a safe state if necessary
- electronic hardware failures must not cause a failure of safety related systems
- systematic software errors must not cause a failure of safety related systems
- diversified control hardware minimizes random failures and systematic errors

The recommended LLNL control system is fundamentally identical to that which is in use on the Balcones 60 MJ power supply and the U.S. Army ARDEC 15 MJ power supply. It is a well demonstrated design, using proven state of the art hardware that will insure maximum reliability and availability of the LLNL control and power

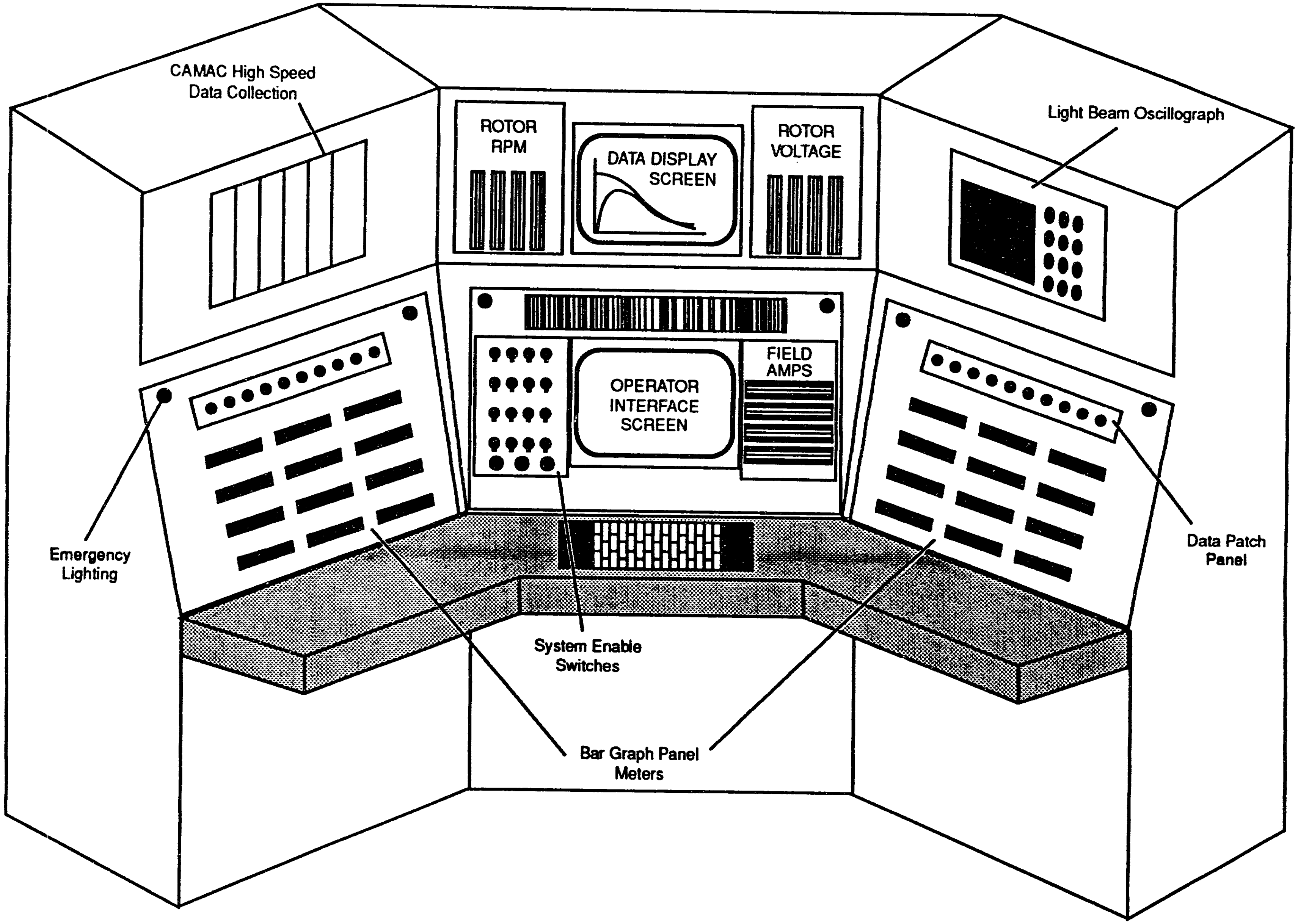


Figure 6-3. Conceptual layout of control panel for LLNL system

supply systems. The self-checking diagnostics of the PLC and the reliability ratings of both that unit and the PRETECT CFM (based on manufacturer's claims and generally known guidelines for programmable electronic circuitry) affords typical failure rates (per 10^6 hours of operation) as shown:

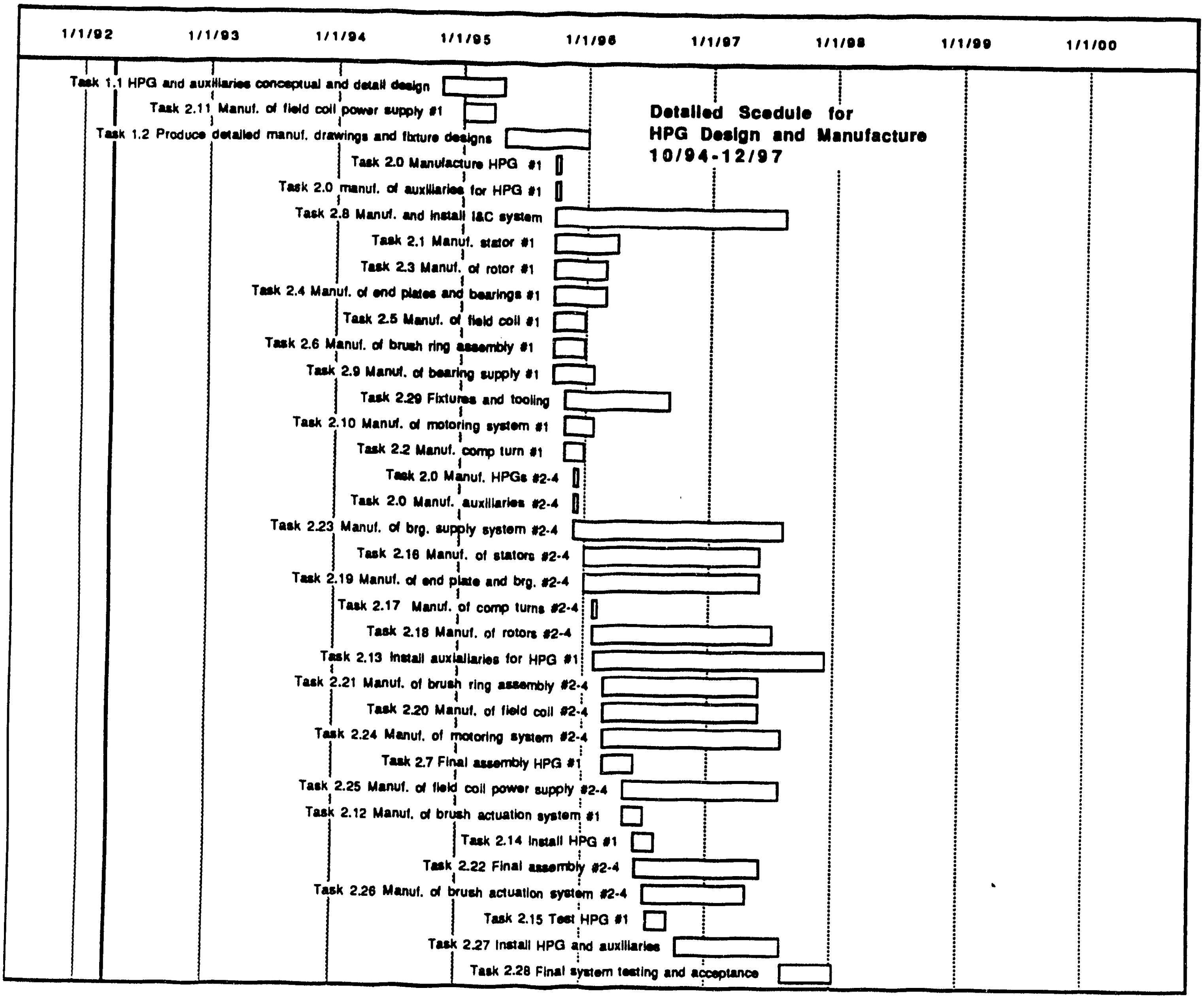
- programmable electronics: 100
- PRETECT control fault monitor: 0.029

The combination of PLC and dedicated CMOS technologies is well suited for a pulsed power environment.

The control system architecture reduces the probability of system failure and increases system availability by providing continuous sensor, interconnect wiring, and CPU status diagnostics. The diagnostics capability enables advance detection of control system malfunctions, allowing corrective action by maintenance personnel before the power supply is called into service. Any need for repairs can be readily determined and more easily scheduled.

System reliability is improved through redundancy. The redundancy in this design is necessary and sufficient to prevent any potential catastrophic failure of the LLNL pulsed power system. Separation of critical safety controls and noncritical process sequence controls enhances its reliability. Furthermore, the CFM "counter bounce filtering" feature allows shut down only when necessary, critical or requested, thereby eliminating the possibility of unwanted shut downs due to spurious contact bounce.

