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"DESIGN, MANUFACTURE, TEST AND
DELIVERY OF A 230 KV EXTRUDED
IRRADIATED CROSSLINKED POLYETHYLENE CABLE"

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FOREWORD

The original contract period of performance was 54 months. In September, 1977, Reynolds asked for an early termination of the contract, necessitated by the closing of the Chester cable plant. It had been intended to manufacture and test the 138/230 kV cable at the Chester facility. The U.S. Department of Energy agreed to reduce the scope of the contract to a point which would indicate the feasibility of continuing the work with another prime contractor.

ABSTRACT

A project has been initiated to develop a 230 kV solid dielectric cable for use in underground transmission. The dielectric is to be polyethylene, crosslinked by electron bombardment. Compared to the more conventional chemically crosslinked polyethylene, the irradiated cable is expected to contain less sensitive defects and thus be more suitable for a 230 kV rating.

A toroidally shaped diode has been developed with the capability of providing a uniform radiation dose to a thick-walled coaxial cable. The diode is to receive an output wave form obtained by ringing a Marx generator into a peaking capacitor.

Initial evaluation of the toroidal diode was performed on thin plaques and tapes of insulating and semi-conducting polyethylene polymers. Additionally, some miscellaneous ethylene plastics were briefly investigated. While the major thrust of the project to date has been the design of the irradiator, particular attention was given to polymer response to dose, the intent being to select component compounds to be used in the 138/230 kV prototype cables.

Using a 4.8MV Van de Graaff pulse generator in conjunction with several diode configurations, 15-35 kV extruded HMW-PE cables were irradiated. Various techniques in addition to diode modifications were tried in an effort to improve response to radiation. Dose rate, temperature, and pressure effects were evaluated. It was found that with limited dose rate it was possible to produce excellent crosslink density and uniformity at room temperature and atmospheric pressure. A subsequent 60 Hz voltage endurance test on an irradiated cable sample indicated it had long term, high stress capability.

ABSTRACT (cont'd.)

Part II of this report presents an engineering study conducted to determine an acceptable irradiator system design. It has been estimated that a 7 MV peak voltage at a rate of 2-3 pulse/sec can be provided by a Marx generator/peaking capacitor and should be capable of crosslinking a polyethylene wall thickness of approximately 2.5 cm.

Based on the accumulated test results and on the performance of the 7 MV irradiator predicted in this report, it appears feasible to continue the work effort into the next scheduled phase. This would involve construction of a full scale system to evaluate two levels of high voltage cable. The first level would correspond to a machine output of 5 MV; the machine would thus be operated at reduced output to test its capability before preceeding to the second level of 7 MV. At 100% output, it is expected that a 230 kV high-purity crosslinked polyethylene cable will be produced.

PART I
CONTENTS

1.	<u>Background and Preliminary Considerations</u>	<u>Page</u>
1.0	Summary of Section 1	1
1.1	Introduction	2
1.1.1	Chemical XLPE	3
1.1.2	Irradiated XLPE	4
1.2	Preliminary Considerations	8
1.2.1	Irradiator Program	8
1.2.2	Safety	12
	Radiation Shield	12
	Ozone Production	13
1.2.3	Irradiation System Design	14
	Marx Generator	14
	Peaking Capacitor	15
	Vacuum Diode	15
	Bushing	16
	Tank	16
1.2.4	Machine Processing Parameters	17
	Operating Voltage	17
	Operating Power	20
1.2.5	Auxiliary Effects of Irradiation	21
	Temperature Rise	22
	Gas Evolution	24
	Charge Collection	25

2.	<u>Demonstrate Feasibility of 360 Degree Diode</u>	<u>Page</u>
2.0	Summary of Section 2	27
2.1	Introduction	28
2.2	Construct 360 Degree Diode	30
	Window Design	31
	Cathode and Vacuum Housing	35
2.3	Measure Dose Uniformity at 300 kV	35
	Depth-Dose Profile and Energy Transfer as a Function of	
	Cable Diameter	36
	Measurements of Charge Transfer	38
	Circumferential Uniformity	40
3.	<u>Evaluation of Potential Cable Polymers with a 300 kV Generator (PEBS I)</u>	
3.0	Summary of Section 3	44
3.1	Introduction	45
3.2	Crosslink Density Measurement	47
3.3	Dosimetry	48
3.4	Dosimetry Mode I	51
3.5	Dosimetry Mode II	52
3.6	Dosimetry Mode III	53
3.7	Irradiation Mode I	55
3.8	Irradiation Mode II	56
3.9	Irradiation Mode III	58
3.10	Evaluation of Insulating Polyethylenes	59
3.11	Evaluation of Miscellaneous Insulating Polymers	70
3.12	Evaluation of Semi-Conducting Copolymers	73

4.	<u>Irradiation of Model Cables</u>	Page
4.0	Summary of Section 4	79
4.1	Early Work	80
4.2	Attempts to Prevent Tree Formation	82
4.2.1	Preheating of Cables	89
4.2.2	Application of Positive Voltage to Conductor	93
4.2.3	Reduction of Dose per Pulse	95
4.2.4	Effects of Shorting Line	100
4.2.5	Experiments of Thin Walled Cables	106
4.2.6	Results of Pulsing Frozen Cables	108
4.2.7	Anti-Treeing Compounds	117
4.3	Pulse Clipping with Gas Insulation	125
4.4	Solvent Extraction Tests on Cable	126
4.5	Summary of Findings	129
5.	<u>References</u>	138i

APPENDICES IN PART II

<u>Appendix A:</u>	Blue Cellophane Calibration Data Calorimetric Verification of Blue Cellophane	353
<u>Appendix B:</u>	Calculation of Charging Circuit Efficiencies Alternate Charging Circuits	362
<u>Appendix C:</u>	Selection of Isolation Component Values	389
<u>Appendix D:</u>	Energy Dissipated in a Faulted Capacitor	399

LIST OF FIGURES
PART I

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
1	Cable Crosslinking Machine	9
2	Typical Dose Profiles in Arbitrary Units	18
3	Schematic of Diode and Window for 300 kV Machine	32
4	Depth Dose Profile Measured for 0.68 and 1.25-Inch Cylinders	37
5	Typical Current Measurement of Marx	39
6	Longitudinal Dose Uniformity	43
7	Determination of Mean Dose	50
8	Calibration Curve for MSC 300 Cellophane	52
9	Dosimetry Mode III for Pulled Mandrel	54
10	Specimen Preparation	57
11	Mean Dose vs. Solvent Extraction for Insulating and Conducting Polymers	64
12	Elongation vs. Dose and Solvent Extractions vs. Dose for Semi-conducting PE 6736	74
13	Typical Appearance of Trees and Bubbles in RG17 A/U Cable	88
14	Cable Sample Looped Through the Diode and Current Transformer	90
15	Cathode Configurations Tested	99
16	Depth Dose Profile for 11-Inch Diameter Perforated Metal Cathode	113
17	Depth Dose Profile Measured on Irradiated No. 187	123
18	Power Cable Sampling for Solvent Extraction	127
19a	Enlarged Photo of Dissection of Test #223 from Irradiated Zone	129a
19b	Enlarged Photo of Dissection of Test #223 from Non-Irradiated Zone	129b

TABLES

<u>TABLE</u>	<u>TITLE</u>	<u>PAGE</u>
Ia	Physical Properties of Insulating Polyethylenes	62
Ib	Physical Properties of Irradiated Crosslinked PE	63
II	Insulating PE, Dose vs. Solvent Extraction	65
III	Misc. Insulating EPR - Dose vs. Solvent Extraction	71
IV	Semi-conducting Polyethylene - Dose vs. Solvent Extraction	76
V	Volume Resistivity of Irradiation Semi-conducting Polyethylene	78
VI	Dimensions of Transmission Line RG Wire	83
VII a-h	Series of Tables Showing Radiation Effect on RG Wire and Power Cable	86
VIII	Summary of Cable Tests Comparing Dose and Solvent Extraction, 15-35 kV Cable	130
IX	Power Cable Descriptions - 15 - 35 kV Cable	137

SECTION 1

BACKGROUND AND PRELIMINARY CONSIDERATIONS

1.0 Summary of Section 1

A project has been initiated to develop a 230 kV solid dielectric cable for use in underground transmission. The dielectric will be polyethylene, crosslinked by electron bombardment. Compared to the more conventional, chemically crosslinked polyethylene, the irradiated cable will contain less stress sensitive defects and thus be more suitable for a 230 kV rating. The major problems to overcome are temperature rise, gas evolution, and charge collection within the dielectric, as a consequence of radiation crosslinking. Safety measures for radiation environments, similar to the type proposed, are well developed and personnel protection has been reduced to standard industrial safety procedures. The system proposed to accomplish crosslinking of a 230 kV rated cable by irradiation consists of a 7 MeV electron beam accelerator and torroidal irradiator. The latter has been designed to provide uniform, 360° irradiation.

1.1 Introduction

This project was initiated to develop a means to extend the voltage ratings of solid dielectric cables up to 230 kV by the use of an alternate means of crosslinking with the potential of producing cable containing a dielectric that is more homogeneous and freer of impurities than currently available. The dielectric involved is high purity polyethylene that has been crosslinked by irradiation.

The basic means of achieving this high voltage cable is through the proposed design of a high power (7 MeV) pulse irradiation system. This system should uniformly crosslink thick sections (23 mm) of polyethylene insulation. Furthermore, the new irradiation technique provides for the uniform crosslinking of a circular cross section such as an electrical cable construction. This feature is not inherent with other irradiation systems in common use today. In this respect, 360° pulse irradiation can be considered as a major breakthrough for the wire and cable manufacturer.

It is anticipated that successful development of this project can provide 138 kV/230 kV solid dielectric cables which are more reliable and which can be manufactured more economically.

1.1.1 Chemically Crosslinked Polyethylene

Chemically crosslinked polyethylene (XLPE) has been used for many years as a dielectric for power cables. It has a low dielectric constant and low loss factor. Its thermosetting properties provide the necessary thermal stability at 90°C operating temperature.

The chemical crosslinking process is a high temperature reaction, and XLPE insulations formed by this process may have inherent weaknesses due to contamination, impurities and microporosity.

When chemically XLPE cables fail in service or under test, the reason is often related to inclusions or voids in the dielectric. If such defects could be eliminated or reduced, the reliability of the dielectric could be greatly enhanced, both in life and voltage rating. The reasons for some of these weaknesses or defects are as follows:

- * XLPE, as a raw material, has a higher level of contamination than virgin polyethylene. The increased contamination is attributed to additional manufacturing steps needed to blend crosslinking additives to the basic polyethylene. The contaminants are trapped in the pellets of raw materials and of course find their way into the finished cable. Furthermore, the chemical crosslinking agent may not be properly dispersed and may be sources of localized stress.

- * Shrinkage voids are more apt to occur due to high temperature differentials occasioned by XLPE processing. Without the need for high curing temperatures, it is possible to reduce or eliminate shrinkage voids.
- * Microporosity of chemically XLPE is characteristic of steam curing, presently the most widely used method of vulcanization.
- * By-products produced during crosslinking include methane and other gases which can result in porosity.
- * Inclusions in the extrudate are due to premature crosslinking of the compound. This takes the form of "yellow bodies" and degraded particles which may occur during the extrusion operation.

1.1.2 Irradiated Crosslinked Polyethylene

To date, the use of conventional polyethylene as a cable insulation has been confined to low voltage, relatively thin wall dielectrics. This limitation has been due to the unavailability of irradiation equipment which could uniformly crosslink thick walls of polyethylene and which have the capability to control the irradiation field to conform with the round physical shape of cable insulations.

While radiation processing has been generally accepted for the many advantages it delivers, it has been commercially limited to low voltage cables in the range of 600 volts. Higher voltage cables are conventionally crosslinked by thermal means which are slow, space consuming, and expensive to install. Irradiation has not found a place here because the electron energy required to penetrate cable insulation demands equipment capable of providing high power at 5 million volts or more. Accelerators with the necessary specifications do not presently exist.

Attempts to process thick cables have always suffered from difficulty in obtaining uniform properties, a direct reflection of the fact that commercially available irradiators are designed to bombard flat surfaces. With such equipment, the possibility of shadowing or overdosing becomes a matter of concern. It is believed that both restrictions, lack of uniformity and shadowing, may be removed by a 360 degree high voltage irradiator.

The primary reason for considering radiation as a means of cross-linking polyethylene is the expectance of a significantly cleaner dielectric. Because irregularities are sites for high localized stress, they increase the risk of decomposition of the polyethylene at the defect, leading to ultimate cable failure. Two recent technical papers (1),(2) have concluded that the dielectric strength of polyethylene has a direct relationship to the size and quantity of contaminants. Accordingly, it is expected that the relatively cleaner irradiated dielectric should represent a decided improvement over chemically XLPE and, for that reason, be better suited for operation at 230 kV.

A further major advantage of crosslinking by irradiation is the potential of faster processing speeds. All chemical crosslinking processes depend upon thermal means to generate radical sites for crosslinkage. The processing speed is hence limited by the thermal resistance of the polyethylene. For thick walled cables, such as required for 138 kV rating, processing speeds of 2 feet per minute are not unusual. Speed for irradiated curing is many times faster, as discussed in Section 1.2.4, Machine Processing Parameters. Also, the total energy for curing is anticipated to be significantly in favor of irradiation.

Large conductor sizes, common to high voltage transmission circuits, should provide a good target for the proposed 360° toroidal diode. In contrast, large conductors represent a heat sink in thermal systems which cause lower crosslink density near the conductor. Both systems have the problem of concentricity for heavy wall cables, however, the need for long curing tubes for chemical systems is thought to be a disadvantage.

Radiation curing will have some unique problem areas. Ozone will be a manufacturing by-product requiring special handling to comply with safety regulations. Obviously shielding must be dealt with, requiring massive barriers. This will make processing line modifications and maintenance less flexible; it will render the cable less accessible during production. There are risks of radiation induced defects, such as gas evolution and charge collection (treeing). An undetected misfire in the diode may result in charge collection with the possible consequence of treeing; this life-shortening defect may or may not be found in subsequent proof tests. Porosity from excessive or random gasing will be easier to detect, but no less damaging to the cable. Concerning the possibility of misfiring, it is technically possible to monitor the diode output, however, the specific instrumentation was not designed into the project. Gasing and treeing are discussed further in this section and in Section 4.

Temperature rise may limit the speed of cable throughput when irradiation is performed immediately after extrusion, while the polyethylene is still hot. A tandem operation is not necessary, and was not planned for this project, but is essential for optimization of cost.

1.2 Preliminary Considerations

1.2.1 Irradiation Program

The program outline was reduced from the original scope because of the early contract termination. The revised scope stopped short of assembling the 7MV machine. The extent of the work done on the 7MV machine is discussed fully in Part II. The evaluation of polymers proposed for the 138 kV cable is discussed in Part I, Section 3. Tests on prototype 15-35 kV cables are considered in Part I, Section 4.

To achieve radiation crosslinking in thick walled power cable, a repetitively pulsed high voltage electron beam accelerator was proposed. The accelerator would be coupled with an innovative design which offers uniquely efficient delivery of radiation in cylindrical geometry. To do this, high voltage pulse power techniques were to be married to high current field emission technology. Feasibility was shown by construction and operation of a low power accelerator prior to undertaking the full scale radiation system. Experience expected from this low power machine was to be integrated with prior knowledge related to various military applications involving design and fabrication of high voltage pulsed systems. It is anticipated that a high voltage cable processor would be the end result.

Figure 1. Cable Crosslinking Machine

Figure 1 outlines the form which the cable crosslinking machine would take. To the left of the sketch is a bank of capacitors which represent a concentrated energy store, the bank would be repetitively charged and discharged at a rate of about two cycles per second. By charging the individual capacitors in parallel and subsequently switching them to series, the bank can be made to function as a voltage multiplier, giving an output many times higher than that of the charging power supply. Circuits of this type are called "Marx Generators". Because of its construction, the discharge characteristic of the bank is usually a slowly falling exponential. This voltage waveform is not optimum for driving an irradiation head, a relatively short duration square wave being more nearly ideal. This square wave can be approximated by ringing the bank with an external capacitance in a damped oscillation. The peaking capacitor shown to the right of the energy store serves this function. In the toroidal head or diode, voltage is applied between anode and cathode, generating extremely high fields and causing emission of electrons. These are subsequently accelerated to high energy by the same fields, emerge through the anode and strike the cable. In commercially available accelerators the anode-cathode arrangement produces a planar source of electrons; for cable irradiation this configuration is not an efficient one. Emission over 360 degrees in cylindrical geometry, as shown in the sketch, represents a marked improvement in this regard, and would eliminate shadows thrown by the conductor when cable is irradiated from one side by a planar source. Utilization of a toroidal diode is one of the major innovations of this program.

Operating characteristics of the machine are expected to be:

- * peak electron energy: 7 million electron volts
- * beam energy per pulse: 15 kilojoules
- * pulse width: 120 nanoseconds at half max.
- * repetition rate: 2 pulses per second
- * average beam power: 30 kilowatts beam power

To assure that the development program would proceed in an orderly manner it was separated into three stages. The first consisted of an initial phase of about six months in which proof of principle was demonstrated for a cylindrical radiation source operated in conjunction with an existing low voltage pulser. This was to be followed by design and fabrication of a full scale system intended to yield production data on prototype cables. This construction phase was in progress at contract's end. The second phase was to be terminated in a series of demonstration tests, at less than full voltage, in which 138 kV cable was crosslinked. The third phase was to consist of taking the machine to rated voltage and proving the feasibility of processing 230 kV cable.

1.2.2 Safety

Radiation Shielding

Deceleration of high velocity charged particles causes them to radiate a small fraction of their total energy as photons, or so-called Bremsstrahlung radiation. Bremsstrahlung is indistinguishable from gamma radiation and must be shielded against, as it represents a potential health hazard for operating personnel.

Techniques for constructing radiation-safe installations are familiar and well developed in commercial practice, having been proven in many isotopic and accelerator powered processing centers. These units have compiled an enviable safety record. Radiation protection has been reduced to a standard industrial safety problem comparable to providing for isolation of personnel from contact with the high voltage equipment found in practically every manufacturing facility.

Radiation protection can be provided by interposing either mass, distance, or a combination of both between the point where photons are generated and that nearest approach of personnel. Shielding schemes are chosen first to provide absolute safety margins as required by Federal Regulations⁽³⁾ and secondly to minimize cost within the constraints of space and floor loading as posed by a particular installation.

Ozone Production

Whenever air is heavily ionized, ozone is produced. In the diode of the irradiator, therefore, substantial quantities of ozone will be manufactured. Ozone is reactive and toxic in high concentrations; the minimum permissible limit for an area occupied on an eight hour basis is 0.1 part per million⁽⁴⁾. To protect personnel and equipment from harmful effects, it will be necessary either to provide a blower system to sweep ozone from the processing zone to an external vent, or to provide an inert gas atmosphere.

1.2.3 Irradiation System Design

Reading in the direction of energy flow through the proposed machine (from left to right in the sketch of Figure 1), the system will consist of a charging circuit input, Marx generator, peaking capacitor, and radiation head. Succeeding paragraphs briefly discuss these elements; details of their design are given in Part II.

Marx Generator

The Marx generator will be constructed in a fashion similar to that of standard multistage impulse generators used to test power equipment. That is, a number of capacitors are charged slowly in parallel and then rapidly discharged in series. This is discussed more fully in Section 1.3 of Part II. The primary difference will be a far more compact design to provide lower inductance. Compactness will be achieved using a liquid dielectric insulating medium and stressing it for a very short time. The technology for such compact energy stores is not new, and has been developed to the point of supplying voltages far higher than that required here⁽⁵⁾.

The generator will have 6 independently removable modules with 20 capacitors per module. Design voltage will be 7 megavolts, yielding an expected component lifetime of 55-million pulses.

Peaking Capacitor

The Marx generator will discharge directly into a peaking capacitor in order to develop an approximate square wave; without a peaking capacitor, the pulse would be a double exponential. The peaking capacitor output will be connected to a toroidal vacuum diode (radiation head) through an overvolted, pressurized sulfur hexafluoride output switch. This is described in more detail in Section 1.6, Part II.

Vacuum Diode

Electron beams are generated by accelerating electrons in vacuum from a cathode to a thin foil anode through which they pass into atmosphere. Cathode geometry is designed on the principle of field emission, in which the impression of a high electric field extracts electrons from the electrode surface; anode geometry is that of a thin sheet. The mechanism for introduction of electrons into the high field between anode and cathode depends on the existence of sharp protuberances on the cathode surface to provide field intensification. This requirement can be met by locating a multitude of microprojections on the surface, or through the introduction of macroscopic points.

Electric fields in excess of 10^7 V/cm are required to cause extraction from cathode protuberances. Field emission is governed by the Fowler-Nordheim equation.⁽⁶⁾

There are several requirements on the anode foil; first, it must act as a transparent window; secondly, it must provide a pressure tight interface between the vacuum diode (10^{-4} torr) and the region in which cable is processed. Therefore, requirements for the window material are that of high electrical conductivity, low atomic number, small thickness, and high mechanical strength. An additional demand is that of good thermal conductivity so that heat can be readily dissipated by conduction. These considerations usually lead to selection of either aluminum or titanium. Overall dimensions of the vacuum diode were determined by maximum operating voltage, desired impedance, and cable geometry.

Bushing

Electrical isolation of the vacuum diode requires a vacuum bushing; the present design proposes to use a capacitively and resistively graded polyethylene cylinder about 7 feet long; this bushing is illustrated in Figure 59 of Part II. Two of these will be required to center the diode.

Tank

Overall dimensions of the tank housing the energy store, peaking capacitor, and diode will be about 40 feet by 15 feet high by 15 feet wide. Roughly 40,000 gallons of oil will be needed to fill it.

1.2.4 Machine Processing Parameters

Fundamental machine parameters for electron beam processing are set by the thickness of insulation to be treated and by desired cable throughput. They are operating voltage and average power; both are estimated here, but discussion of the implications for machine design have been delayed to Part II, where a detailed discussion of irradiator design and construction is given.

Operating Voltage

Operating voltage is determined by the requirement for electrons to penetrate the insulation, delivering as uniform a dose as possible throughout the irradiated volume*. Electrons produced by a planar source will deposit their energy in a planar target according to a profile having the general shape shown in Figure 2, curve (a). For irradiation with a cylindrical source, energy density may be increased somewhat to all points due to the geometrical effect of decreasing surface area as electrons move radially inward. Curve (b) illustrates this.

* Radiation dose, or energy absorbed per unit mass, is commonly measured in "rads". One rad is equal to 100 ergs/gm. A megarad is a million rads, or 10^8 ergs/gm.

Figure 2. Typical Dose Profiles in Arbitrary Units

Curves (a) and (b) have been drawn for monoenergetic electrons; in practice, pulsed accelerators produce a distribution of electron energies whose spectrum is determined by details of the voltage waveform. Scattering and absorption in the window also effect the spectrum, but this is a small perturbation for high energy beams. Rising and falling portions of the voltage pulse generate electrons with energy well below the average, and these will be absorbed near the surface of the insulation. They have the effect of filling in the dose profile, giving absorption curves with better uniformity than those shown in Figure 2. Because voltage waveshape is a design parameter in pulsed machines, it can be used to exercise control over dose profile. Rise and fall times can be specified in such a way as to optimize uniformity and minimize overdosing, thus reducing power requirements.

Electron absorption curves are characterized by a maximum depth of penetration, the range, which is approximately proportional to energy.* Katz and Penfold⁽⁷⁾ have assembled and fitted range data from a number of experiments and, for electron energies between 1 and 20 MeV, have determined the following curvefit:

$$R = 530E - 106 \text{ milligrams/cm}^2 \quad (1)$$

E is energy in millions of electron volts (meV). Given a high density polyethylene cable whose insulation thickness is 3 cm, the voltage required to provide penetration to the center conductor is about 6 million volts. However, to achieve approximately uniform energy deposition it is necessary to specify a voltage which is higher than this. To meet the criterion for uniform irradiation, range should be at least 20 percent greater than the insulator thickness, as indicated in Figure 2. In practice, it can be expected that a certain fraction of the electrons reaching the center conductor will be reflected (scattered) back into the jacket, increasing dose near the interface between insulator and conductor

*for accelerating voltage. The two are essentially identical for high voltage machines

to a value higher than that indicated in Figure 2. This will have the effect of further improving uniformity.