7.0 SCHEDULE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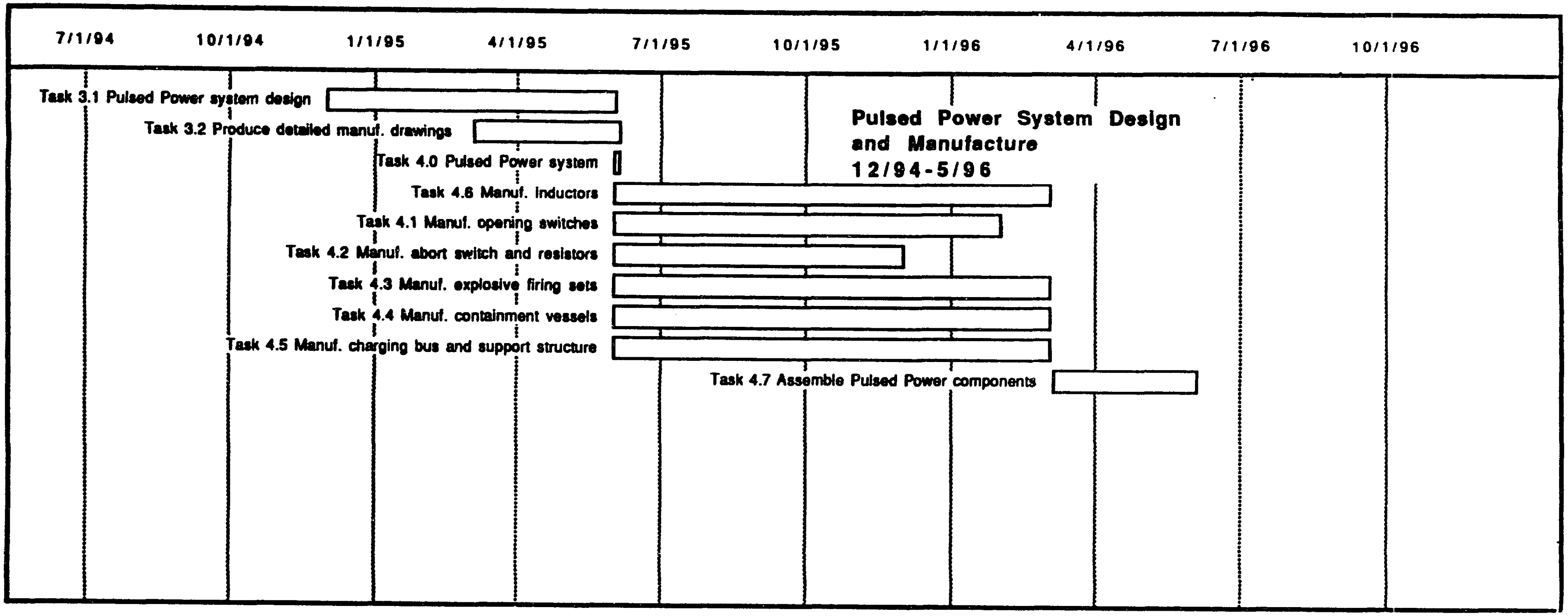
Detailed Scedule for
HPG Design and Manufacture
10/94-12/97
Task 1.1 HPG and auxiliaries conceptual and detail design
Task 2.11 Manuf. of field coil power supply #1
Task 1.2 Produce detailed manuf. drawings and fixture designs
Task 2.0 Manufacture HPG #1
Task 2.0 manuf. of auxiliaries for HPG #1
Task 2.8 Manuf. and install I&C system
Task 2.1 Manuf. stator #1
Task 2.3 Manuf. of rotor #1
Task 2.4 Manuf. of end plates and bearings #1
Task 2.5 Manuf. of field coil #1
Task 2.6 Manuf. of brush ring assembly #1
Task 2.9 Manuf. of bearing supply #1
Task 2.29 Fixtures and tooling
Task 2.10 Manuf. of motoring system #1
Task 2.2 Manuf. comp turn #1
Task 2.0 Manuf. HPGs #2-4
Task 2.0 Manuf. auxiliaries #2-4
Task 2.23 Manuf. of brg. supply system #2-4
Task 2.16 Manuf. of stators #2-4
Task 2.19 Manuf. of end plate and brg. #2-4
Task 2.17 Manuf. of comp turns #2-4
Task 2.18 Manuf. of rotors #2-4
Task 2.13 Install auxiliaries for HPG #1
Task 2.21 Manuf. of brush ring assembly #2-4
Task 2.20 Manuf. of field coil #2-4
Task 2.24 Manuf. of motoring system #2-4
Task 2.7 Final assembly HPG #1
Task 2.25 Manuf. of field coil power supply #2-4
Task 2.12 Manuf. of brush actuation system #1
Task 2.14 Install HPG #1
Task 2.22 Final assembly #2-4
Task 2.26 Manuf. of brush actuation system #2-4
Task 2.15 Test HPG #1
Task 2.27 Install HPG and auxiliaries
Task 2.28 Final system testing and acceptance


Pulsed Power System Design
and Manufacture
12/94-5/96
7/1/94
10/1/94
1/1/95
4/1/95
7/1/95
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1/1/96
4/1/96
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10/1/96
Task 3.1 Pulsed Power system design
Task 3.2 Produce detailed manuf. drawings
Task 4.0 Pulsed Power system
Task 4.6 Manuf. inductors
Task 4.1 Manuf. opening switches
Task 4.2 Manuf. abort switch and resistors
Task 4.3 Manuf. explosive firing sets
Task 4.4 Manuf. containment vessels
Task 4.5 Manuf. charging bus and support structure
Task 4.7 Assemble Pulsed Power components

REFERENCES

[1] W.L. Bird, Jr., D.R. Brown, S.B. Pratap, "Application of Rotating Machines for Prime Energy Stores for Particle Beam Accelerators", Final Report for Sandia National Laboratories Contract No. 26-4642, September 1982.

APPENDIX A

Preliminary Investigation of a Compulsator to Provide Pulsed Power for the NOVA Upgrade

Preliminary Investigation of a Compulsator to Provide Pulsed Power for the NOVA Upgrade

A compulsator based power supply was investigated for requirements listed in table A-1.

Table A-1. Requirements of the load

Type Of Load	Xenon laser flashlamps
Number Of Lamps	9800
Energy Delivered To Each Lamp	21 kJ
Total Energy Delivered	206 MJ
Pulse Width	500 μs
Load Characteristics	$V_L = K_0\sqrt{I}$; $K_0 = 80$

Two types of compulsators were investigated

- the passively compensated compulsator
- the actively compensated compulsator

The passive compulsator was considered first due to its simple and robust construction which does not require high power brushes and slip rings. Also, the pulse shape from the passive compulsator is closer to the pulse shape obtained from present experiments. The pulse width obtained from this machine is the natural pulse width without any pulse compression. For the present application, this results in a very large number of poles and a corresponding low pole pitch. A low pole pitch results in lower coupling between rotor and stator windings. Associated with the poor coupling is, of course, poor performance.

A more elegant approach is to use the active compulsator which reduces the natural pulse width with active pulse compression. The only drawback of this approach is that the pulse shape is altered compared to the pulse shapes obtained presently. This causes some uncertainty in the prediction of the performance of the flashlamps. The pulse shapes typically obtained from this machine when driving a flashlamp is specified in table A-1 and are shown in figures A-1 and A-2 on different time scales. The number of poles is reduced considerably compared to the passive machine and the performance is quite acceptable. Table A-2 summarizes the machine parameters.