Designing for a range 20 percent greater than the jacket thickness implies (using Equation 1) an operating potential of about 7 million volts.

Operating Power

Curing dose determines the amount of energy which must be delivered in a given time for a specified throughput, therefore fixing power requirements.

In his classic text on radiation effects in polymers, Charlesby⁽⁸⁾ gives data showing that tensile strength and elongation in low density polyethylene reach simultaneous maxima at an electron dose of about 10 megarads. Other authors have reported that doses sufficient to give acceptable cross-link density generally fall somewhere in the range 15 to 30 megarads, exact value depending upon composition and molecular weight.⁽⁹⁾ These findings suggest that a radiation dose in the vicinity of 20 megarads should be sufficient to cross-link.

For a given set of cable dimensions and linear rate of transport through the machine, the mass of insulation to be treated per unit time can be computed from the expression

$$\dot{m} = \frac{\rho \pi}{4} (d_o^2 - d_i^2) \quad (2)$$

where

ρ = insulator density

π = linear rate of transport

d_o = outside diameter of cable

d_i = inner diameter of insulation

Beam power required is given by the product of $\dot{m}$ and the dose required to cross-link, increased by an appropriate factor to account for the inefficiency of electrons lost through the cable jacket to the center conductor and for those backscattered from the surface of the polyethylene. Falloff of the absorption curve means that portions of the insulation will have to be over-dosed to some extent to assure that all regions are treated with a minimum dose of 20 megarads. This represents an additional inefficiency which must be considered in estimating power.

Transmission and backscattering losses are minimal and would not exceed 10 percent of incident beam power; overdosing can probably be held to 25 percent or less. These factors would combine to increase beam power by about a third over that required for uniform irradiation of the jacket, hence power can be estimated from

$$P = 1.33 \dot{m} D \quad (3)$$

with D being cross-linking dose. Assuming a 3.2-inch cable having a 0.81-inch center conductor and requiring a throughput of 5 ft/min at 20 megarads gives beam power as about 30 kw.

For design purposes it has been assumed that energy transfer from the Marx bank to the cable will be no more than 20 percent efficient, hence the store has been required to have power handling capability up to 160 kw at 2 hz. Should efficiency prove to be higher than 20 percent, then line speeds greater than 5 ft/min can be run; if 100 percent transfer were achieved (this is unlikely) speeds would go to 25 ft/min.

1.2.5 Auxiliary Effects of Irradiation

Irradiation will be accompanied by several auxiliary effects, some of which may have an impact on cable quality; the more important of these are discussed below.

Temperature Rise

Electrons are thermalized through a series of ionizing collisions which result in their kinetic energy being transferred to the matrix, where it is eventually manifested as heat. The temperature rise accompanying irradiation is readily calculated; it is given by

$$T = \frac{D}{c} \quad (4)$$

where D is absorbed dose and c is specific heat. Specific heat of polyethylene is given as 0.55 cal/gm °C by Kresser⁽¹⁰⁾ and again by Poli⁽¹¹⁾; this implies a temperature rise of about 4°C per megarad. For an average dose of 20 megarads, temperature rise would be 80°C if energy were instantaneously deposited in the insulation. Net temperature after irradiation will be 100°C, (for a cable at room temperature as it enters the machine), well below the softening point of crosslinked polyethylene.

Charlesby⁽⁸⁾ cites data which show that the extent of cross-linking produced in polyethylene by a given radiation dose increases with initial temperature of the stock. This suggests that an increase in crosslinking efficiency might be gained by extruding in-line with the irradiator. Provided that the temperature increase due to irradiation, when added to the extruder residual, does not lead to handling problems, locating the electron beam processor near the extruder to take advantage of preheating could result in a decreased power requirement.

Because some electrons will necessarily be transmitted into the center conductor, effects of differential temperature rise between insulation and conductor must be considered. To a first approximation, dose will be continuous across the interface between jacket and conductor and equal to 20 megarads; because specific heat of the metal is smaller than that of the plastic,

temperature rise on the conductor side will be two to five times greater (depending on whether the conductor is aluminum or copper). Thermal gradients will equilibrate rapidly in the conductor due to high conductivity, so that a differential temperature will exist over the interface for only a short time. Nevertheless, expansion stresses could occur if thermal relaxation were long compared to the time scale of mechanical motion on adjacent sides of the interface. Expansion of the conductor along its length could occur no faster than the propagation speed of an acoustic wave. This suggests that an assessment of the possibility of insulation separating from the conductor due to differential expansion can be made by comparing characteristic times for thermal relaxation and propagation of an acoustic signal over a distance equal to half the irradiated cable length.

A $1/e$ decrease in temperature over a distance r requires a time equal to r^2/α , where α is thermal diffusivity. Time for an acoustic wave to travel a distance ℓ is given by ℓ/v , with v the sound speed. If thermal relaxation into the conductor is rapid compared to mechanical motion along its surface, then the quantity $F = (r^2/\alpha) (v/\ell)$ should be much less than one.

Relevant parameters are listed below.

Material	Diffusivity, α cm/sec	Acoustic Velocity, v , cm/sec	r , cm	ℓ , cm
Cu	1.2	4×10^5	.07	1.2
Al	0.8	5×10^5	.20	1.2

The distance r has been computed as the residual range in the conductor, established earlier to be 20 percent of the insulator thickness, or 0.6 gm/cm^2 . Cathode length has been set to the value which would correspond to crosslinking with a single pulse at 25 ft/min throughput, as this represents the worst case for differential temperature effects.

Values of F are 1400 for copper and 21,000 for aluminum; these results are not small, hence they indicate that differential expansion may be a

problem if curing is accomplished in one pulse. The solution to this lies in delivering the dose over several pulses, allowing time between each for thermal relaxation in the conductor. Relaxation would require less than a millisecond in copper and about 50 milliseconds in aluminum. Extending irradiation over 10 pulses delivered at a rate of 2 Hz would provide an interpulse time of 500 milliseconds, thus reducing the possibility of cable damage from this source.

Gas Evolution

Polyethylene is known to evolve copious quantities of hydrogen (and traces of other gases) when subjected to irradiation. G-values* for hydrogen abstraction and for crosslinking are similar, indicating that on the average a free hydrogen atom is released for each bridge formed. A fraction of these atoms may be rebound to reactive sites which do not crosslink, while the remainder diffuse through the matrix and can aggregate to give gas pockets or microbubbles. Eventually most of the unbound hydrogen will diffuse out of the cable, but porosity may be left behind.

If hydrogen evolution is coupled with an increase in temperature to a value near the melting point, foaming can occur (unless the cable is pressurized). Foaming or porosity is clearly not acceptable.

To estimate the potential seriousness of hydrogen release, the simplified calculation which follows was made.

Irradiation to 20 megarads corresponds to the injection of about 10^{21} ev/gm. With a G-value of 3 reactions per 100 ev,⁽¹³⁾ this means that about 10^{19} hydrogen atoms will be released. Because a gram of polyethylene contains about 10^{23} hydrogen atoms, scission points are relatively far apart, being separated by 10^4 atoms on the average. For this reason freed hydrogen behaves as if it were dissolved in the solid matrix, and the matrix is not stressed significantly. However, the potential for destructive release remains, as can be shown by computing the pressure which would be exerted by the 10^{19} atoms if

*G-value is the number of chemical changes per 100 ev of energy absorbed.

conditions allowed them to behave as a perfect gas. Because the density of polyethylene is approximately 1, the volume occupied by 1 gm is 1 cc. Number of moles of hydrogen is 10^{-4} , therefore at room temperature the partial pressure would be

$$p = \frac{nRT}{v} = 2.4 \text{ atmospheres}$$

Parameters and units are:

$$n = 10^{-4} \text{ moles}$$

$$R = .082 \text{ liter-atmosphere/mole} \cdot ^\circ\text{K}$$

$$T = 290 ^\circ\text{K}$$

$$v = 10^{-3} \text{ liters}$$

In view of this it is not surprising that violent disruption occurs when polyethylene is simultaneously irradiated and heated above its softening point, allowing evolved gases to bubble out of solution. However, unless softening accompanies irradiation, macroscopic effects can probably be avoided.

Charge Collection

It is well known that charge injected into certain materials can be trapped to form an "electret". If sufficient charge is stored, then treeing can result at a later time when discharge is initiated by an appropriate stimulus, such as a mechanical blow. In dc low-current irradiators this phenomenon is sometimes employed to produce decorative patterns known as Lichtenberg figures. In most processing situations, however, charge buildup leading to treeing is undesirable. In the case of high voltage cables, it would be intolerable.

Many factors influence the extent of charge trapping; some of these are nature of the material, ambient temperature, and dose rate. In general, conditions which would pertain for pulsed irradiation tend to minimize charge buildup.

Charge stored in dielectrics will leak away in time at a relaxation

rate which is characteristic of the material. This rate is accelerated by temperature, so that heated dielectrics make poor electrets. By processing cable at a location near the extruder, polyethylene can be prevented from quenching to ambient and temperature at irradiation will be elevated. Application of heat is a means, therefore, which can be applied to prevent formation of Lichtenburg figures. At the high dose rates characteristic of pulsed operation, local ionization density is high and dielectrics become conducting for a short period of time. A number of authors have reported on this effect; a synthesis of their findings is that prompt radiation induced conductivity is given by

$$\sigma = 10^{-17} R \quad (R = \text{dose rate, rads/sec})$$

within a factor of 10, for a wide range of polymer dielectrics. In addition to creating high ionization density, pulsed irradiation also increases temperature and therefore works against charge trapping by promoting rapid relaxation.

SECTION 2

DEMONSTRATION OF THE FEASIBILITY OF 360 DEGREE IRRADIATION CONCEPT

2.0 Summary of Section 2

The concept of irradiating a coaxial cable using a torroidal diode was shown to be valid. A ring-shaped cathode was fabricated containing sharp needle points directed inward to a thin wall cylindrical anode called a window. The cathode and outer surface of the anode were housed in an evacuated housing and connected to a pulse generator.

Short coaxial specimens were passed through the center of the tubular anode while the Marx generator supplied pulsed energy to the cathode. Each specimen was thus bombarded by accelerated electrons passing radially through the anodic window into the plastic specimens.

The resulting crosslinked polymers were subsequently evaluated to determine the density and uniformity of crosslinkage. The circumferential dose imposed on the specimens was shown to be generally even. Longitudinal uniformity along the specimen axis was progressively improved as the work effort progressed by transporting the specimen in a continuous motion through the diode. Attenuation of the electrons, however, caused a lower crosslink density toward the inner core (conductor).

This was of some initial concern in that cable dielectric would be overcured on the outside or undercured on the inside. Subsequent work on 15 kV cable models, however, revealed that the attenuation was a function of electron energy and reflection from the conductor. Crosslink density throughout the wall of the dielectric was later shown to be very good. This is discussed further in Section 4.

2.1 Introduction

At program inception a primary concern was to determine quickly and at low cost whether unforeseen technical problems might exist which would invalidate the concept of 360 degree irradiation. It was also considered important to demonstrate that good azimuthal uniformity of surface dose could be obtained. It was felt that both objectives could be achieved by fabricating a small scale radiation head and mating this to an existing pulse generator; two such generators were available. The first PEBS I (for Pulsed Electron Beam Systems), a 30 Hz machine whose nominal parameters were 300 kV peak voltage, approximately 50 ns pulsewidth at half maximum of the voltage pulse, and average beam power of about 0.5 kw at 30 Hz. A 3 MV generator designated FX-35 was the second possibility; FX-35 was designed as a flash X-ray machine with 20 ns pulsewidth, capable of being discharged at a rate of about one shot every 30 seconds. It delivers about a kilojoule per pulse, whereas beams produced by PEBS are limited to 15 joules per pulse. PEBS offered the advantage of average power high enough to be informative on problems relating to diode and window heating, effect of outgassing on diode performance, and long term stability of cathode emission characteristics. Investigations therefore began with PEBS, although it was recognized that, because of its low voltage, the machine would not crosslink insulation thicknesses much greater than 10 mils (0.025 cm).