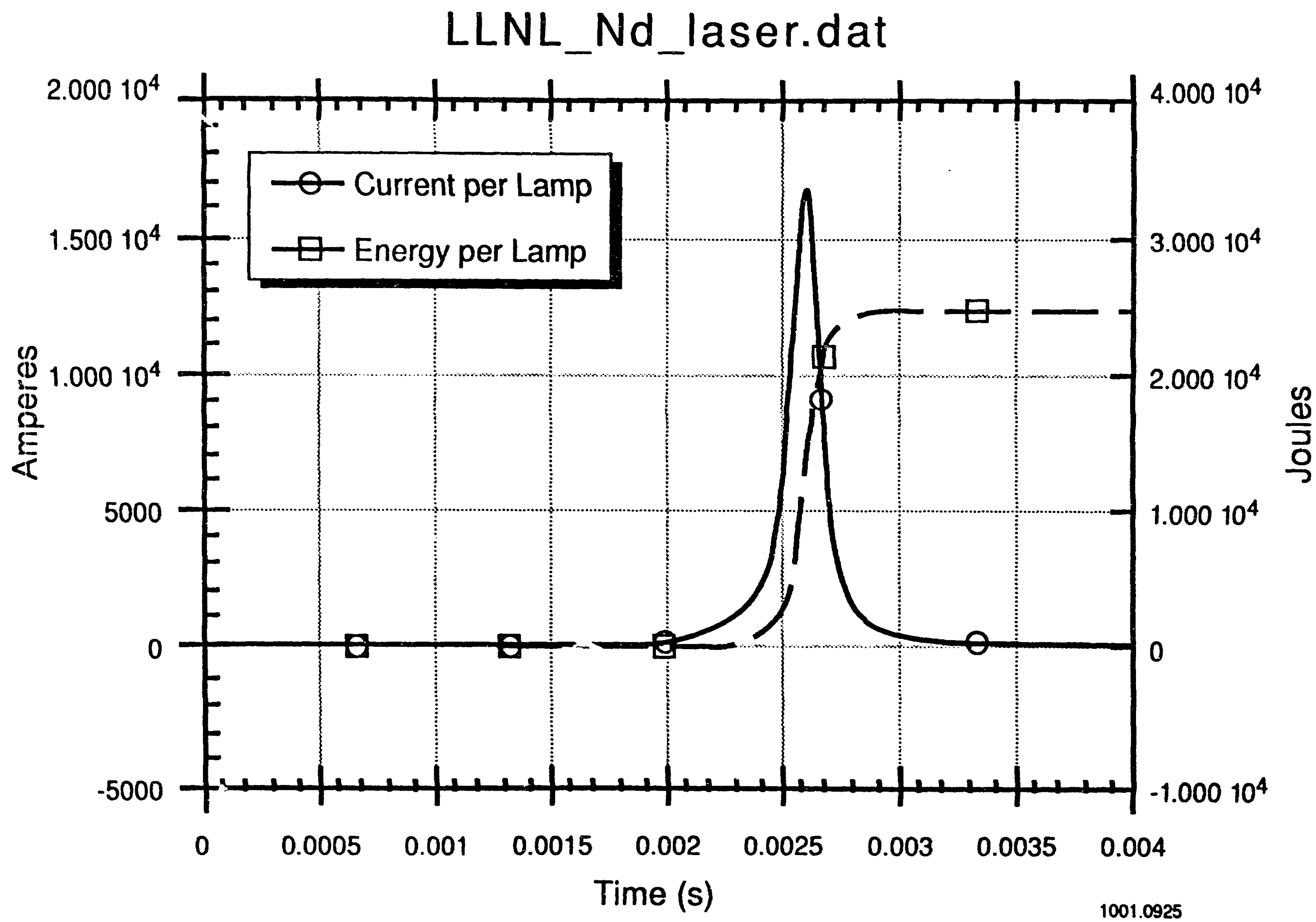

Figure A-1. Typical compulsator driven flashlamp pulse, long time scale

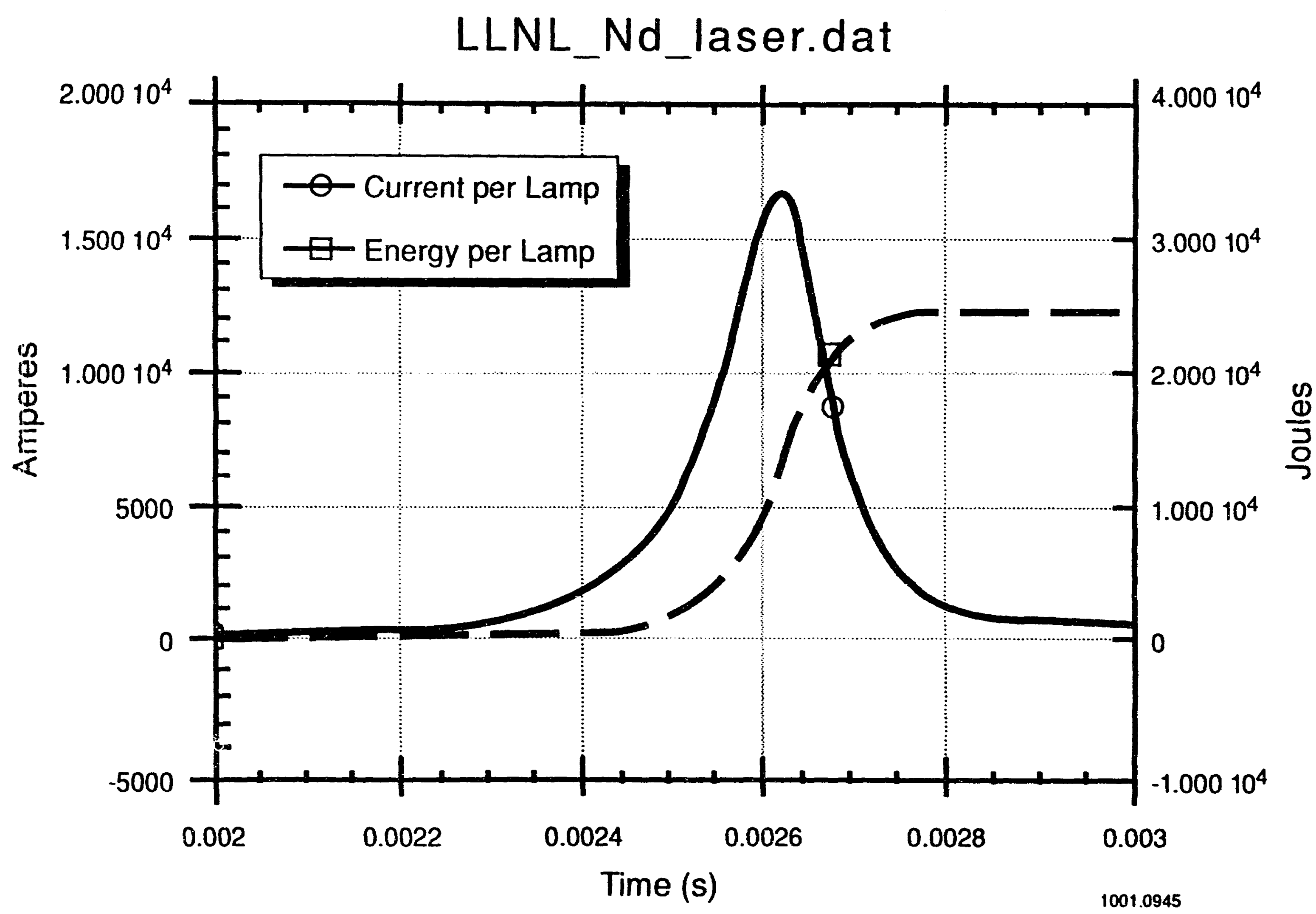

Figure A-2. Typical compulsator driven flashlamp pulse, short time scale

Table A-2. Machine parameters for the actively compensated iron core compulsator

PARAMETER	UNITS	VALUE
Number of machines		15
Number of lamps per machine		2 x 327 = 654
Number of poles		6
Speed	rpm	2,000
Energy stored	MJ	630
Mass of machine	kg	85,000
Outer diameter	m	2.3
Length	m	3.0
Peak open circuit voltage	kV	10.0
Peak machine current	MA	5.0

APPENDIX B

Task 2. Study of Alternate System Switch

Task 2. Study of Alternate System Switch Configurations

B.1 System Design

B.1.1 Low Cost Alternative, No Common Bus

The original system which was designed was the lowest cost alternative. This design electrically connected nine amplifiers to each inductor in the power supply. Either eight or nine inductors were electrically in parallel at each homopolar. The opening switches were placed in series with the HPGs and inductors with the nine amplifiers being parallel to the opening switch. This can be seen in the electrical schematic figure B-1. Each inductor was essentially a separate power supply for the amplifiers connected to it with no method to transfer the current from one inductor to the flashlamps connected to another inductor.

The HPGs and inductors were distributed around the experiment as close to the amplifier distribution as feasible. This minimized the length of distribution bus from inductor to amplifier which minimized the cost. By keeping the distribution bus as short as possible, the energy dissipated due to resistive heating and switching into a high inductance were minimized. By minimizing these energy losses the energy stored inductively prior to driving the flashlamps was minimized. Additionally, the required generator, switch and buswork size was reduced. The required initial magnetic energy was kept to approximately 400 MJ for this system.

There were several problems associated with this system. The first was that the system design was strongly driven by the number of amplifiers and the amplifier placement. With the assumed amplifier layout there were 18 beamlines of 17 amplifiers. Assuming that identical inductors and opening switches are used throughout the system, each inductor needs to have an identical number of amplifiers to keep the energy delivered to each amplifier balanced. The 306 amplifiers can be divided into groups of 306 groups of 1 amplifier, 153 groups of 2 amplifiers, 102 groups of 3 amplifiers, 51 groups of 6 amplifiers, 34 groups of 9 amplifiers and the converse such as 9 groups of 34 amplifiers.

Each flashlamp series pair needs about 10 kA when driven with the proper pulse shape, resulting in 160 kA per amplifier. This is increased to 200 kA per amplifier to account for switching losses. This implies a total system current prior to driving the flashlamps of approximately 60 MA.

For the designs investigated, appropriate design guidelines and cost constraints limited the generator current to 15 to 18 MA. Assuming a value nearer the low end requires a minimum of four generators to drive the system. The more generators that are used the more expensive the system.

Because of the physical layout of the system a reasonable grouping of amplifiers is 2 groups of 81 amplifiers and 2 groups of 72 amplifiers. If each group of amplifiers was further divided into groups of 9 amplifiers each at a particular stage of the amplification this leads to 2 groups of 9 sets of 9 amplifiers and 2 groups of 8 sets of 9 amplifiers. The system was arranged such that the outside generators would each have 9 inductors connected per generator and the inside generators would each have 8

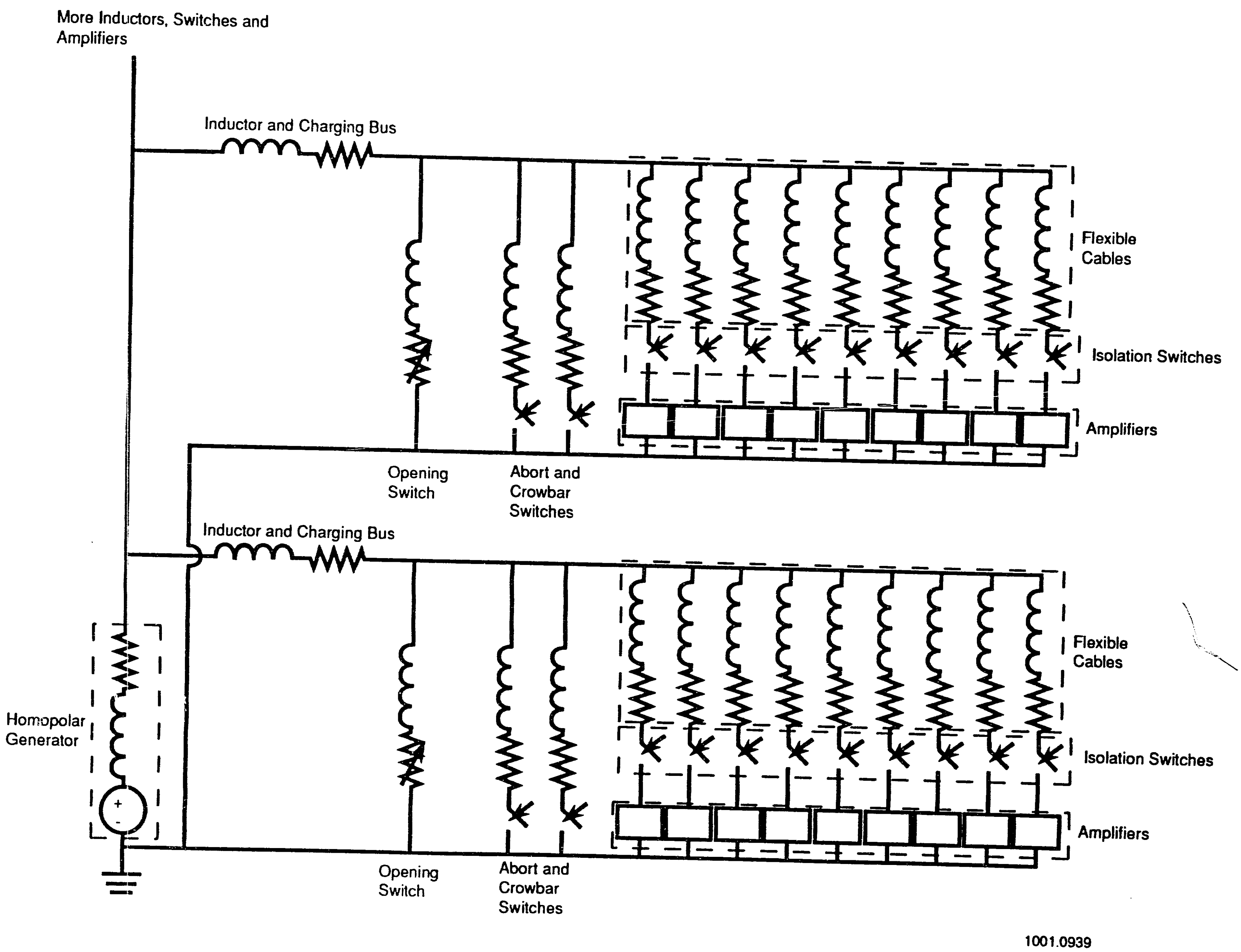

Figure B-1. Initial design circuit schematic inductor connected per generator. By varying the rotor speeds and field coil currents it is possible to have the currents in all of the inductors at the same peak current when the opening switches are opened using identical generators for the inside and outside circuits.

The main problem with this initial system is its flexibility. If one of the HPGs is nonoperational then the amplifiers connected to it would also become nonoperational. One solution would be to keep a spare HPG on hand in case an HPG has problems. Keeping a spare HPG in case of problems would be an expensive proposition, around $4 million plus labor and time while the spare was being installed. A second problem is that if some of the amplifiers were not operational a decision would have to be made of whether to overdrive the rest of the amplifiers connected to that inductor or to not use the amplifiers connected to that inductor at all since all of the inductors connected to a generator would have to have the same peak current. Upon considering the flexibility problems with this system, the decision was made that another system design was needed even if it were slightly more expensive.

B.1.2 Final Design, Common Bus

The final configuration gets around the problems of the initial system by bringing all of the inductor currents to a common bus and then distributing the current to all of the amplifiers. This system requires significantly more distribution buswork than the original system. This system does de-couple the individual inductors from individual amplifiers. The result was that a system could be designed which could supply the required current and energy by the best combination of number of generators and inductors without respect to the amplifier placement. A circuit schematic for this system can be seen in figure 2-1.

The impedance from the common bus to each of the amplifiers is kept identical and the inductance of this buswork is higher than the equivalent internal amplifier buswork inductance. This report assumes that there are 16 flashlamp pairs per amplifier with around 70 μH of inductance per flashlamp pair internal to the amplifier. The HPGs are brought near the center of the experiment to reduce the bus lengths between the inductors and the common collection bus.

If some of the generators are non-operational then the system can be used with either all of the flashlamps driven at reduced power or any chosen part of the flashlamps driven at full power. If isolation switches are placed between the inductors and the common bus it would be possible to perform pulse shaping by switching the inductors into the flashlamps at different times. The only closing switches which currently are rated for this high current and coulomb duty without very high initial costs are explosive closing switches such as are used at CEM-UT in various power supplies. This is not currently being considered because of the need to achieve quick turnaround and low per shot costs. If there were some reason to perform this pulse shaping it could be done. Figure B-2 shows an example of the type of pulse shaping which could be performed using staged inductors. At the time this report was written there wasn't any significant reason to add high cost isolation switches to provide this pulse shaping.

The impedance for the distribution bus in the chosen system is higher than the first system. The increased buswork resistance increases the ohmic losses. The

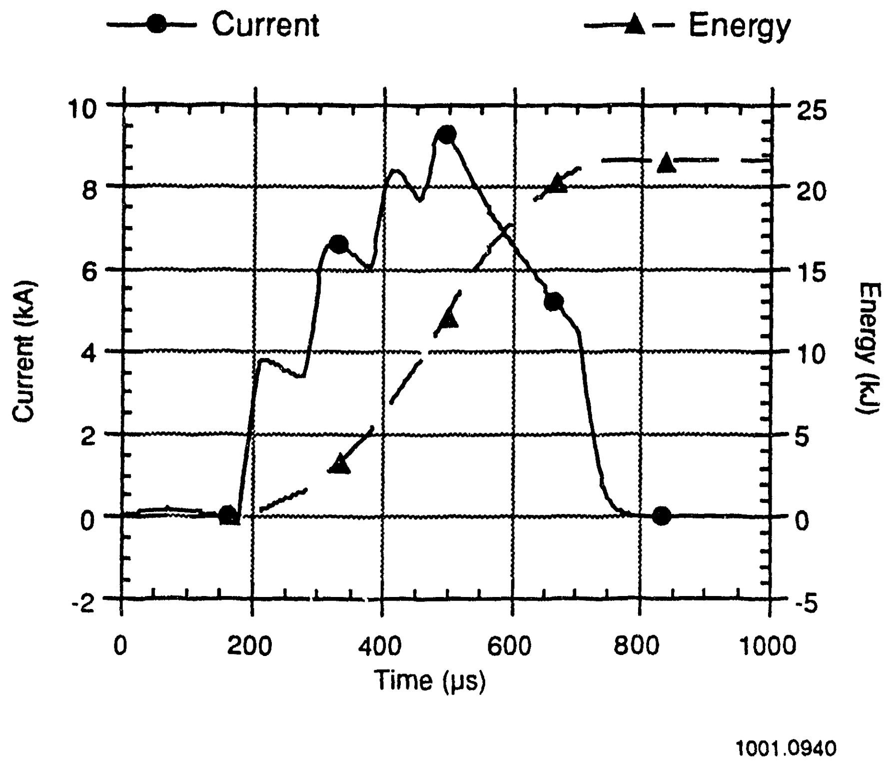

Figure B-2. Sample staged inductor pulse shaping increased buswork inductance increases energy absorbed by the opening switches. The increased buswork impedance has a positive effect in that it forces a more even current distribution from amplifier to amplifier regardless of individual amplifier impedance. The required initial magnetic energy for this system was 520 MJ.

B.2 Maximum Current per Opening Switch

The opening switches currently in use at CEM-UT have been tested at the 1.25 MA level for individual switch plates. Up to three of these switches have been opened simultaneously in parallel to divert 3.75 MA initial current from three inductors into a railgun experiment. These switches are used as part of the Balcones HPG and inductor power supply to power railgun experiments on a regular basis. As a result of this experience the initial plan was to use opening switches up to approximately 2 MA per opening switch. With the system designed for 70 MA system current this would imply around 35 opening switches and inductors. The costs for the containment vessels, inductors, and opening switches increase when building more smaller devices for the approximate size devices which we priced.

Switches similar to the ones in use on the Balcones power supply are currently being built by CEM-UT to open 5.6 MA of current from an inductive power supply. These switches are to be used on a battery power supply and have a time at peak current of seconds prior to opening which produces much more ohmic heating on the switch elements. The initial tests on this design have been favorable and no problems are expected.

As mentioned earlier when describing the design of the system in Section 3.0 the desired number of inductors per generator is six for magnetic containment reasons. This requires a switch which can handle 2.92 MA during charging and then opening. This is very close to using two of the current BHPG opening switches in parallel per inductor. Because of the success with the current switches and tests performed so far with even larger switches the risks associated with 2.9 MA opening switches seem minimal and so the system using 6 inductors per generator with 2.9 MA switches has been designed.

APPENDIX C

Detailed Cost Information

Task I. HPG Design

PROJECT: HPG DESIGN
DURATION: 10/94-12/95

	Oct-94	Nov-94	Dec-94	Jan-95	Feb-95	Mar-95	Apr-95	May-95	Jun-95	Jul-95	Aug-95	Sep-95	Oct-95	Nov-95
SALARIES AND WAGES	$49,987	$49,987	$49,987	$49,987	$49,987	$49,987	$46,491	$46,491	$40,837	$40,837	$40,837	$42,473	$42,473	$42,473
ENGINEERING														
PI	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
REA V PROJ ENGR	1	1	1	1	1	1	1	1	1	1	1	1	1	1
REA IV MAGNETIC ANAL	0.5	0.5	0.5	0.5	0.5	0.5	0	0	0	0	0	0	0	0
REA IV BEARINGS & AUX	1	1	1	1	1	1	1	1	1	1	1	1	1	1
REA IV DYNAMICS & STRESS	1	1	1	1	1	1	1	1	0	0	0	0	0	0
REA IV INSTRU. & CONTROL	1	1	1	1	1	1	1	1	1	1	1	1	1	1
REA III THERMAL ANAL	1	1	1	1	1	1	0	0	0	0	0	0	0	0
REA III CIRC. ANAL. & MOTORING SPE	1	1	1	1	1	1	0	0	0	0	0	0	0	0
REA II MANUF. FIXTURE DES	0	0	0	0	0	0	1	1	1	1	1	1	1	1
TECHNICIANS														
T1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OTHER														
DTA IV LAYOUT HPG & AUX	1	1	1	1	1	1	1	1	1	1	1	1	1	1
DTA IV LAYOUT I&C	1	1	1	1	1	1	1	1	1	1	1	1	1	1
DTA III DETAIL HPG	0	0	0	0	0	0	1	1	1	1	1	1	1	1
DTA III DETAIL AUX	0	0	0	0	0	0	1	1	1	1	1	1	1	1
DTA III DETAIL I&C	0	0	0	0	0	0	1	1	1	1	1	1	1	1
ADMIN	$7,981	$7,981	$7,981	$7,981	$7,981	$7,981	$7,423	$7,423	$6,520	$6,520	$6,520	$6,781	$6,781	$6,781
FRINGE BENEFITS	$13,346	$13,346	$13,346	$13,346	$13,346	$13,346	$12,413	$12,413	$10,904	$10,904	$10,904	$11,340	$11,340	$11,340
OPERATING EXPENSES	$4,499	$4,499	$4,499	$4,499	$4,499	$4,499	$4,219	$4,219	$3,767	$3,767	$3,767	$3,898	$3,898	$3,898
REPRO CLRNG	$2,999	$2,999	$2,999	$2,999	$2,999	$2,999	$2,789	$2,789	$2,450	$2,450	$2,450	$2,548	$2,548	$2,548
LAB CLRNG	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$930	$930	$817	$817	$817	$849	$849	$849
VAX CLRNG	$500	$500	$500	$500	$500	$500	$500	$500	$500	$500	$500	$500	$500	$500
MISC	$0	$0	$0	$0	$0	$0	$0	$0	$0					
COMPUTATION	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000
TRAVEL	$0	$0	$2,000	$0	$0	$2,000	$0	$0	$2,000	$0	$0	$2,000	$0	$0
MTDC	$68,832	$68,832	$70,832	$68,832	$68,832	$70,832	$64,123	$64,123	$58,508	$56,508	$56,508	$60,711	$58,711	$58,711
OVERHEAD	$33,728	$33,728	$34,708	$33,728	$33,728	$34,708	$31,420	$31,420	$28,669	$27,6[illegible]	$27,689	$29,749	$28,768	$28,768
EQUIP. SFAB.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
ACCT-1	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
ACCT-2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
ACCT-3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
ACCT-4	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
MONTH TOTAL SPENDING	$102,559	$102,559	$105,539	$102,559	$102,559	$105,539	$95,544	$95,544	$87,177	$84,197	$84,197	$90,459	$87,479	$87,479
CUMULATIVE SPENDING	$102,559	$205,119	$310,658	$413,218	$515,777	$621,317	$716,861	$812,404	$899,581	$983,777	$1,067,974	$1,158,433	$1,245,912	$1,333,391
BEGINNING BALANCE	$0													
NEW INCREMENT														
BALANCE NOW	($102,559)	($205,119)	($310,658)	($413,218)	($515,777)	($621,317)	($716,861)	($812,404)	($899,581)	($983,777)	($1,067,974)	($1,158,433)	($1,245,912)	($1,333,391)