Later in the program, after experiments on PEBS had shown the 360 degree irradiation concept was feasible at low power levels, attention shifted away from mechanical and electrical design and focused on quality of cable which might be produced. To examine this aspect, the radiation head was decoupled from PEBS and mounted on FX-35, where it was felt that penetrating power would be adequate to treat cable up to 35 kV rating. Results of this subsequent work with cables is detailed in Section 4.

2.2 Construct 360 Degree Diode

Much of the early technical effort was directed toward installation of a cylindrical irradiator on an existing 300 kV repetitively pulsed electron beam system. This system, IPC Standard Model PEBS 3-10, consisted of an eight stage Marx generator directly coupled to a field emission diode.

Characteristics of the machine were:

Peak Voltage:	$100 \text{ kV} \leq V \leq 300 \text{ kV}$
Peak Current on Cathode Shank:	1500 A
Pulse Width:	50 nanoseconds FWHM**
Repetition Rate:	3 to 30 Hz
Average Beam Power:	$\sim 0.5 \text{ kW}$ at 30 Hz
Energy per Pulse:	15 joules

Pulse shape and duration were approximately the same as those expected to characterize the full scale irradiator output, therefore it was anticipated that experiments with PEBS would provide data from which behavior of the cable processing diode could be estimated. In addition, the machine was used to crosslink specimens of high density polyethylene plaques and tape, thus generating data on doses necessary to produce acceptable properties.

Objectives of testing at 300 kV were the following:

- * Demonstrate 360 degree irradiation
- * Determine crosslinking dose
- * Study uniformity of crosslinking in circumferential and radial directions
- * Determine efficiency of electron delivery in cylindrical geometry
- * Evolve design for a thin foil, cylindrical electron beam window and window support structure.

** Full width at one-half maximum of voltage peak.

- Study window lifetime under pulsed heating
- Develop a model for diode impedance as a function of interelectrode spacing and electrode length

Window Design

In order that electrons may be accelerated without collisional losses it is necessary to operate with a vacuum in the interelectrode space; a diode is simplified and made more compact if the electrodes are housed in an evacuated bushing, vacuum being continuous from the accelerating region into the body of the bushing. In such an arrangement, vacuum serves as the high voltage insulating medium. It becomes necessary, however, to provide a means of permitting electrons to exit the diode into ambient air where cross-linking is to take place. This function is performed by a "window" which must be relatively transparent to electrons while at the same time making a good pressure seal and carrying a differential loading of one atmosphere.

Thin foils of low atomic number metal are sufficiently transparent to make efficient windows, but may require some structural support to enable them to carry pressure forces. A supporting grid can be used to supply rigidity and structural strength.

The approach which was adopted in designing a cylindrical window was essentially that described above; a 1-mil rolled aluminum foil was seam welded into a 2-inch diameter by 12-inch long cylinder and supported on a grid structure where end sealing was provided. This arrangement is shown schematically in Figure 3, a sketch of the PEBS diode as it looked when the system was assembled.

Critical points in the design are: (1) effecting a vacuum tight seam down the length of the foil and (2) achieving good sealing at the window ends. A number of processes are available for welding thin foil; some which were investigated include electron beam, laser, and ultrasonic. Samples submitted to several e-beam and laser welding companies proved to be unsatisfactory, but ultrasonics appeared to give a seam with good properties. One mil thick

Figure 3. Schematic of Diode and Window for 300 kV Machine.

1100 H18 and 5052-H38 aluminum foil, seam width of about 1/8-inch and thickness of 1.5 times that of the foil, were welded successfully.

To test these samples for their ability to carry pressure over a typical supporting structure, a flat grid was fabricated with a pattern similar to that designed into the cylindrical support, and one side of the grid was evacuated. Seams were centered on the pattern to assure that this region was stressed in a representative fashion. Both alloys were tested in the annealed and as received condition; it was found that 1100 failed at the seam in both heat treats, although the annealed sample held pressure for a longer time. Aluminum 5052 was satisfactory in both conditions. To check fatigue in the seam, unannealed 5052 foil was cycled from pressure to vacuum and back ten times without failure.

Weld integrity, as measured by pressure in the evacuated region, was not affected by cycling.

From these experiments it was concluded that high alloy aluminum foil offered a better probability of success than does 1100, hence 5052 foil was selected as the material of choice.

In addition to the supported window, a free-standing cylindrical foil was also considered. This shape can be effective at carrying internal pressures; it was felt that if a 2-inch diameter by 1-mil thick foil could carry 15 psi without support, then the efficiency of electron transfer would be improved. Removal of the supporting grid would remove a source of parasitic electron absorption and, since the grid distorts fields in the diode, better electron distribution might be obtained without it. A simpler and less expensive system could also result. Some compelling reasons therefore existed for investigating the possibility of freestanding windows.

Hoop stress in a thin walled cylinder with free ends is given by

$$\sigma = \frac{PD}{2t}$$

where

P = internal pressure

D = diameter

t = thickness.

With P = 15 psi, D = 2-inches, and t = .001-inch, stress is computed to be 15,000 psi. In the vicinity of the weld this may be higher; the ASME Boiler Code specifies weld efficiencies be taken as 0.5 for lap joints and 0.6 for butt welds. This implies that working stress in the weld might approach 30,000 psi. Yield strength of 5052-H38 at 75°F is 37,000 psi. Allowing for manufacturing variations of 10 percent in foil thickness and considering that service temperature will be elevated, however, suggests that an unsupported window would operate very close to the yield point. Safe design therefore calls for providing support, and this is the route that was taken. Nevertheless, because the concept has potential advantages, an attempt was made to evaluate a free-standing window in the 300 kV pulser.

The window holder was modified to allow removal of the support structure, and several foils were installed and pumped down. These proved capable of carrying the pressure differential, but were not anchored sufficiently well at the ends to prevent pulling through the vacuum seal and slipping free. This could probably have been prevented by redesigning the holding scheme, but it was decided to stay with the supported window, a system which was working well and required no further effort.

Looking to the 7 MV machine, where titanium would probably be the material of choice, foil thickness necessary to carry one atmosphere unsupported can be computed from

$$t = \frac{PD}{2E\sigma}$$

where

σ = yield stress

E = weld efficiency = 0.5

Yield at 800°F for most titanium alloys is 80,000 psi or more; using this figure with a diameter of 6 inches gives foil thickness slightly greater than 1-mil. A much thicker sheet (2 or 3 mils) would still be sufficiently transparent to function satisfactorily as a window, hence the use of a free-standing foil may be attractive in this case.

Cathode and Vacuum Housing

The cathode was fabricated from a torus and eight uniformly spaced phonograph needles. The torus was about 8-inches inside diameter and eleven inches outside. Needle tips were characteristically placed on a 17 centimeter diameter. Support for the cathode was provided by a 1-1/2 inch diameter stainless steel shank which was cantilevered from PEBS' high voltage output plate. The shank was placed in a 6-inch diameter vacuum line, to which the cathode housing was affixed. Housing was made from the body of a standard Ion Physics Mini Marx[®] trigger generator and consisted of a 16-inch diameter aluminum tube about 18-inches long capped by end plates designed to carry the window housing. (see Figure 3.)

Vacuum was obtained through a tee in the line between housing and PEBS, and was provided by a small mechanical pump. It was nominally in the vicinity of 10^{-3} torr.

2.3 Measure Dose Uniformity at 300 kV

A set of experiments was conducted to measure circumferential beam uniformity, depth dose profile, and energy and charge transfer efficiencies. These utilized a 1 mil ultrasonically welded aluminum 5052 window and support structure. Throughout the experiments PEBS was operated at the following conditions:

Charging Voltage:	± 28 kV (220 VAC)
Diode Pressure:	<1 torr
Cathode:	4 phonograph needles with tips on a 17 cm diameter circle
Window Diameter:	5 cm

Depth-Dose Profile and Energy Transfer as a Function of "Cable" Diameter

Aluminum dowels having diameters of 0.687 and 1.25 inches were wrapped with 20 layers of DuPont MSC blue cellophane and centered in the test volume with both ends grounded to the chamber through bus wire. These dowels correspond to nominal "cable"-to-window diameter ratios of 0.34 and 0.62; for the full scale machine it is assumed that a 6-inch window will be needed to give adequate room to maneuver a 3.2-inch cable through the head without undue bend removal. This configuration gives a ratio of 0.52. For each dowel, PEBS was run for 100 shots and the cellophane was removed and read at the centerline using a Model ICT-106 densetometer supplied by High Voltage Engineering Corporation.

Pulse rate was about 1 pps, achieved by manual triggering.

Results of dose profile measurements are summarized in Figure 4. The figure is plotted in megarads (obtained from the dose versus optical density calibration supplied with the ICT-106) versus mils of cellophane. In a past experiment the cellophane density was determined to be 1.45 gm/cm^3 . One mil (.0025 cm) on the plot therefore equals $3.63 \text{ milligrams per cm}^2$, and is equivalent to 1.58 mils (.0040 cm) of low density polyethylene. Points to note about the plot are the following:

- (a) Both curves are similar in shape and amplitude. Surface dose was about 20 percent higher on the small diameter dowel, suggesting that a greater number of electrons made glancing impacts with the "cable"; this would be expected if electrons were moving on trajectories somewhat off the radial.

Figure 4 . Depth Dose Profiles Measured for 0.687 and 1.25-in. Cylinders

- (b) Because integrals of the two curves are roughly equal, the energy absorbed per unit area is approximately equal in both cases. Since surface areas are in the ratio of diameters, this indicates that the smaller dowel intercepted about half the total energy stopped by the larger one.

Approximating the dose curves as triangular in shape, having peak dose of 10 megarads and extrapolated range of 17 mils ($62 \text{ milligrams/cm}^2$), gives energy absorbed per unit area equal to $0.031 \text{ joules/cm}^2/\text{pulse}$. In getting to this figure, compression of the beam with radius has been neglected as the change in curvature across the cellophane is small. Examination of the cellophane before cutting it for reading suggested an actively irradiated length of about 4.5 inches (11.4 cm); if this region were uniformly illuminated, then total energy transferred to the dowels was 2.2 joules/pulse for the small diameter and 3.5 for the larger. Assuming energy stored in the Marx to be 40 joules, these figures correspond to energy transfer efficiencies of 6 and 9 percent for small and large dowels respectively. This is in accord with the notion that transfer efficiency should improve as the cable diameter approaches that of the window.

Measurements of Charge Transfer

Current collected on bare (no cellophane) aluminum dowels was recorded with a 1 amp/volt standard IPC Rogowski coil terminated in 50 ohms.* Rods were placed on the window axis, isolated from the head; current passed to ground through the coil to the chamber. A simultaneous record of shank current at the Marx output was read from the 4-inch diameter 120 amp/volt Rogowski coil mounted there. Figure 5 shows typical output traces which were obtained for the 1.25-inch dowel. Current collected on the rod is shown in the upper trace, while Marx output is indicated in the lower. It appears that

*Rogowski coil was an IPC Model CM-100-S

CURRENT
ON DOWEL
1 A/V

MARX
OUTPUT
CURRENT
120 A/V

FIG. 5 TYPICAL CURRENT MEASUREMENTS
OF THE MARX OUTPUT

the cathode lights up slowly and that current reaching the "cable" was crowbarred in the diode at about 150 ns. This would account for the relatively inefficient charge transfer which was observed, roughly 5 percent for the small dowel and 6 percent for the larger.

These efficiencies are on the same order as those obtained from cellophane measurements.

Circumferential Uniformity

In an initial experiment to measure circumferential uniformity, a length of 10-mil PVC tubing was shrunk over the 1.25-inch rod and wrapped with a single layer of cellophane. The PVC and dowel were used to give representative scattering conditions. Doses determined from the cellophane using the ICT-106* were as follows (for 100 pulses at 3.75 pps):

<u>Angular Location, Degrees</u>	<u>Dose, Megarads</u>
0	8.9
90	9.0
180	8.0
270	8.9

Deviations were +2 percent and -8 percent from the mean value.

To make this measurement, the dowel was left stationary in the diode, and not pulled through it as a cable would be. Proceeding in this way should have no effect on conclusions relating to azimuthal uniformity, although it can be expected that there will be nonuniformity along the lengthwise dimension of the cylinder, particularly as the ends of the window are approached.