Task II. HPG Manufacture

PROJECT:	HPG MANUF.
PERIOD:	10/1/95-12/31/97

	Oct-95	Nov-95	Dec-95	Jan-96	Feb-96	Mar-96	Apr-96	May-96	Jun-96	Jul-96	Aug-96	Sep-96	Oct-[illegible]
SALARIES AND WAGES	$29,424	$29,424	$29,424	$29,424	$29,424	$29,424	$29,424	$29,424	$30,726	$30,726	$30,726	$31,957	$31,95[illegible]
ENGINEERING													
PI	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.[illegible]
REA V PROJ ENGR	1	1	1	1	1	1	1	1	1	1	1	1	
REA III STATOR	1	1	1	1	1	1	1	1	1	1	1	1	
REA III ROTOR AND BEARINGS	1	1	1	1	1	1	1	1	1	1	1	1	
REA III I&C	1	1	1	1	1	1	1	1	1	1	1	1	
	0	0	0	0	0	0	0	0	0	0	0	0	
	0	0	0	0	0	0	0	0	0	0	0	0	
	0	0	0	0	0	0	0	0	0	0	0	0	
TECHNICIANS													
T1	0	0	0	0	0	0	0	0	0	0	0	0	
T2	0	0	0	0	0	0	0	0	0	0	0	0	
T3	0	0	0	0	0	0	0	0	0	0	0	0	
T4	0	0	0	0	0	0	0	0	0	0	0	0	
T5	0	0	0	0	0	0	0	0	0	0	0	0	
OTHER													
DTA III DOCUMENTATION	1	1	1	1	1	1	1	1	1	1	1	1	
O2	0	0	0	0	0	0	0	0	0	0	0	0	
O3	0	0	0	0	0	0	0	0	0	0	0	0	
ADMIN	$4,698	$4,698	$4,698	$4,698	$4,698	$4,698	$4,698	$4,698	$4,906	$4,906	$4,906	$5,102	$5,102
FRINGE BENEFITS	$7,856	$7,856	$7,856	$7,856	$7,856	$7,856	$7,856	$7,856	$8,204	$8,204	$8,204	$8,533	$8,533
OPERATING EXPENSES	$2,354	$2,354	$2,354	$2,354	$2,354	$2,354	$2,354	$2,354	$2,458	$2,458	$2,458	$2,557	$2,557
REPRO CLRING	$1,765	$1,765	$1 765	$1,765	$1,765	$1,765	$1,765	$1,765	$1,844	$1,844	$1,844	$1,917	$1,917
LAB CLRING	$588	$588	$588	$588	$588	$588	$588	$588	$615	$615	$615	$639	$639
VAX CLRING	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
MISC	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
COMPUTATION	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
TRAVEL	$1,000	$0	$0	$0	$0	$1,000	$0	$0	$0	$0	$1,000	$0	$0
MTDC	$40,635	$39,635	$39,635	$39,635	$39,635	$40,635	$39,635	$39,635	$41,388	$41,388	$42,388	$43,046	$43,046
OVERHEAD	$19,911	$19,421	$19,421	$19,421	$19,421	$19,911	$19,421	$19,421	$20,280	$20,280	$20,770	$21,093	$21,093
EQUIP. & FAB.	$697,834	$796,256	$836,035	$1,035,530	$1,086,562	$1,072,983	$869,088	$917,476	$909,990	$928,429	$886,769	$760,367	$782,578
MANUF. OF HPG STATOR #1	$157,416	$157,416	$157,416	$157,416	$157,416	$157,416	$0	$0	$0	$0	$0	$0	$0
MANUF. OF COMP. TURN HPG #1	$0	$31,503	$31,503	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
MANUF. OF ROTOR HPG#1	$71,396	$71,396	$71,396	$71,396	$71,396	$0	$0	$0	$0	$0	$0	$0	$0
MANUF. OF END PLATE & BRG HPG #1	$130,153	$130,153	$130,153	$130,153	$130,153	$0	$0	$0	$0	$0	$0	$0	$0
MANUF. OF FIELD COIL HPG #1	$39,833	$39,833	$39,833										
MANUF. OF BRUSH RING ASSEM. HPG #1	$57,164	$57,164	$57,164										
FINAL ASSEM. HPG#1						$146,876	$146,876	$146,876					
MANUF. & INSTALL I&C SYSTEM	$75,575	$75,575	$75,575	$75,575	$75,575	$75,575	$75,575	$75,575	$75,575	$75,575	$75,575	$75,575	$75,575
MANUF. OF BRG. SUPPLY HPG#1	$66,297	$66,297	$66,297	$66,297									
MANUF. OF MOTORING SYSTEM HPG #1		$58,157	$58,157	$58,157	$58,157								
MANUF. FIELD COIL POWER SUPPLY HPG #1				$46,478	$46,478	$46,478							
MANUF. OF BRUSH ACTUATION SYS HPG #1								$20,501	$20,501				
INSTALL AUXILIARIES					$38,581	$38,581	$38,581	$38,581	$38,581	$38,581	$38,581	$38,581	$38,581
INSTALL HPG#1									$42,660	$42,660			
TEST HPG #1										$26,640	$26,640		
MANUF. OF HPG STATOR #2-4				$166,676	$166,676	$166,676	$166,676	$166,676	$166,676	$166,676	$166,676	$166,676	$166,676
MANUF. OF COMP. TURN HPG #2-4					$15,752	$15,752	$15,752	$15,752	$15,752	$15,752	$15,752	$15,752	$15,752
MANUF. OF ROTOR HPG #2-4					$62,996	$62,996	$62,996	$62,996	$62,996	$62,996	$62,996	$62,996	$62,996
MANUF. OF END PLATE & BRG HPG #2-4				$114,841	$114,841	$114,841	$114,841	$114,841	$114,841	$114,841	$114,841	$114,841	$114,841
MANUF. OF FIELD COIL HPG #2-4						$23,900	$23,900	$23,900	$23,900	$23,900	$23,900	$23,900	[illegible]
MANUF. OF BRUSH RING ASSEM. HPG #2-4						$34,298	$34,298	$34,298	$34,298	$34,298	$34,298	$34,298	$34,298
FINAL ASSEM. HPG #2-4									$96,730	$96,730	$96,730	$96,730	$96,730
MANUF. OF BRG. SUPPLY HPG #2-4			$39,778	$39,778	$39,778	$39,778	$39,778	$39,778	$39,778	$39,778	$39,778	$39,778	$39,778
MANUF. OF MOTORING SYSTEM HPG #2-4						$41,052	$41,052	$41,052	$41,052	$41,052	$41,052	$41,052	$41,052
MANUF. FIELD COIL POWER SUPPLY HPG #2-4								$27,887	$27,887	$27,887	$27,887	$27,887	$27,887
MANUF. OF BRUSH ACTUATION SYS HPG #2-4										$12,301	$12,301	$12,301	$12,301
INSTALL HPG #2-4													$32,21[illegible]
FINAL SYSTEM TESTING AND ACCEPTANCE													
FIXTURES AND TOOLING		$108,762	$108,762	$108,762	$108,762	$108,762	$108,762	$108,762	$108,762	$108,762	$108,762		
MONTH TOTAL SPENDING	$658,380	$855,312	$895,090	$1,094,586	$1,145,618	$1,133,528	$928,144	$976,532	$971,658	$990,098	$948,928	$814,506	$846,717
CUMULATIVE SPENDING	$658,380	$1,513,692	$2,408,782	$3,503,368	$4,648,986	$5,782,514	$6,710,657	$7,687,189	$8,658,848	$9,648,946	$10,597,874	$11,412,379	$12,259,096
BEGINNING BALANCE	$0												
NEW INCREMENT													
BALANCE NOW	($658,380)	($1,513,692)	($2,408,782)	($3,503,368)	($4,648,986)	($5,782,514)	($6,710,657)	($7,687,189)	($8,658,848)	($9,648,946)	($10,597,874)	($11,412,379)	($12,259,096)

Nov-96	Dec-96	Jan-97	Feb-97	Mar-97	Apr-97	May-97	Jun-97	Jul-97	Aug-97	Sep-97	Oct-97	Nov-97	Dec-97
$31,957	$31,957	$31,957	$31,957	$31,957	$31,957	$31,957	$31,957	$21,209	$21,209	$22,057	$22,057	$22,057	$22,057
0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	0	0	0	0	0	0
1	1	1	1	1	1	1	1	0	0	0	0	0	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
$5,102	$5,102	$5,102	$5,102	$5,102	$5,102	$5,102	$5,102	$3,386	$3,386	$3,522	$3,522	$3,522	$3,522
$8,533	$8,533	$8,533	$8,533	$8,533	$8,533	$8,533	$8,533	$5,663	$5,663	$5,889	$5,889	$5,889	$5,889
$2,557	$2,557	$2,557	$2,557	$2,557	$2,557	$2,557	$2,557	$1,697	$1,697	$1,765	$1,765	$1,765	$1,765
$1,917	$1,917	$1,917	$1,917	$1,917	$1,917	$1,917	$1,917	$1,273	$1,273	$1,323	$1,323	$1,323	$1,323
$639	$639	$639	$639	$639	$639	$639	$639	$424	$424	$441	$441	$441	$441
$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
$0	$0	$0	$1,000	$0	$0	$0	$0	$1,000	$0	$0	$0	$0	$1,000
$43,046	$43,046	$43,046	$44,046	$43,046	$43,046	$43,046	$43,046	$29,568	$28,568	$29,711	$29,711	$29,711	$30,711
$21,093	$21,093	$21,093	$21,583	$21,093	$21,093	$21,093	$21,093	$14,489	$13,999	$14,559	$14,559	$14,559	$15,049
$782,578	$782,578	$782,578	$766,827	$766,827	$766,827	$754,526	$414,810	$255,084	$52,783	$52,783	$52,783	$52,783	$14,202
$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
$75,575	$75,575	$75,575	$75,575	$75,575	$75,575	$75,575	$75,575	$75,575					
$38,581	$38,581	$38,581	$38,581	$38,581	$38,581	$38,581	$38,581	$38,581	$38,581	$38,581	$38,581	$38,581	
$166,676	$166,676	$166,676	$166,676	$166,676	$166,676	$166,676							
$15,752	$15,752	$15,752											
$62,996	$62,996	$62,996	$62,996	$62,996	$62,996	$62,996	$62,996						
$114,841	$114,841	$114,841	$114,841	$114,841	$114,841	$114,841							
$23,900	$23,900	$23,900	$23,900	$23,900	$23,900	$23,900							
$34,298	$34,298	$34,298	$34,298	$34,298	$34,298	$34,298							
$96,730	$96,730	$96,730	$96,730	$96,730	$96,730	$96,730	$96,730						
$39,778	$39,778	$39,778	$39,778	$39,778	$39,778	$39,778	$39,778	$39,778					
$41,052	$41,052	$41,052	$41,052	$41,052	$41,052	$41,052	$41,052	$41,052					
$27,887	$27,887	$27,887	$27,887	$27,887	$27,887	$27,887	$27,887	$27,887					
$12,301	$12,301	$12,301	$12,301	$12,301	$12,301								
$32,211	$32,211	$32,211	$32,211	$32,211	$32,211	$32,211	$32,211	$32,211					
									$14,202	$14,202	$14,202	$14,202	$14,202
$846,717	$846,717	$846,717	$832,455	$830,965	$830,965	$818,664	$478,949	$299,141	$95,350	$97,053	$97,053	$97,053	$59,962
$13,105,813	$13,952,529	$14,799,246	$15,631,701	$16,462,666	$17,293,631	$18,'12,296	$18,591,245	$18,890,386	$18,985,736	$19,082,790	$19,179,843	$19,276,896	$19,336,858
($13,105,8'3)	($13,952,529)	($14,799,246)	($15,631,701)	($16,462,666)	($17,293,631)	($18,'12,296)	($18,591,245)	($18,890,386)	($18,985,736)	($19,082,790)	($19,179,843)	($19,276,896)	($19,336,858)

MANUF. OF END PLATE & BRG HPG #1			$650,767
LABOR:			
HRS	RATE/HR		
	1045	$75	$78,375
	6226	$45	$280,170
TOTAL LABOR			$358,545
PURCHASED PARTS:			
RAW MATERIAL:			
STEEL			$245,630
ALUMINUM BRONZE			$12,927
TOTAL RAW MATERIALS			$258,557
SUBCONTRACTED PARTS:			
RADIAL BRGS			$33,665
TOTAL SUBCONTRACTED PARTS			$33,665

MANUF. OF FIELD COIL HPG #1			$119,499
LABOR:			
HRS	RATE/HR		
	0	$75	$0
	1473	$45	$66,285
TOTAL LABOR			$66,285
PURCHASED PARTS:			
RAW MATERIAL:			
COPPER			$34,284
ALUMINUM			$5,275
FIBERGLASS			$5,275
EPOXY			$5,275
G-10			$2,637
TOTAL RAW MATERIALS			$52,745
SUBCONTRACTED PARTS:			
COATING			$469
TOTAL SUBCONTRACTED PARTS			$469

MANUF. OF BRUSH RING ASSEM. HPG #1			$171,492
LABOR:			
HRS	RATE/HR		
	0	$75	$0
	1164	$45	$52,380
TOTAL LABOR			$52,380
PURCHASED PARTS:			
RAW MATERIAL:			
COPPER			$19,266
G-10			$2,965
MISC. HARDWARE			$7,409
TOTAL RAW MATERIALS			$29,640
SUBCONTRACTED PARTS:			
BRUSH MACHINING			$35,789
COMP STRAP MACHINING			$53,683
TOTAL SUBCONTRACTED PARTS			$89,472