Longitudinal Uniformity

During the course of the program, as a number of thin plaques and/or tapes of various polyethylene formulations were irradiated with PEBS, efforts were continuously made to improve longitudinal uniformity. This was done by going first to a stepwise procedure in which samples remained stationary while under irradiation, but were manually advanced in a series of steps

* High Voltage Engineering Model ICT-106 Optical Densimeter.

through the diode and later by employing a small electric motor to pull mandrels through. This last approach resulted in essentially constant surface dose everywhere along and around the exposed area. This is discussed further in Section 3.

First irradiations of sheet polymers conducted with samples wrapped around a stationary mandrel centered in the diode produced an approximately gaussian distribution of dose along the diode axis (corresponding to long dimension of the sheets) and complicated the interpretation of solvent extraction results. Furthermore, samples were subjected to a significant variation across their thickness, a manifestation of the rapid falloff in dose with depth at 300 kV. Both of these conditions were corrected using the techniques described below.

Falloff in dose along the diode axis can be compensated by shifting sample location to simulate a cable in continuous motion. A continuous sweep under the emitters would serve to integrate dose delivered to a fixed cable point so that uniformity is assured. This condition was at first approximated by stepping sheets through the diode; regimens involving three and five zones were evaluated. In the "three zone" protocol, sheets were handled as indicated in the sketch below. Block numbers 0, 50 and 100 are the percent of final dose which has been accumulated in each zone after each step.

To irradiate five zones, a similar procedure was used, with 25 percent of the final dose being delivered in each step.

Blue cellophane readout with a Kipp and Zonnen single channel scanning photometer was used (in contrast to centerline readings of the ICI-106 densitometer) to produce a scan of longitudinal uniformity for both three and five step sequences. Results are shown in Figure 6 where vertical displacement is proportional in dose. It can be seen that the three zone protocol produces a dose which is constant over length of the sheet to within 10 percent. Depressions appearing at the 1/2 and 1/4 points result from shadowing by circumferential ribs of the window support; these depressions are locations of the largest deviations from mean dose.

Five zones were tried in an effort to minimize the effect of structural ribs. Bottom portion of the figure shows that depressions were not eliminated by this strategy; more showed up, and overall uniformity provided by three zones remained about the same. Conclusion was that the ± 10 percent uniformity provided by three zones was sufficient for our purposes and was the more efficient approach.

Further improvement in longitudinal uniformity followed when samples were continuously transported through the diode; depressions arising from shadows cast by the support structure were eliminated.

Uniformity through-the-thickness was improved by reversing sheets at the halfway point in each irradiation. This involved removing the plaque or tape from the mandrel and rewinding so that the side which had faced outward now faced inward toward the mandrel. Reversing had the effect of irradiating half the time from one side and half from the other; under these conditions the net dose was approximately constant.

Figure 6. Longitudinal Dose Uniformity

SECTION 3
EVALUATION OF POTENTIAL CABLE POLYMERS
WITH A 300 kV GENERATOR (PEBS I)

3.0 Summary of Section 3

Following satisfactory results with the toroidal diode, a program was initiated to evaluate potential cable polymers for use in the 138/230 kV cables.

Solvent extraction was the primary method of evaluating crosslink density since it was found to be responsive to small changes in dose. Irradiation and dosimetry techniques were improved as the project progressed; the most satisfactory technique consisted of pulling specimens through the diode at a constant speed.

Selection of insulating and shielding polymers were weighted heavily on their response to irradiation. Selected polyethylene compounds required the least dose for the specified crosslink density, without compromising dielectric properties. The concept of minimum dose is expected to reduce the burden on the 7 MV irradiator; the possibility of operational difficulties, particularly during initial tests, cannot be overlooked.

Physical properties of insulating polyethylenes and resistivity of semi-conducting polymers were not adversely affected at moderate dose levels.

3.1 Introduction

As indicated in Section 2, first efforts to produce a 360 degree beam were made with a toroidal diode connected to a 300 kV pulse generator. When this system was found to function well, a program of using it to evaluate plaques and tapes of potential cable polymers was initiated.

The types of polymers evaluated were selected from those readily obtainable from commercial suppliers; special types of polyethylenes and antioxidants were generally avoided. Exceptions are noted in Table III where some experimental polymers were utilized in some 15-35 kV cable constructions. Also ESMV-871-30, a new tree-resistant HMW PE, was an experimental compound when evaluated by this project. ESMV-871-30, independently developed by Du Pont, is now marketed as TREBAN-100.

While irradiation accelerators were not programmed for evaluation in this project, a polyethylene homopolymer employing a 3% trimethylol propane trimethacrylate accelerating resin was tested. Results were not promising nor conclusive. Tests on two EPR and two chlorinated polyethylene compounds formulated with accelerators, however, responded very well to radiation crosslinking. The chlorinated polyethylene required about half the dose necessary on the most sensitive polyethylene homopolymer. Although accelerators can allow lower dose levels without sacrificing crosslink density, they are not without disadvantages. Higher probability of contamination, the possibility of poor performance under high electrical stress, and

higher cost are the main drawbacks. The use of accelerators with semi-conducting polymers may be considered if it is not possible to achieve a good crosslink match for simultaneous dosing of the insulating and semi-conducting polymers.

3.2 Crosslink Density Measurement

The extent to which crosslinking has been accomplished in ethylene plastics can be measured by extracting in decahydronaphthalene that portion of the material which has not been crosslinked. This is called solvent extraction, and is described in ASTM D2765. Method B of D2765 has been developed especially for cable insulation, and specifies shavings rather than ground samples. Method B was used, involving 300 mg samples measuring approximately 6 x 6 x .3 mm. Each sample was enclosed in 120 mesh stainless steel cloth specimen holders. The specimen holders were simultaneously immersed in 2000 ml round bottom flask filled with 946 ml of decalin and 8.6 g Plastanox #2246 antioxidant - (1% by weight of decalin). The antioxidant inhibits further crosslinking, particularly intended for chemical crosslinking.

Six samples, comprising one test group, were immersed simultaneously in the flask of boiling (193°C) extractant for 6 hours. The decalin-antioxidant solution was renewed after testing two groups, or 12 samples. After extraction, the specimen and holder were heated in a vacuum oven for 24 hours at 28" Hg or better. The percent extract was calculated as follows:

$$\% \text{ Extract} = (W_3 - W_4)/(W_2 - W_1) \times 100$$

W_1 = Weight of holder, unsealed

W_2 = Weight of specimen and holder, unsealed

W_3 = Weight of specimen and holder, sealed

W_4 = Weight of specimen and holder after
extraction and drying, sealed

$W_2 - W_1$ = Initial sample weight

$W_3 - W_4$ = Final sample weight

3.3 Dosimetry

The dosimetry used throughout this study was made using Du Pont MSC-300 blue cellophane as described in Section 2. The 1 mil (.025 mm) radiation-sensitive cellophane was placed over and under a polymer specimen in cylindrical configuration and then irradiated. See Fig. 10 depicting specimen preparation.

Absorbed dose by the MSC-300 cellophane, as measured by bleaching, was assumed to correspond to the mid-thickness of the 1 mil cellophane. Accordingly, the dose on an adjacent polyethylene surface was slightly more or less. The slope of a curve such as Fig.7 was extrapolated from MSC-300 plotting points to estimate surface dose and the mean volumetric dose of the polyethylene. The area under each curve was then used to calculate "mean Mrad" listed in Tables II, III, IV and V.

The methods of employing the MSC-300 cellophane were improved as the work developed; they are described below as "Dosimetry Modes I, II and III". Similarly, the procedures for exposing the samples within the irradiating diode were also improved and are described as "Irradiation Modes I, II and III". The progression of the various modes is pertinent to indicate the relative reliability of data taken at various points in the program. Data listed in Tables II, III and IV include the specific modes.

Figure 7 Determination of Typical Mean Dose

Dosimetry modes discussed below describe methods of measuring the absorbed radiation.

3.4 Dosimetry Mode I

A single sheet of MSC-300 cellophane was used for each stack position throughout the sample exposure within the irradiating diode. A major limitation was noted: a dose above 12 Mrad was inaccurate as shown in Fig. 8 . Above 20 Mrad, the cellophane was almost totally bleached and the dose interminant. See Blue Cellophane Calibration Data, in Appendix A.

3.5 Dosimetry Mode II

Because most of the irradiation testing involved dosing over 12 Mrad, Mode II tests called for replacement of the MSC-300 one, two, or more times to limit exposure to about 10 Mrad. The total dose was then estimated by summation of the dose on each sheet. By noting its position in the stack, it was possible to determine the level of absorbed dose on both sides of the polymer layer(s) by measuring the interleaved cellophane.

3.6 Dosimetry Mode III

With the adoption of Irradiation Mode III, described below, where the stack was pulled through the diode, the outermost MSC-300 was repositioned. The cellophane was now wrapped over the mandrel to one side of the stack. The outer dose was then read after one pass and the total dose calculated by multiplying by the number of passes. See Fig. 9.

Inner MSC-300 sheets normally did not exceed 10 Mrad and they were generally left undisturbed throughout each test. Dosimetry Mode III allowed considerable time savings with little compromise of accuracy. It was necessary, however, to assume that the pulling speed was uniform and that there were no missed shots.

DOSIMETRY MODE III FOR PULLED MANDREL

FIG. 9

The irradiation modes discussed below describe methods of exposing the polymeric specimens to radiation within the diode.

3.7 Irradiation Mode I

Initially polyethylene plaques or tapes were wrapped on a 50 mm diameter mandrel interleaved with sheets of MSC-300 cellophane. The stack was then centered in the diode and irradiated in a fixed position. This resulted in some longitudinal non-uniformity as measured by solvent extraction tests on polyethylene. The non-uniformity created difficulty in relating dose and crosslink density as measured by solvent extraction. The relationship was important to the evaluation of different types of polymers. Recall that this phase of the project (Section 3) included evaluation and selection of compounds for insulation and shield for the first cable to be irradiated on the 7 MV machine at reduced voltage (5 MV). The same compounds may be used on the 230 kV cable pending successful results on the first cable.

3.8 Irradiation Mode II

An effort was made to improve longitudinal uniformity by "stepping" samples through the diode. Results of optical densitometer scans made on cellophane sheets exposed in this mode are given above under "Circumferential Uniformity", Sec. 2.3; the three step protocol was found to offer much improved uniformity and was used in all Irradiation Mode II tests.

In addition to moving the stack in three steps through the diode, the polymer plaques or tapes were reversed on the mandrel after 50% of the total dose. That is, the surface facing radially outward was turned over and was made to face inward; see Fig. 10. If more than one layer of polyethylene was involved, as in some initial tests, the layer position in the stack was not altered. For example, the "outer layer specimen" would be turned over, but would remain the "outer layer specimen". Reversing the polyethylene sample had the beneficial effect of moving the minimum dose from the inner surface to its mid-thickness. On thin samples where the exponential depth-dose curve was more linear, the mean dose was approximately equal to surface dose.

While the limited output of the PEBS machine made it necessary to reverse sheets, it did not follow that similar attenuation occurred in thicker walled cable samples as will be reported in Section 4.

Detail Describing Specimen Preparation

Fig. 10
Specimen Preparation

3.9 Irradiation Mode III

Stepping the samples through the diode improved longitudinal uniformity and more closely simulated the eventual method of irradiating cable. An even better parallel was devised in "Irradiation Mode III" where samples were pulled through the diode at constant speed. The puller consisted of a motor driven drum which reeled a line attached to a 1 m long aluminum pipe; the pipe served as a mandrel upon which specimen tapes were wrapped. The PEBS was fired at a constant pulse rate of 3.75 pps.

Linear velocity of the puller, essential to reproducibility, was excellent. This enabled building high doses in a series of constant amplitude steps or passes. Total dose at the end of the process was equal to the product of dose per pass and the number of passes. The constant speed of cable transport through the diode with the corresponding uniform dosing, made possible "Dosimetry III", described above.

3.10 Evaluation of Insulating Polyethylenes

Tables I and II list all the potential insulating polyethylene homopolymers considered as candidates for the first cable prototype to be irradiated at 5 MV. The last two columns of Table III list the "Mean Dose", described in Fig. 7, versus solvent extraction. The latter, being a measure of crosslink density, is plotted versus dose in Fig. 11. The plots clearly indicate that Alathon PE 3505, having the highest molecular weight of the polymers tested, was more responsive to irradiation than any of the tested polyethylenes. This was predictable⁽⁹⁾: irradiation acts to increase molecular weight to the gel stage, therefore, it follows that a high molecular weight polymer will reach the desired gel stage sooner than a lower molecular weight polymer. Table Ia lists physical properties in descending order of molecular weights. Table Ib compares the tensile and elongation measurements with dose for three of the primary insulation candidates. The test used is described in a widely used industrial document⁽¹³⁾ for specifying cable materials. Comparing these physical parameters before (0 Mrads) and after two dose levels, it can be seen that little degradation had taken place. The minor loss in properties is typical of non-irradiated polyethylene, eg. chemical XLPE, and is not attributed to irradiation.

Of the eleven types of polyethylene homopolymers tested, three appear to offer good potential as insulation for the first cable: Alathon PE 3505, NA-310-06 and ESMV 871-30 (TREBAN 100). Of the three, 310-06 has the highest commercial use, and extrudes very well. At the time of this report, ESMV 871-30 was still relatively new. All three have good electrical and physical properties.

Selection of the initial insulating polymer must recognize the absolute necessity of achieving sufficient crosslinking density (minimum 70%) of heavy walled cable without causing radiation-induced-defects - such as porosity and treeing. It must be further understood that the probability of encountering operational difficulties with the 7 MV machine is very real, particularly in the initial stages. For these reasons it is recommended that Alathon PE 3505, requiring less dose to crosslink, be selected for the first heavy wall cable, tentatively rated at 138 kV. NA-310-06 would be a satisfactory second choice.

It is essential for whatever semi-conducting and insulating polymers are used that they be carefully inspected and sufficiently screened to provide the cleanest, most contaminant-free raw material that is possible to obtain. It is apparent that contamination may be the source of high localized stress in the cable both during irradiation and in subsequent operation at power frequency.

With respect to the potential tree resistance of ESMV 871-30 (TREBAN 100), some comments are warranted. All types of thermoplastic polyethylene have been considered more prone to electrical and electrochemical treeing than chemically cured polyethylene⁽¹⁴⁾⁽¹⁵⁾. One reason for this is thought to be a voltage stabilizing effect of the by-products of chemical cross-linking, primarily acetophenones. Tree-resistant polymers would offer irradiated polyethylene similar benefits and may be even more permanent in tree-resistant characteristics. At the present stage of development, TREBAN 100 should not be considered a prime candidate because it requires approximately twice the dose indicated for PE 3505. After the radiator has been perfected, TREBAN 100 should be reconsidered for the 230 kV cable, where the cable properties must be optimized. Likewise other tree resistant polymers as may be available should be considered.

TABLE Ia
PHYSICAL PROPERTIES OF INSULATING POLYETHYLENES

<u>Resin</u>	<u>Supplier</u>	<u>$\bar{M}_n$</u>	<u>$\bar{M}_w$</u>	<u>MWD</u>	<u>MI</u>	<u>Density</u>
Alathon PE 3505	Du Pont	30,000	500,000	16.7	.31	920
ESMV 871-30 (TREBAN 100)	Du Pont	31,000	480,000	15.5	.35	920
Alathon PE 2560	Du Pont	30,000	400,000	13.3	1.80	919
DFDA-6005	Carbide	45,000	400,000	8.9	.20	920
DFDA-6603	Carbide	45,000	400,000	8.9	.20	920
HFDA-4201 (base)	Carbide	35,000	300,000	8.6	2.00	---
NA-310-06	USI	20,500	115,900	5.7	.25	917
A and B (Note 1)	USI	20,500	115,900	5.7	.25	917
C and D (Note 2)	USI	17,000	112,000	6.6	1.0	---

$\bar{M}_n$ Number average molecular weight

$\bar{M}_w$ Weight average molecular weight

MWD $\bar{M}_w \div \bar{M}_n$

MI Melt Index

Density Kg/m³

Note 1: USI experimental compound with NA-310-06 base

Note 2: USI experimental compound with unknown base

TABLE Ib
PHYSICAL PROPERTIES OF IRRADIATED CROSSLINKED POLYETHYLENE

Reference IPCEA Pub. No. S66-524, Sections 3.7, 6.4.11 and 6.4.12

Material		Specimen #	Thickness mils	Dose MR	Sol Ext %	** 200% Mod psi	** Elong. %	** Tensile psi	Unaged/ Aged % Chg Elong.	Unaged/ Aged % Chg Tensile	Unaged/ Aged % Chg Reqd.
3505N	Orig.	-	10	0	-	2000	460	3013			
	Unaged	#3	10	3.5	50.4	2400	447	3600			
	Aged	#3	12	3.5	50.4	-	473	4000	106	83	75
	Unaged	#6	10	13.7	25.8	2400	473	3467			
	Aged	#6	9	13.7	25.8	-	417	3805	88	110	75
	Orig.	-	20	0	-	2000	620	2893			
871-30 (TREBAN)	Unaged	#2	9	10.2	41.1	2505	317	3097			
	Aged	#2	12	10.2	41.1	-	540	3022	170	98	75
	Unaged	#3	12	19.8	28.9	2000	567	3311			
	Aged	#3	12	19.8	28.9	-	560	3400	99	103	75
310-06	Orig.	-	13	0	-	1933	523	2439			
	Unaged	#4	14	7.1	43.7	2286	550	2857			
	Aged	#4	14	7.1	43.7	-	437	1904	80	67	75
	Unaged	#2	14	19.4	25.9	1657	413	2857			
	Aged	#2	14	19.4	25.9	-	447	2952	109	103	75
	Orig.	-	13	0	-	1933	523	2439			

**Listed values are the average of three measurements for each specimen number.

MEAN DOSE VS. SOLVENT EXTRACTION
FOIL INSULATING AND CONDUCTING POLYMERS

Fig. 11

TABLE II
INSULATING POLYETHYLENE TAPES AND PLAQUES
DOSE VS. SOLVENT EXTRACTION

<u>Specimen Description</u>	<u>Dosimetry Mode</u>	<u>Irrad. Mode</u>	<u>Thickness</u> <u>Mils mm</u>		<u>Mean Dose Mrad</u>	<u>% Sol. Ext.</u>
HFDA-6005	I	I	11	.29	77.8	5.6
HFDA-6005	I	I	12	.31	46.8	14.4
HFDA-6005	I	I	12	.31	33.5	17.2
HFDA-6005	I	I	12	.31	29.8	24.4
HFDA-6005	I	I	11	.29	25.7	28.6
HFDA-6005	I	I	12	.31	27.7	31.9
HFDA-5006	I	I	11	.29	9.4	36.1
HFDA-6005	I	I	12	.31	14.3	40.0
HFDA-6005	I	I	11	.29	7.8	46.2
HFDA-6005	I	I	11	.29	8.4	50.3
HFDA-4201 ⁽¹⁾	II	II	5	.13	63.3	17.4
HFDA-4201 ⁽¹⁾	II	II	5	.13	32.9	19.8
HFDA-4201 ⁽¹⁾	II	II	5	.13	23.9	26.1
HFDA-4201 ⁽¹⁾	II	II	5	.13	29.4	30.0
HFDA-4201 ⁽¹⁾	II	II	5	.14	16.8	34.7
HFDA-4201 ⁽¹⁾	II	II	5	.14	13.8	41.6
HFDA-4201 ⁽¹⁾	II	II	5	.13	10.1	41.7
HFDA-4201 ⁽¹⁾	II	II	6	.15	9.2	49.0
HFDA-4201 ⁽¹⁾	II	II	5	.13	4.1	56.2

(1) No chemical crosslinking agent (dicup)

TABLE II (cont'd.)
INSULATING POLYETHYLENE TAPES AND PLAQUES
DOSE VS. SOLVENT EXTRACTION

<u>Specimen Description</u>	<u>Dosimetry Mode</u>	<u>Irrad. Mode</u>	<u>Thickness</u>		<u>Mean Dose Mrad</u>	<u>% Sol. Ext.</u>
			<u>Mils</u>	<u>mm</u>		
Alathon PE 2560	II	II	2.6	.067	54.4	19.8
Alathon PE 2560	II	II	2.7	.067	36.8	27.5
Alathon PE 2560	II	II	2.6	.067	32.8	30.7
Alathon PE 2560	II	II	2.6	.065	23.1	31.9
Alathon PE 2560	II	II	2.6	.067	19.4	41.1
Alathon PE 2560	II	II	2.6	.067	12.0	46.7
Alathon PE 2560	II	II	2.6	.067	14.5	47.7
Alathon PE 2560	II	II	2.7	.068	9.5	-
Alathon PE 2560	II	II	2.7	.069	8.2	54.1
Alathon PE 2560	II	II	2.6	.066	6.2	58.6

TABLE II (cont'd.)
INSULATING POLYETHYLENE TAPES AND PLAQUES
DOSE VS. SOLVENT EXTRACTION

<u>Specimen Description</u>	<u>Dosimetry Mode</u>	<u>Irrad. Mode</u>	<u>Thickness</u>		<u>Mean Dose Mrad</u>	<u>% Sol. Ext.</u>
			<u>Mils</u>	<u>mm</u>		
DFDA 6603	II	II	8	.20	47.0	14.9
DFDA 6603	III	III	7	.19	52.8	15.4
DFDA 6603	III	III	8	.21	42.7	20.2
DFDA 6603	III	III	8	.21	27.8	21.8
DFDA 6603	II	II	8	.20	22.3	24.1
DFDA 6603	II	II	8	.21	24.5	25.7
DFDA 6603	II	II	8	.21	15.8	32.9
DFDA 6603	III	III	-	-	-	34.5
DFDA 6603	II	II	8	.20	8.9	40.0
DFDA 6603	II	II	8	.20	7.4	44.7
DFDA 6603	III	III	8	.21	10.2	44.9
DFDA 6603	II	II	8	.20	4.4	64.9
DFDA 6603	II	II	8	.20	2.1	74.5
DFDA 6603	II	II	8	.21	0.9	98.3

TABLE II (cont'd.)
INSULATING POLYETHYLENE TAPES AND PLAQUES
DOSE VS. SOLVENT EXTRACTION

<u>Specimen Description</u>	<u>Dosimetry Mode</u>	<u>Irrad. Mode</u>	<u>Thickness</u> <u>Mils</u> <u>mm</u>		<u>Mean Dose Mrad</u>	<u>% Sol. Ext.</u>
ESMV871-30 (TREBAN 100)	III	III	13	.33	31.4	20.2
ESMV871-30 (TREBAN 100)	III	III	10	.26	19.8	28.9
ESMV871-30 (TREBAN 100)	III	III	10	.26	10.2	41.1
ESMV871-30 (TREBAN 100)	III	III	10	.26	9.5	43.2
ESMV871-30 (TREBAN 100)	III	III	13	.32	12.5	47.3
Alathon PE 3505	II	III	10	.25	20.5	22.3
Alathon PE 3505	II	III	10	.25	13.7	25.8
Alathon PE 3505	II	III	10	.25	13.6	26.6
Alathon PE 3505	II	III	10	.26	3.5	50.4
Alathon PE 3505 & SR	II	III	10	.25	21.8	20.8
Alathon PE 3505 & SR	II	III	10	.24	17.6	23.8
Alathon PE 3505 & SR	II	III	10	.24	15.7	25.6
Alathon PE 3505 & SR	II	III	10	.25	4.8	44.5

TABLE II (cont'd.)
INSULATING POLYETHYLENE TAPES AND PLAQUES
DOSE VS. SOLVENT EXTRACTION

<u>Specimen Description</u>	<u>Dosimetry Mode</u>	<u>Irrad. Mode</u>	<u>Thickness</u>		<u>Mean Dose Mrad</u>	<u>% Sol. Ext.</u>
			<u>Mils</u>	<u>mm</u>		
NA 310-06	III	III	13	.32	33.4	17.4
NA 310-06	III	III	.13	.33	19.4	25.9
NA 310-06	III	III	12	.31	8.4	36.3
NA 310-06	III	III	13	.33	7.1	43.7
USI "A"	III	III	10	.25	11.7	42.2
USI "A"	III	III	10	.26	23.8	30.4
USI "A"	III	III	10	.26	32.7	25.2
USI "B"	III	III	10	.25	13.5	42.3
USI "B"	III	III	10	.25	22.0	32.9
USI "B"	III	III	10	.26	32.4	25.6
USI "C"	III	III	12	.31	11.9	40.9
USI "C"	III	III	12	.31	20.9	32.9
USI "C"	III	III	12	.31	31.0	25.6
USI "D"	III	III	12	.32	10.6	41.4
USI "D"	III	III	12	.32	20.8	34.1
USI "D"	III	III	12	.32	30.2	27.2

3.11 Evaluation of Miscellaneous Insulating Polymers

Four types of miscellaneous ethylene polymers containing radiation accelerators were evaluated. Chlorinated polyethylene (CPE 1109-16) and chlorosulfonated polyethylene (PS 438) achieved 70% gel content at about one-half the dose required for the best radiation sensitive polyethylene. The EPR's (PS 454 and PS 528) also responded very well. The chlorinated polyethylene was a Dow Chemical compound containing 4 phr of trimethylol propane trimethacrylate. The PS compounds are supplied by Polymer Services, Inc., and contain proprietary quantities of accelerators.