MANUF. OF END PLATE & BRG HPG #2-4			$1,952,302
LABOR:			
HRS	RATE/HR		
	3135	$75	$235,125
	18678	$45	$840,510
TOTAL LABOR			$1,075,635
PURCHASED PARTS:			
RAW MATERIAL:			
STEEL			$736,890
ALUMINUM BRONZE			$38,782
TOTAL RAW MATERIALS			$775,672
SUBCONTRACTED PARTS:			
RADIAL BRGS			$100,995
TOTAL SUBCONTRACTED PARTS			$100,995

MANUF. OF FIELD COIL HPG #2-4			$358,496
LABOR:			
HRS	RATE/HR		
	0	$75	$0
	4419	$45	$198,855
TOTAL LABOR			$198,855
PURCHASED PARTS:			
RAW MATERIAL:			
COPPER			$102,853
ALUMINUM			$15,824
FIBERGLASS			$15,824
EPOXY			$15,824
G-10			$7,912
TOTAL RAW MATERIALS			$158,235
SUBCONTRACTED PARTS:			
COATING			$1,406
TOTAL SUBCONTRACTED PARTS			$1,406

MANUF. OF BRUSH RING ASSEM. HPG #2-4			$514,476
LABOR:			
HRS	RATE/HR		
	0	$75	$0
	3492	$45	$157,140
TOTAL LABOR			$157,140
PURCHASED PARTS:			
RAW MATERIAL:			
COPPER			$57,799
G-10			$8,894
MISC. HARDWARE			$22,227
TOTAL RAW MATERIALS			$88,920
SUBCONTRACTED PARTS:			
BRUSH MACHINING			$107,366
COMP STRAP MACHINING			$161,050
TOTAL SUBCONTRACTED PARTS			$268,416

FINAL ASSEM. HPG#1			$440,629
LABOR:			
HRS	RATE/HR		
0	$75		$0
3883	$45		$174,735
TOTAL LABOR			$174,735
PURCHASED PARTS:			
RAW MATERIAL:			
STAINLESS STEEL			$16,388
EPOXY			$4,683
MISC. HARDWARE			$25,752
TOTAL RAW MATERIALS			$46,822
SUBCONTRACTED PARTS:			
MANIFOLDS			$138,314
MACHINING			$6,777
SHIPPING			$73,980
TOTAL SUBCONTRACTED PARTS			$219,071

FINAL ASSEM. HPG #2-4			$1,257,487
LABOR:			
HRS	RATE/HR		
0	$75		$0
11649	$45		$524,205
TOTAL LABOR			$524,205
PURCHASED PARTS:			
RAW MATERIAL:			
STAINLESS STEEL			$49,164
EPOXY			$14,048
MISC. HARDWARE			$18,797
TOTAL RAW MATERIALS			$82,009
SUBCONTRACTED PARTS:			
MANIFOLDS			$414,941
MACHINING			$20,332
SHIPPING			$216,000
TOTAL SUBCONTRACTED PARTS			$651,274

MANUF. & INSTALL I&C SYSTEM			$1,662,653
LABOR:			
HRS	RATE/HR		
0	$75		$0
15930	$45		$716,850
TOTAL LABOR			$716,850
PURCHASED PARTS:			
RAW MATERIAL:			
TOTAL RAW MATERIALS			$0
SUBCONTRACTED PARTS:			
I&C SYSTEM			$945,803
TOTAL SUBCONTRACTED PARTS			$945,803

MANUF. OF BRG. SUPPLY HPG#1			$265,188
LABOR:			
HRS	RATE/HR		
0	$75		$0
1703	$45		$76,635
TOTAL LABOR			$76,635
PURCHASED PARTS:			
RAW MATERIAL:			
ELECTRIC MOTOR & STARTER, DIESEL ENGINE PRIMARY & SECONDARY BEARING OIL PUMPS, RESERVOIR, HEAT EXCHANGER, FILTERS, VALVES, &MISC. EQUIPMENT			$169,698
STEEL			$18,855
TOTAL RAW MATERIALS			$188,553
SUBCONTRACTED PARTS:			
TOTAL SUBCONTRACTED PARTS			$0

MANUF. OF BRG. SUPPLY HPG #2-4			$795,564
LABOR:			
HRS	RATE/HR		
0	$75		$0
5109	$45		$229,905
TOTAL LABOR			$229,905
PURCHASED PARTS:			
RAW MATERIAL:			
ELECTRIC MOTOR & STARTER, DIESEL ENGINE. PRIMARY & SECONDARY BEARING OIL PUMPS, RESERVOIR, HEAT EXCHANGER, FILTERS, VALVES, &MISC. EQUIPMENT			$509,083
STEEL			$56,586
TOTAL RAW MATERIALS			$565,659
SUBCONTRACTED PARTS:			
TOTAL SUBCONTRACTED PARTS			$0

MANUF. OF MOTORING SYSTEM HPG #1			$232,626
LABOR:			
HRS	RATE/HR		
0	$75		$0
299	$45		$13,455
TOTAL LABOR			$13,455
PURCHASED PARTS:			
RAW MATERIAL:			
DC ELECTRIC MOTOR, MOTOR CONTROLLERS, PNEUMATIC CLUTCHES, COUPLINGS, AND MISC. HARDWARE			$197,254
STEEL			$21,917
TOTAL RAW MATERIALS			$219,171
SUBCONTRACTED PARTS:			
TOTAL SUBCONTRACTED PARTS			$0

MANUF. FIELD COIL POWER SUPPLY HPG #1			$139,435
LABOR:			
HRS	RATE/HR		
0	$75		$0
663	$45		$29,835
TOTAL LABOR			$29,835
PURCHASED PARTS:			
RAW MATERIAL:			
SCR POWER SUPPLY, FUSED MAUAL DISCONNECT & ELECTRIC SIGNAL CONDITIONING EQUIP. & GENERATOR FIELD COIL WIRING			$104,120
STEEL			$5,480
TOTAL RAW MATERIALS			$109,600
SUBCONTRACTED PARTS:			
TOTAL SUBCONTRACTED PARTS			$0

MANUF. OF BRUSH ACTUATION SYS HPG #1			$41,002
LABOR:			
HRS	RATE/HR		
0	$75		$0
387	$45		$17,415
TOTAL LABOR			$17,415
PURCHASED PARTS:			
RAW MATERIAL:			
ACCUMULATORS, FILTERS, REGULATORS, HIGH SPEED VALVES, PRESSURE SWITCHES, &TRANSDUCERS, ELECTRONIC SIGNAL CONDITIOI EQUIPMENT & MISC. EQUIPMENT			$20,048
STEEL			$3,539
TOTAL RAW MATERIALS			$23,587
SUBCONTRACTED PARTS:			
TOTAL SUBCONTRACTED PARTS			$0

MANUF. OF MOTORING SYSTEM HPG #2-4			$697,879
LABOR:			
HRS	RATE/HR		
0	$75		$0
897	$45		$40,365
TOTAL LABOR			$40,365
PURCHASED PARTS:			
RAW MATERIAL:			
DC ELECTRIC MOTOR, MOTOR CONTROLLERS, PNEUMATIC CLUTCHES, COUPLINGS, AND MISC. HARDWARE			$591,762
STEEL			$65,752
TOTAL RAW MATERIALS			$657,514
SUBCONTRACTED PARTS:			
TOTAL SUBCONTRACTED PARTS			$0

MANUF. FIELD COIL POWER SUPPLY HPG #2-4			$418,305
LABOR:			
HRS	RATE/HR		
0	$75		$0
1989	$45		$89,505
TOTAL LABOR			$89,505
PURCHASED PARTS:			
RAW MATERIAL:			
SCR POWER SUPPLY, FUSED MAUAL DISCONNECT & ELECTRIC SIGNAL CONDITIONING EQUIP. & GENERATOR FIELD COIL WIRING			$312,360
STEEL			$16,440
TOTAL RAW MATERIALS			$328,800
SUBCONTRACTED PARTS:			
TOTAL SUBCONTRACTED PARTS			$0

MANUF. OF BRUSH ACTUATION SYS HPG #2-4			$123,007
LABOR:			
HRS	RATE/HR		
0	$75		$0
1161	$45		$52,245
TOTAL LABOR			$52,245
PURCHASED PARTS:			
RAW MATERIAL:			
ACCUMULATORS, FILTERS, REGULATORS, HIGH SPEED VALVES, PRESSURE SWITCHES, &TRANSDUCERS, ELECTRONIC SIGNAL CONDITIONI EQUIPMENT & MISC. EQUIPMENT			$60,146
STEEL			$10,616
TOTAL RAW MATERIALS			$70,762
SUBCONTRACTED PARTS:			
TOTAL SUBCONTRACTED PARTS			$0

INSTALL AUXILIARIES $848,790

LABOR:

HRS	RATE/HR	
16275	$42	$683,550
3672	$45	$165,240
TOTAL LABOR		$848,790

PURCHASED PARTS:

RAW MATERIAL:

TOTAL RAW MATERIALS $0

SUBCONTRACTED PARTS:

TOTAL SUBCONTRACTED PARTS $0

INSTALL HPG#1 $85,320

LABOR:

HRS	RATE/HR	
1575	$42	$66,150
426	$45	$19,170
TOTAL LABOR		$85,320

PURCHASED PARTS:

RAW MATERIAL:

TOTAL RAW MATERIALS $0

SUBCONTRACTED PARTS:

TOTAL SUBCONTRACTED PARTS $0

TEST HPG #1 $53,280

LABOR:

HRS	RATE/HR	
0	$75	$0
1184	$45	$53,280
TOTAL LABOR		$53,280

PURCHASED PARTS:

RAW MATERIAL:

TOTAL RAW MATERIALS $0

SUBCONTRACTED PARTS:

TOTAL SUBCONTRACTED PARTS $0

INSTALL HPG #2-4 $322,110

LABOR:

HRS	RATE/HR	
6300	$42	$264,600
1278	$45	$57,510
TOTAL LABOR		$322,110

PURCHASED PARTS:

RAW MATERIAL:

TOTAL RAW MATERIALS $0

SUBCONTRACTED PARTS:

TOTAL SUBCONTRACTED PARTS $0

FINAL SYSTEM TESTING AND ACCEPTANCE $71,010

LABOR:

HRS	RATE/HR	
0	$75	$0
1578	$45	$71,010
TOTAL LABOR		$71,010

PURCHASED PARTS:

RAW MATERIAL:

TOTAL RAW MATERIALS $0

SUBCONTRACTED PARTS:

TOTAL SUBCONTRACTED PARTS $0

FIXTURES AND TOOLING $1,087,623

DESCRIPTION	QTY	TOTAL PRICE
1. BRUSH RING HOLDING FIXTURE (A)	2	$12,609
2. BEARING HOUSING HOLDING FIXTURE	2	$8,038
3. GRIT BLASTER FRAME	2	$45,169
4. BRUSH RING HOLDING FIXTURE (B)	2	$4,750
5. BRUSH RING FINAL MACHINING FIXTURE (N.T.E	2	$14,614
6. BRUSH RING FINAL MACHINING FIXTURE (T.E.)	2	$39,527
7. COMP TURN MACHINING FIXTURE (A)	2	$24,627
8. COMP TURN MACHINING FIXTURE (B)	2	$20,246
9. COMP TURN ISOLATOR MACHINING FIXTURE	2	$12,345
10. ROTOR VERICAL SUPPORT	2	$5,165
11. FIELD COIL WRAP MANDRIL	2	$8,485
12. STATOR END CAP ROUGH MACHINE FIXTURE	2	$5,250
13. ROTOR SHIPPING CRATE & SKID	4	$30,419
14. POTTING TANK (WELD)	2	$5,823
15. POTTING TANK (MACHINE)	2	$3,659
16. FIELD COIL POTTING SUPPORT FIXTURE	2	$7,424
17. STATOR SUPPORT WELDMENT FIXTURE	2	$18,338
18. STATOR SUPPORT, MACHINE FIXTURE	2	$23,088
19. PEDISTAL, WELDING FIXTURE	2	$13,055
20. SKID WELDING FIXTURE	2	$18,337
21. VERTICAL STAND WELDING FIXTURE	2	$17,488
22. BUSBAR FIXTURE A	2	$2,323
23. BUSBAR FIXTURE B	2	$3,838
24. BUSBAR BENDING DIES	2	$19,048
25. END PLATES INSPECTION FIXTURE	2	$23,936
26. LOWER PLATE WELDING FIXTURE	2	$14,486
27. UPPER PLATE WELDING FIXTURE	2	$10,127
28. STATOR SUPPORT WELDMENT FIXTURE	2	$17,711
29. COMP TURN EPOXY FIXTURE-TAB BOTTOM	2	$29,462
30. COMP TURN EPOXY FIXTURE-TAB TOP	2	$26,884
31. COMP TURN EPOXY FIXTURE-CENTRAL TOP	2	$6,320
32. COMP TURN A FIXTURE-CENTRAL BOTTOM	2	$15,060
33. FIELD COIL MACHINE FIXTURE	2	$46,749
34. END CAP ALIGNMENT FIXTURE	2	$11,475
35. COMP TURN FIXTURE I.D.	2	$24,170
36. FLIP STAND FIXTURE	4	$90,784
37. FIELD COIL LEVELING BLOCKS	24	$29,843
38. STATOR SUPPORT WELDMENT FIXTURE	9	$152,974
39. SPIDER EPOXY HANDLING FIXTURE	2	$16,831
40. BUS BAR ASSEMBLY DRILLING FIXTURE	2	$19,449
41. SPECIAL TOOLING		$187,697

Task III. Pulsed Power Design

PROJECT: P.P. DESIGN PERIOD: 10/1/94-5/1/95	Dec-94	Jan-95	Feb-95	Mar-95	Apr-95	May-95
SALARIES AND WAGES	$29,909	$29,909	$29,909	$29,909	$29,909	$29,909
ENGINEERING						
PI	0.1	0.1	0.1	0.1	0.1	0.1
REA V PROJ. ENGR.	1	1	1	1	1	1
REA IV INDUCTOR & CHRG. BUS	1	1	1	1	1	1
REA III OPENING SWITCHES	1	1	1	1	1	1
REA III DISTRIBUTION	1	1	1	1	1	1
	0	0	0	0	0	0
TECHNICIANS						
	0	0	0	0	0	0
OTHER						
DTA IV SYSTEM LAYOUTS	1	1	1	1	1	1
DTA III DETAIL	1	1	1	1	1	1
ADMIN	$4,775	$4,775	$4,775	$4,775	$4,775	$4,775
FRINGE BENEFITS	$7,986	$7,986	$7,986	$7,986	$7,986	$7,986
OPERATING EXPENSES	$2,893	$2,893	$2,893	$2,893	$2,893	$2,893
REPRO CLRNG	$1,795	$1,795	$1,795	$1,795	$1,795	$1,795
LAB CLRNG	$598	$598	$598	$598	$598	$598
VAX CLRNG	$500	$500	$500	$500	$500	$500
MISC	$0	$0	$0	$0	$0	$0
COMPUTATION	$0	$0	$0	$0	$0	$0
TRAVEL	$0	$0	$1,000	$0	$0	$1,000
MTDC	$40,787	$40,787	$41,787	$40,787	$40,787	$41,787
OVERHEAD	$19,986	$19,986	$20,476	$19,986	$19,986	$20,476
EQUIP. &FAB.	$0	$0	$0	$0	$0	$0
ACCT-1	$0	$0	$0	$0	$0	$0
ACCT-2	$0	$0	$0	$0	$0	$0
ACCT-3	$0	$0	$0	$0	$0	$0
ACCT-4	$0	$0	$0	$0	$0	$0
SUBCONTRACT					$25,000	
SUBCONTRACT OVERHEAD					$11,500	
MONTH TOTAL SPENDING	$60,773	$60,773	$62,263	$60,773	$97,273	$62,263
CUMULATIVE SPENDING	$60,773	$121,546	$183,809	$244,582	$341,855	$404,118
BEGINNING BALANCE						
NEW INCREMENT						
BALANCE NOW	($60,773)	($121,546)	($183,809)	($244,582)	($341,855)	($404,118)

Task IV. Pulsed Power Manufacture

PROJECT:	P.P. MANUF.
PERIOD:	6/1/95-5/1/96

	Jun-95	Jul-95	Aug-95	Sep-95	Oct-95	Nov-95	Dec-95	Jan-96	Feb-96	Mar-96	Apr-96	May-96
SALARIES AND WAGES	$27,745	$27,745	$27,745	$28,856	$28,856	$28,856	$26,337	$26,337	$26,337	$26,337	$26,337	$26,337
ENGINEERING												
PI	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
REA V PROJ. ENGR. (OPEN SW.)	1	1	1	1	1	1	1	1	1	1	1	1
REA III CHARGING BUS	1	1	1	1	1	1	1	1	1	1	1	1
REA II MANUF. FIXTURE DES.	1	1	1	1	1	1	0	0	0	0	0	0
TECHNICIANS												
TSA V FIRING BOXES	1	1	1	1	1	1	0	0	0	0	0	0
TSA III CONTAINMENT ASSEM.	1	1	1	1	1	1	1	1	1	1	1	1
TSA II CONTAINMENT ASSEM.	1	1	1	1	1	1	1	1	1	1	1	1
TSA II BUSSWORK	0	0	0	0	0	0	1	1	1	1	1	1
TSA III DISTRIBUTION	0	0	0	0	0	0	1	1	1	1	1	1
TSA II DISTRIBUTION	0	0	0	0	0	0	1	1	1	1	1	1
OTHER												
DTA III DOCUMENTATION	1	1	1	1	1	1	1	1	1	1	1	1
ADMIN	$4,430	$4,430	$4,430	$4,607	$4,607	$4,607	$4,205	$4,205	$4,205	$4,205	$4,205	$4,205
FRINGE BENEFITS	$7,408	$7,408	$7,408	$7,705	$7,705	$7,705	$7,032	$7,032	$7,032	$7,032	$7,032	$7,032
OPERATING EXPENSES	$2,720	$2,720	$2,720	$2,809	$2,809	$2,809	$2,607	$2,607	$2,607	$2,607	$2,607	$2,607
REPRO CLRNG	$1,665	$1,665	$1,665	$1,731	$1,731	$1,731	$1,580	$1,580	$1,580	$1,580	$1,580	$1,580
LAB CLRNG	$555	$555	$555	$577	$577	$577	$527	$527	$527	$527	$527	$527
VAX CLRNG	$500	$500	$500	$500	$500	$500	$500	$500	$500	$500	$500	$500
MISC	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
COMPUTATION	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
TRAVEL	$1,000	$0	$0	$0	$1,000	$0	$0	$1,000	$0		$0	$1,000
MTDC	$38,872	$37,872	$37,872	$39,369	$40,369	$39,369	$35,976	$36,976	$35,976	$35,976	$35,976	$36,976
OVERHEAD	$19,047	$18,557	$18,557	$19,291	$19,781	$19,291	$17,628	$18,118				
EQUIP. &FAB.	$458,031	$458,031	$458,031	$458,031	$458,031	$458,031	$444,769	$444,769	$422,742	$422,742	$422,742	$422,742
OPENING SWITCH	$22,027	$22,027	$22,027	$22,027	$22,027	$22,027	$22,027	$22,027	$0	$0	$0	$0
ABORT SWITCH AND RESISTOR	$13,263	$13,263	$13,263	$13,263	$13,263	$13,263	$0	$0	$0	$0	$0	$0
FIRING SETS	$12,182	$12,182	$12,182	$12,182	$12,182	$12,182	$12,182	$12,182	$12,182	$12,182	$12,182	$12,182
CONTAINMENT VESSEL	$68,432	$68,432	$68,432	$68,432	$68,432	$68,432	$68,432	$68,432	$68,432	$68,432	$68,432	$68,432
CHARGING BUS AND SUP. STRUCTURE	$56,963	$56,963	$56,963	$56,963	$56,963	$56,963	$56,963	$56,963	$56,963	$56,963	$56,963	$56,963
INDUCTORS	$114,121	$114,121	$114,121	$114,121	$114,121	$114,121	$114,121	$114,121	$114,121	$114,121	$114,121	$114,121
DISTRIBUTION BUSWORK AND CABLES	$171,043	$171,043	$171,043	$171,043	$171,043	$171,043	$171,043	$171,043	$171,043	$171,043	$171,043	$171,043
MONTH TOTAL SPENDING	$515,951	$514,461	$514,461	$516,692	$518,182	$516,692	$498,373	$499,863	$458,718	$458,718	$458,718	$459,718
CUMULATIVE SPENDING	$515,951	$1,030,412	$1,544,873	$2,061,564	$2,579,746	$3,096,438	$3,594,811	$4,094,673	$4,553,391	$5,012,109	$5,470,827	$5,930,545
BEGINNING BALANCE	$0											
NEW INCREMENT												
BALANCE NOW	($515,951)	($1,030,412)	($1,544,873)	($2,061,564)	($2,579,746)	($3,096,438)	($3,594,811)	($4,094,673)	($4,553,391)	($5,012,109)	($5,470,827)	($5,930,545)

OPENING SWITCH $176,214

LABOR:			
HRS	RATE/HR		
612	$35		$21,420
TOTAL LABOR			$21,420

PURCHASED PARTS:	CODE	
HYDRAULIC PUMPS	VO	$32,400
HYDRAULIC RAMS	VO	$75,600
HOSES, FITTINGS, VALVES	VO	$13,200
TENSIONING RODS	FO	$4,644
CONTACT PLATES	FO	$3,132
FOUNDATION PLATE	VO/S	$11,376
SWITCH BASE	VO/S	$2,832
DET. BOLTS	PO/RA	$144
TOTAL PARTS		$154,794

FIRING SETS $146,189

LABOR:			
HRS	RATE/HR		
			$0
TOTAL LABOR			$0

PURCHASED PARTS:	CODE	
FIRING BOX ENCL	PO/RA	31,800
REYNOLDS FS-10 & MODS	PO/RA	$50,400
CONTROLLER CARD	PO/RA	$7,200
LI BATTERIES	PO/RA	$12,600
F.O. INTERFACE CARD	PO/RA	$14,400
30 KV CABLES		$43,200
TOTAL PARTS		$139,968
SUBCONTRACTED PARTS:		
CIRCUIT BOARD PRINTING	PO/RA	$5,760
TOTAL SUBCONTRACTED PARTS		$6,221