It is not suggested that any of these compounds be considered at this time. It is apparent, however, that radiation crosslinking of high voltage power cable need not be limited to polyethylene. Indeed, radiation-crosslinked EPR with or without an accelerator would be a logical consideration for the 7 MV machine.

Table III lists the miscellaneous insulating polymers tested, comparing solvent extraction and dose.

TABLE III
MISCELLANEOUS INSULATING ETHYLENE POLYMERS
DOSE VS. SOLVENT EXTRACTION

<u>Specimen*</u> <u>Description</u>	<u>Dosimetry</u> <u>Mode</u>	<u>Irrad.</u> <u>Mode</u>	<u>Thickness</u>		<u>Mean</u> <u>Dose</u> <u>Mrad</u>	<u>%</u> <u>Sol.</u> <u>Ext.</u>
			<u>Mils</u>	<u>mm</u>		
PS 454 EPR	II	II	9	.23	4.1	25.1
PS 454 EPR	II	II	8	.19	19.0**	27.4
PS 454 EPR	II	II	8	.21	9.4	28.2
PS 454 EPR	II	II	8	.21	29.7**	34.6
PS 454 EPR	II	II	8	.20	3.7	37.6
PS 454 EPR	II	II	9	.23	3.2	45.5
PS 454 EPR	II	II	8	.20	6.3	52.7
PS 528 EPR	II	III	10	.25	19.5	12.9
PS 528 EPR	II	III	10	.24	15.4	17.4
PS 528 EPR	II	III	10	.24	14.8	18.1
PS 528 EPR	II	II	9	.22	32.2**	19.4
PS 528 EPR	II	II	9	.22	6.3	31.8
PS 528 EPR	II	II	10	.25	4.1	32.3
PS 528 EPR	II	II	9	.23	18.3**	32.9
PS 528 EPR	II	II	11	.28	2.8	61.1

* All miscellaneous polymers contained radiation accelerators.

** Apparent error in dose or solvent extraction
or non-uniformity of material.

TABLE III (cont'd.)
MISCELLANEOUS INSULATING ETHYLENE POLYMERS
DOSE VS. SOLVENT EXTRACTION

<u>Specimen*</u> <u>Description</u>	<u>Dosimetry</u> <u>Mode</u>	<u>Irrad.</u> <u>Mode</u>	<u>Thickness</u>		<u>Mean</u> <u>Dose</u> <u>Mrad</u>	<u>%</u> <u>Sol.</u> <u>Ext.</u>
			<u>Mils</u>	<u>mm</u>		
PS 438 Hypalon	II	II	13	.34	22.4	18.3
PS 438 Hypalon	II	III	11	.27	15.5	21.2
PS 438 Hypalon	II	II	14	.35	12.9	23.0
PS 438 Hypalon	II	III	11	.27	9.9	24.4
PS 438 Hypalon	II	III	11	.28	2.7	38.8
CPE 1109-16 Chlor. PE	II	III	10	.24	14.5	18.8
CPE 1109-16 Chlor. PE	II	III	9	.24	9.8	23.3
CPE 1109-16 Chlor. PE	II	III	10	.24	2.7	39.1

* All miscellaneous polymers contained radiation accelerators.

3.12 Evaluation of Semi-Conducting Polymers

Five semi-conducting polymers have been evaluated: HFDA 0580 (less dicup), Alathon PE 6736 and 6739, YR92-126 and DHDA 7704. All are commercially available and are thought to comply with cable industry specifications: AEIC 5-75, and IPCEA S-66-524 and S-61-402. Comparison of the response to radiation is shown in Fig. 11, a plot of mean dose versus solvent extraction, ASTM 2765. While industry practice does not generally use solvent extraction to specify crosslink density of semi-conducting polymers, it has been used in this study. Proper allowance for the insoluble fillers believed to be sufficient for a qualitative comparison. Fig. 11 indicates Alathon PE 6736 to be the most responsive to radiation. Assuming solvent extraction to be a valid test, PE 6736 required 13 Mrad to achieve a 70% gel content. Table IV compares solvent extraction and dose.

An alternate test method to extraction, now employed in Europe and currently under evaluation in this country, is a deformation resistance test. The procedure measures creep: elongation for a tensile stress of 20 N/cm² (30 psi) with the specimen at 150°C or 200°C. It appears valid for insulating and semi-conducting plaques having the necessary thermal ratings.

Fig. 12 illustrates elongation at 150°C versus dose for PE 6736. An elongation of 75% is considered equivalent to a 75% gel content; specified by IEC-20 in Europe and tentatively accepted by Task Group 524E of IPCEA. Accordingly, PE 6736 would have an acceptable deformation resistance (175% elongation) for use in cable rated at 130°C emergency operating temperature, when dosed at 11.5 Mrad. This compares very favorably with the 11.8 Mrad required for the Alathon 3505 insulating polyethylene, Fig. 11.

Figure 12 ELONGATION VS DOSE
AND SOLVENT EXTRACTION
VS DOSE FOR SEMICONDUCTING
PE 6736 POLYETHYLENE

For radiation and crosslinking of power cable, it is essential that the insulation and both inner and outer shields be properly crosslinked simultaneously without overdosing or underdosing. Hence, it will be necessary to assure that the cable is sufficiently dosed to provide adequate deformation resistance of all components to operate up to 130°C at the conductor. Likewise, it is essential that acceptable conductivity of both shields be maintained after radiation. Table V lists three polymers comparing dose, solvent extraction, and conductivity (volume resistivity). The test results show that 6736 and 6739 have uniform conductivity from 25-130°C for a dose range of 10-40 Mrads. This suggests that conductivity can be maintained after the required dose necessary for adequate crosslinkage.

It will be shown in Section 4 that it is possible to achieve uniform crosslink density at the inner, middle and outer zones of a 15kV cable. Assuming similar uniformity on the first cable to be irradiated at 5 MV, it should be possible to obtain the desired thermal properties at a dose of 11-13 Mrad, using PE 3505 as insulation and PE 6736 for both semiconducting shields.

TABLE IV
SEMICONDUCTING POLYETHYLENE TAPES AND PLAQUES
DOSE VS. SOLVENT EXTRACTION

<u>Specimen Description</u>	<u>Dosimetry Mode</u>	<u>Irrad. Mode</u>	<u>Thickness</u>		<u>Mean Dose Mrad</u>	<u>% Sol. Ext.</u>
			<u>Mils</u>	<u>mm</u>		
HFDA 0580*	I	I	-	-	>>10	7.4
HFDA 0580*	I	I	11	.28	>10	16.1
HFDA 0580*	I	I	12	.30	23.4	22.9
HFDA 0580*	I	I	15	.38	18.1	25.5
HFDA 0580*	I	I	-	-	>10	31.6
HFDA 0580*	I	I	14	.36	12.2	48.5
HFDA 0580*	I	I	16	.41	7.7	67.2
HFDA 0580*	I	I	15	.38	5.9	81.7
Alathon PE 6736	II	II	15	.38	43.6	11.0
Alathon PE 6736	II	II	12	.31	26.1	17.3
Alathon PE 6736	II	II	11	.29	16.0	26.8
Alathon PE 6736	II	II	12	.31	10.5	37.0
Alathon PE 6736	II	II	13	.33	7.9	38.4

* Union Carbide chemically crosslinked compound, but without crosslinking additive (dicup).

TABLE IV (cont'd.)
SEMICONDUCTING POLYETHYLENE TAPES AND PLAQUES
DOSE VS. SOLVENT EXTRACTION

<u>Specimen Description</u>	<u>Dosimetry Mode</u>	<u>Irrad. Mode</u>	<u>Thickness</u> <u>Mils</u> <u>mm</u>		<u>Mean Dose Mrad</u>	<u>% Sol. Ext.</u>
Alathon PE 6739	II	II	13	.34	41.7	17.2
Alathon PE 6739	II	II	14	.35	27.5	24.7
Alathon PE 6739	II	II	14	.35	23.4	26.9
Alathon PE 6739	II	II	15	.38	9.0	49.0
Alathon PE 6739	II	II	14	.35	8.7	57.1
YR 92-126	III	III	14	.36	27.0	22.7
YR 92-126	III	III	13	.34	16.7	38.2
YR 92-126	III	III	13	.34	7.5	64.6
YR 92-126	III	III	14	.35	5.5	77.2
DHDA 7704 BK 55	III	III	11	.27	23.4	25.5
DHDA 7704 BK 55	III	III	10	.26	14.4	39.9
DHDA 7704 BK 55	III	III	10	.26	8.0	60.2

TABLE V
VOLUME RESISTIVITY OF IRRADIATED CROSSLINKED
SEMI-CONDUCTING POLYETHYLENE

Compound No.	Volume Resistivity, ohm-cm			Dose Mrad	Solvent Ext. %
	25°C	90°C	130°C		
6736	8	13	9	10	37
	10	16	13	16	27
	5	8	9	44	11
6739	13	18	15	9	49
	11	15	24	23	27
	15	21	50	42	17
7704	30	328	1580	8	60
	26	342	3847	14	40
	25	379	8398	23	26

SECTION 4

IRRADIATION OF MODEL CABLES

4.0 Summary of Section 4

The availability of a 4.8 MV Van de Graaff pulse generator provided a fortunate opportunity to investigate the radiation response of medium walled PE cable using a toroidal diode. Initial tests were plagued by serious treeing and outgassing. Various techniques to correct these defects were investigated, eg. temperature variation, pressure, DC bias and cathode modification. Regardless of technique, elimination of defects required the limiting of specimen thickness substantially below the electron range. Eventually, samples were produced without apparent treeing or bubbling. This was accomplished using a modified cathode and reduced dose per pulse. No variation of temperature or pressure was required. A voltage endurance test at high stress indicated the dielectric was not adversely affected by radiation.

4.1 Early Work

To irradiate cable samples having walls of representative thickness and cross sections of typical construction, the 360 degree diode was moved to a 4.8 MV pulse generator, and mounted there. First items irradiated included mock cables made of rolled mylar with interleaved blue cellophane and short lengths of extruded polyethylene insulated cable of various wall thicknesses, comparable to 15 to 35 kV cable. Experiments with stepwise radiation of mock cables were among the first conducted, objective being to develop a procedure which would give good axial uniformity; it was found that 2 inch steps through the diode proved satisfactory.

Following radiation exposure, cable segments were evaluated to determine the extent of crosslinking. Solvent extraction tests were conducted on shavings taken from radial strips, Fig. 18, machined from each cable, thus making it possible to measure crosslink density versus depth. The 35 kV cable was not crosslinked all the way to the center conductor; this result was expected, as electron range measured with mylar mock-ups was 0.80 gm/cm^2 ,* corresponding to an insulation thickness of 0.34 inches (8.64 mm) in polyethylene density 0.92 gm/cm^3 . Including insulation and both semi-conducting shields, the 35 kV cable contained about 0.42 inches (10 mm) of polyethylene, considerably greater than range.