ABORT SWITCH AND RESISTOR $79,576

LABOR:			
HRS	RATE/HR		
494	$35		$17,290
TOTAL LABOR			$17,290

PURCHASED PARTS:	CODE	
INNER CATCH RING	PO/F	$2,256
OUTER CATCH RING	PO/F	$4,512
CARTRIDGE RING	PO/F	$624
DETONATOR RING	PO/F	$2,640
DET. BOLTS	PO/F	$240
ABORT RESISTOR:		
1/4" STAINLESS PLATE	FO	$29,000
G-10	VPL	$14,400
CLAMPS	FO	$4,000
TOTAL PARTS		$62,286

CONTAINMENT VESSEL $821,188

LABOR:			
HRS	RATE/HR		
2688	$35		$94,080
TOTAL LABOR			$94,080

PURCHASED PARTS:	CODE	
END CAPS	WO/S	$165,360
TOP CYLINDER	WO/S	$163,440
BOTTOM CYLINDER	WO/S	$34,320
WELD CAPS TO CYLINDER	WO/S	$152,160
FLANGE	WO/S	$68,976
FLANGE QUICK RELEASE	WO/S	$240,000
FOUNDATION PLATE	VO/S	$11,376
SWITCH BASE	PO/RA	$2,832
DET. BOLTS		$144
TOTAL PARTS		$727,108

CHARGING BUS AND SUP. STRUCTURE			$683,557
LABOR:			
HRS	RATE/HR		
5184	$35		$181,440
TOTAL LABOR			$181,440
PURCHASED PARTS:		CODE	
UPPER BUS		VO/S	$128,592
LOWER BUS		VO/S	$167,184
SWITCH PADS		VO	$8,592
INSULATION		VO	$4,080
BUS URETHANE COATING		PO/RA	$54,000
BUS HARDWARE		PO/RA	$70,875
CATWALK 750 SQ.FT.		PO/RA	$15,000
LADDERS		PO/RA	$400
SUPPORTS		PO/RA	$10,800
SUPPORT TIEDOWN		PO/RA	$5,400
TOTAL PARTS			$502,117

INDUCTORS			$1,359,452
LABOR:			
HRS	RATE/HR		
1536	$60		$92,160
22320	$35		$781,200
TOTAL LABOR			$873,360
PURCHASED PARTS:		CODE	
ALUMINUM		PO	$202,896
NOMEX		PO	$72,000
POLYURETHANE		PO	$8,448
S-GLASS OVERWRAP		PO	$96,000
CONNECTING BUS		PO	$80,000
TOTAL PARTS			$486,092

DISTRIBUTION BUSWORK AND CABLES			$2,052,516
LABOR:			
HRS	RATE/HR		
236	$75		$17,700
TOTAL LABOR			$17,700
PURCHASED PARTS:		CODE	
COMMON COAX:			
RING CASTINGS		PO	$20,420
URETHANE INSULATION		PO	$1,900
HEXAPOLAR CABLE		PO	$1,545,300
IMPEDANCE MATCHING BUSWORK:			
1/2" STAINLESS PLATE		PO	$16,913
1/2" G-10 PLATE		VPL	$8,640
ALUMINUM CLAMPS		PO	$22,320
CONTACT BOLTS		EE	$3,888
CLAMP BOLTS		PO	$11,088
URETHANE		PO	$25,920
MISC. HARDWARE		EE	$7,200
CONNECTORS		WO	$220,500
TOTAL PARTS:			$2,034,816

APPENDIX D

A Review of the Developmental and Operational History of the 10 Megajoule Disk-Type Homopolar Generator at The University of Texas at Austin

A REVIEW OF THE DEVELOPMENTAL AND OPERATIONAL HISTORY OF THE 10 MEGAJOULE DISK-TYPE HOMOPOLAR GENERATOR AT THE UNIVERSITY OF TEXAS AT AUSTIN

Introduction

The Energy Storage Group (chartered as the Center for Electromechanics in 1977) at The University of Texas at Austin began development of homopolar machines with energy storage rotors in the early 1970's. A 5.0 MJ, self motored, disk-type homopolar generator (HPG) was designed, built and tested in 1974 as a proof of principle test to demonstrate inertial energy storage as a pulsed power supply for fusion devices. This device surpassed its design goals and served as the test stand for most of the designs and componentry used in state-of-the-art pulsed iron core devices today. Furthermore, being rugged and reliable, the 5 MJ HPG (upgraded to 10 MJ in 1980) has served as the power supply for more than two dozen funded research projects in various applications of pulsed power. This device has developed several significant technologies, including homopolar pulsed welding (HPW) and single residency homopolar pulsed consolidation (HPC) of powder metallurgy parts. Approximately 18 advanced degrees have been granted for research on or with this device. Today the 10 MJ HPG, equipped with a flexible fixturing system capable of handling a wide range of experimental loads, remains in service. With more than 2,000 discharges for funded experiments, the 10 MJ at CEM-UT is the most active homopolar generator in the free world.

Development History

Proof of Principle Device-1974

Based on experiments with a 0.5 MJ device, the original 5.0 MJ homopolar motor-generator was designed, built, and commissioned in 1974 with funding from the Atomic Energy Commission, the Texas Atomic Energy Research Foundation, and the Electric Power Research Institute.[1] Design goals for this demonstrator included 42 V open circuit, and 150,000 A peak current capability. Significant aspects of the design included high stiffness orifice compensated hydrostatic journal and thrust bearings and a configurable sliding contact system that allowed self-motoring of the device with part of the armature brush system. Conventional dc commutator contact material was used for the brushes.

Because the internal impedance of the machine proved to be far lower than predicted, and because the brushes proved capable of peak current densities far higher than similar brushes in commutation duty, this device repeatably generated current pulses as high as 560,000 A. The 5.0 MJ continued to serve as a verification experiment and as a power supply for early welding experiments until 1977, with more than 260 discharges.

Componentry Upgrade-1977

The 5.0 MJ was relocated and rebuilt in 1977 with an improved sliding contact design and a lower impedance busbar system. Experience with the original hydrostatic bearings indicated their susceptibility to fringing magnetic fields--these bearings were redesigned to be magnetically and electrically isolated from the stator assembly.[2]

Several important research programs were undertaken during this period, including development of an air core HPG excited by pulsed discharge of the 5.0 MJ,[3] and development of resistance welding by HPG discharge.[4] The generator operated reliably for the following three years, during which period more than 385 discharges were performed for funded experiments.

Rotor Upgrade-1981

The need for enhanced energy storage and peak current capability for large cross-section joints by homopolar pulsed welding resulted in a funded project to rebuild the 5.0 MJ as a 10.0 MJ HPG in 1980.[5] Numerous design improvements were required to enable the doubling of the generator's energy density (the original stator and bearing assemblies were retained). A high amp-turn, cooled field coil and a compensated, trailing arm brush system were designed for minimum radial profile, thus permiting a rotor of larger mass moment of inertia. A copper alloy shaft was used to improve the internal impedance, and an improved busbar system was incorporated. A hydrostatic drive hydraulic motoring system was designed, thus greatly improving brush life and reducing motoring times.

Numerous major research programs were funded on the 10 MJ HPG in the following four years of operation. The generator was coupled to a cryogenic energy storage inductor for developmental testing of electromagnetic guns and related hardware. Several welding and pulsed heating projects were undertaken, culminating in a program to join large cross section high strength steel line pipe. In-house experiments demonstrated that powder metallurgy parts could be consolidated directly by HPG discharge--these initial tests led to two phased, multi-year research efforts in homopolar pulsed consolidation. The 10.0 MJ HPG, although designed for peak current duty of 750 kA, successfully generated more than 1.0 MA from a discharge speed of 5,000 rpm twice during this phase. From 1981 to 1985, more than 645 funded discharges were performed by the 10 MJ HPG.

Rebrush and Refit-1986

The 10 MJ was disassembled and moved in 1985 to accommodate the transfer of CEM-UT to new laboratories. Although the majority of the sliding contacts showed nominal wear, it was decided to replace all brushes in conjunction with improvements to the control and motoring systems. The hydrostatic bearings were inspected and cleaned, but were determined to be in like new condition after some 1300 operations. A complete experimental system was erected around the reassembled 10 MJ, including two hydraulic fixtures for coupling to resistive loads, and two stations dedicated for testing prototype designs at very high coulomb transfer rates or electromagnetic loading.

From recommissioning to present, the 10 MJ HPG continues to serve as a power supply for projects in homopolar pulsed welding and consolidation. Because these efforts mainly involve processing of novel materials such as intermetallics, high T_c superconductors, superalloys and other specialty items, the generator is mainly required to perform at approximately half its energy and current capabilities. In this duty, the generator is expected to last indefinitely, with only preventive maintenance required. Operating at rates as high as 12 discharges per shift, the 10 MJ has delivered approximately 730 discharges since the 1986 rebrush, for a cumulative history of more than 2,000 funded experiments.

Research History

The 10 MJ HPG has served as a test stand for developing pulsed hardware, verifying transient circuit and magnetic codes, and improving generator designs throughout its operational history at CEM-UT. In addition, however, the generator has been offered to government agencies, public foundations, and corporations as a high power, high current power supply for funded research in many applications of pulsed power. Table D-1 summarizes these research contracts, describing the research and showing funded amounts and dates.

Table D-1. Summary of funded research utilizing the CEM-UT 10 MJ HPG

Sponsor	Project Description	Funded Amount	Year Funded
ASTEC	HPW of 2-in sch 40 A-106-B Pipe	19,300	1976
ERDA/DOE	Fast Discharge HPG	340,000	1977
NSF	HPW of Various Alloys	356,700	1977
EPRI	HPW of 4-in sch 40 304SS Pipe	47,000	1978
OTIS	Hot Forge Upsetting of Drill Tube	6,300	1979
NSF	HPW of Rail, Vehicle Components	364,900	1979
NSF	Pulsed Heating of Various Alloys	90,200	1979
INT'L. HRVSTR.	HPW of Power Trans. Compns...	9,200	1979
SANDIA NL	HPW of 304L SS, Various Treats	58,000	1982
NASA LEWIS	Repetitive Opening Sw. Testing	108,000	1982
GD	Single Shot EM Gun Tests	168,329	1982
OIME	HPW of 6-in X-60 Line Pipe	94,000	1983
ATC	HPW of HSLA Steel Pipe	40,100	1983
GD	Multiple Shot EM Gun Tests	114,000	1984
GM-AC	HPW of 409 SS Projected Seam	10,000	1984
DARPA/NADC	Pulsed Power Processing of Mat'ls.	134,700	1984
DARPA/ARO	HPC of Various PM Materials	266,200	1987
ALCOA	Pulsed Heating of Specialty Alloys	25,000	1987
GE-AEBG	HPW of Specialty Alloys	44,000	1987
GD-FW	Advanced Joining Techniques	18,000	1988
TEXAS-ATP	Advanced Current Collectors	60,000	1988
GD-FW	HPW of Dissimilar Composites	31,300	1988
PKD/RCKWLL.	HPW of Specialty Parts	14,800	1989
NSF-OTRC	HPW for Offshore Technology	83,000	1989

References for Appendix D

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