* For the following conditions: 4.85 MV charging voltage, 8 cathode needles on 7.25 in centers, 1 mil aluminum window, 2 inch cathode shank, shank coated with shrink tubing. Range was subsequently extended with modification of the cathode.

The 15 kV cable consisted of 0.02 inches (.51 mm) semi-conducting PE strand shield, 0.175 inches (4.45 mm) insulation, and 0.03 inches (.76 mm) PE semi-conducting insulation shield. Total mass thickness was about 0.53 gm/cm², somewhat less than the .80 gm/cm² range measured in mylar. Extraction tests showed excellent radial uniformity of cross-linking: 20.6 percent next to insulation shield and 28.6 percent adjacent to conductor shield.*

This was obtained with an irradiation protocol which called for 2 inch steps through the diode with 12 shots at each step, the cable being rotated a quarter turn after every three shots to compensate for circumferential non-uniformity introduced by shank emission. Peak dose was estimated to be 13.8 megarads for the 15 kV cable sample.

In both 15 and 25 kV cables, however, trees were found which ran axially along the cable with branches spreading circumferentially at approximately constant radius. The treeing often took the form of a single widespread tree rather than many smaller ones. It is believed that trees resulted from an accumulation of charge near range, with the buildup of high internal fields, relief being obtained by puncturing through to the conductor and draining of the charge sheet. If this is the mechanism, it is surmised that treeing would be eliminated by preventing charge buildup. There are a number of ways in which this might be done; some are listed below.

* Test results for cable samples are summarized in Table VIII listing solvent extraction versus dose.

- * provide sufficiently energetic electrons such that electrons thermalize primarily in the center conductor
- * reduce insulation thickness (has same effect as above, i.e. increase ratio of range to thickness)
- * decrease dose per pulse, employ multiple passes, and allow time for charge leakage between exposures
- * increase dose rate to take advantage of radiation-induced conductivity, promoting charge leakage during a pulse
- * heat the insulation to reduce sensitivity and increase the rate of charge leakage
- * blend in additives to increase sensitivity of internal conduction phenomena to dose rate, to decrease resistivity, or to provide local stress relief through ionization.

4.2 Attempts to Prevent Tree Formation

Preliminary experiments were conducted to investigate these possibilities using RG17A/U transmission line cable, because it was available in relatively large quantities, is extruded polyethylene insulated, and its insulation thickness of .25 inches (6.3 mm) corresponded roughly to that of 15 kV shielded power cable. Center conductor diameter was smaller than power cable, hence its maximum stress would be higher.

Dimensions of the transmission line wire are listed in Table VI.

TABLE VI
 DIMENSIONS OF TRANSMISSION LINE WIRE
 WITH EXTERNAL SHIELD AND JACKET REMOVED
 RG TYPE WIRE

RG	Avg OD		Avg Cdr		Avg Wall		Min Wall		Max	
	mils	mm	mils	mm	mils	mm	mils	mm	mils	mm
8-solid	290	7.37	82	2.1	104	2.64	90	2.3	121	3.07
8 U	293	7.44	69	1.8	113	2.87	105	2.67	119	3.02
14 A/U	367	9.32	104	2.64	131	3.33	127	3.23	140	3.56
17 A/U	688	17.5	190	4.83	249	6.32	246	6.25	253	6.43

NOTE: Published versus actual dimensions differ considerably for these coaxial cables. The above values represent typical dimensions of the cable specimens irradiated. Because this material is mass produced it was not possible to identify the type plastics used. It can be reported that it was unfilled, unshielded low density polyethylene with a density of 920 kg/m³.

An initial concern was that treeing might be caused by circumferential non-uniformity of charge deposition. This was raised as a possible explanation for the observation that trees seem to run circumferentially at constant radius, along paths that ought to be isopotential. By installing the same cathode used in 300 kV irradiations it was possible, however, to get good circumferential uniformity. Still, treeing did not disappear.

In a second experiment, RG17 was irradiated through a 1 inch wide circumferential slit in an attempt to block out any electrons which might be striking the cable at large angles of incidence. This followed from the discovery that trees seemed to appear not directly under the diode center-line, but slightly off to one side, where penetration might be foreshortened by oblique incidence. Screening cable in this fashion did not eliminate treeing.

An attempt was made to reduce total dose by limiting the number of shots delivered to a particular irradiation site to one; in previous work many shots had been accumulated. This appeared to be successful on the first attempt, whereupon an expanded series of pulses was made to obtain statistics. It was found that seven of ten single pulses, injected at a discreet location on previously unirradiated RG17, produced treeing. While reduced charge injection did not eliminate trees, it was noted that they did not always occur, suggesting that this could be a step in the right direction.

It should be noted that treeing was determined by unmagnified observation; the possibility of microscopic trees is not ruled out.* Samples were immersed in hot oil of sufficient temperature to make the polyethylene transparent. Frequently one heavily carbonized tree was involved, with a main channel running parallel and close to the conductor. Branches wrapped around the conductor, sometimes emerging to the outside surface. See Fig.

To determine whether there was a polyethylene thickness below which treeing would not occur, a segment of RG17 was cut into a series of steps with insulation ranging from 0.125 inches to full thickness, 0.250 inches. Single pulses were fired into each step, with the results indicated in Table VIIa. Results are based on one test per step.

TABLE VIIa

Polyethylene Thickness, Inches	Thickness gm/cm ²	Treeing?
0.125	0.302	No
0.156	0.378	No
0.188	0.454	Yes
0.218	0.529	Yes
0.250	0.605	Yes

Treeing was observed only in the thicker sections, indicating that it is a function of thickness as a fraction of range. For conditions of this experiment, i.e. the type of diode, character of sample, minimum sampling, it appears that insulation equal to about half range in thickness can be irradiated without producing trees.

A brief investigation of the effect of grounding configurations was made, again using a stepped RG17 segment. Steps were machined onto both ends of a segment; one end was irradiated with the center conductor grounded to the diode, the other with the conductor floating. Results based on one test per step:

Table VIIb

Step Thickness, Inches	Treeing?	
	Conductor Grounded	Conductor Floating
0.125	No	No
0.188	No	Yes
0.250	Yes	Yes

As a final experiment, an attempt was made to diffuse sulfur hexafluoride into full thickness of RG17 by soaking the cable at 250 psi for three days. The intent was to fill any microscopic voids that might exist with SF_6 . A void is considered to be a potential site for tree initiation. Based upon data for gas diffusion rates in polyethylene at atmospheric pressure (obtained from a recent issue of Modern Packaging) it would appear that molecules the size of SF_6 should not readily diffuse through to the center conductor, so hopes were not high for this being effective. Whether or not SF_6 penetrated the polyethylene, treeing was not eliminated.

Figure 13 shows examples of each of the two major types of defects induced in RG17 A/U cable - trees and bubbles. In most instances, bubbles appeared only after the insulation was heated to transparency by plunging samples into hot oil. Prolonged immersion at high temperature usually caused them to disappear. For this reason it is felt that aggregation of gas into bubbles of visible size can probably be prevented by allowing a waiting period after irradiation, during which diffusion can relieve internal pressure. Cable samples irradiated and then stored for several days were found to contain less porosity.

Cables heated prior to exposure showed a tendency to bubble immediately upon irradiation. This suggests that outgassing may limit the temperature at which cable can be preheated to suppress tree formation.

Heating was found to be effective against treeing, although optimum temperature may approach the melt point of thermoplastic polyethylene. As temperature was raised, it was generally observed that severity of treeing decreased while extent of bubble generation increased. It was hoped that an intermediate point might be found where treeing stopped before bubbling began, but the two phenomena overlapped in most of the samples tested.

Figure 13 Typical appearance of trees and bubbles in RG 17 A/U cable (solid conductor).

In the pages which follow, results of experiments are presented in chronological order as they were conducted. Data have been lumped together into several general study areas, as indicated below.

- * Effect of irradiation at elevated temperature
- * Effect of positively charged conductor
- * Effect of reducing dose through
 - (a) Screening
 - (b) Cathode modification
- * Thin walled RG cable
- * Cable precooled to 77°K

4.2.1 Effect of Irradiation at Elevated Temperature

Cable samples were heated in place in the diode using a transformer to generate current in the looped conductor. The setup is shown in Fig. 14 with a sample in place. Two tests were made with the conductor floating. The balance of tests were made with the conductor grounded: one end of the center conductor strand was grounded to the diode housing with a clip lead to provide a leakage path for injected current. Aluminum foil served as an insulation shield grounded with the conductor to prevent surface charging and sparking to the window.

Figure 14 Heating loop on FX-35

Thermal control was achieved by monitoring the sheath with thermocouples taped to cable surfaces outside the aluminum foil screen; conductor temperatures were calculated. All temperatures reported correspond to the outer cable surface, unless otherwise stated. The thermal gradient causing a higher temperature on the conductor was considered an advantage if elevated temperatures would suppress treeing as anticipated. The higher temperature near the conductor coincided to the zone where treeing predominated.

Initial experiments were conducted at room temperature with the loop in place, but with the current transformer deenergized; this tested against the possibility that there might be coupling which could damage the transformer, but primarily provided a baseline against which to measure the effectiveness of heating. In irradiation numbers 42 through 45, and 47, 18 single shots were made; of these, 11 produced trees. Thus treeing occurred in 61 percent of the single shots at room temperature. Multiple shot sets of 2 and 3 pulses each were accumulated on test number 45, and treeing occurred under each of these tests.

Test number 46 and 49 were made at a sheath temperature of 43°C. Eleven single shots were made, and trees were found under 10 of the 11 (91 percent). Sets of 2 and 3 pulses were also made on cable 46, and both treed. At 71°C (irradiations 46a and 48), 13 single shots were made, and trees were found under 3; this heating therefore reduced the probability of treeing to about 23 percent, a significant improvement. Intermediate temperatures seemed to be ineffective. See Table VII c.

TABLE VIc
RG17 A/U SAMPLES

Irrad. Test #	Temperature, Sheath	°C Condr.	Number of Shots	Comments	Results
42	20	20	1	Pulsed cable with single shot. Cable floating.	No trees visible under oil. No bubbles.
43	20	20	1	Pulsed cable with single shot in 3 adjacent locations. Cable floating.	Treed. Bubbles in insulation and along conductor.
44	20	20	1	Pulsed cable with 3 shots in adjacent locations. Cable grounded.	No trees. Small bubbles collected on the conductor.
45	20	20	1 2 3	Pulsed adjacent segments 1, 2, and 3 times respectively. Cable grounded.	Massive treeing. Large blackened bubbles on conductor.
47	20	20	1	Pulsed cable with single shots at each of ten locations. Cable grounded.	Trees under seven of the ten sites.
46	43	55	1 2 3	Pulsed adjacent segments segments, 1, 2, and 3 times respectively. Cable grounded.	Massive treeing, much outgassing. Bubbling in the insulation.
49	53	55	1	Pulsed cable with single shots at each of ten locations. Cable grounded.	Treed at nine of ten locations.
48	71	82	1	Pulsed cable with single shots at each of ten locations. Cable grounded.	Treed under one of ten sites. Bubbles under annealed out at temperature.
46a	Near Melt		1	Single shots on each of three locations.	Some small trees. Large bubble areas in the insulation.

NOTES: All irradiations were made with the following conditions:

4.8 MV charging
8. needle cathode, needle tips on 18.8 cm dia.
 2×10^{-4} torr vacuum
shorting coil in place
1 mil Al window

In summary, heating to 71°C dropped the percentage of single shots which resulted in treeing from 61 to 23 percent; multiple shots at the same site produced massive treeing at room temperature and at 43°C. At both 43 and 71°C, bubbles were generated in the polyethylene.

4.2.2 Application of Positive Voltage to Conductor

It was hypothesized that space charge fields which initiate breakdown might be countered by raising the conductor to a sufficiently high positive voltage prior to irradiation. This could also result in range extension and transport of residual electrons to the conductor, thus clearing the insulation and promoting crosslinking near the conductor. In keeping with this, a positive DC supply rated for nominal 180 kV was set up as shown in the circuit sketched below. The storage capacity was chosen to be much greater than the cable so that the conductor would remain grounded during irradiation. On the first attempt to pulse a cable sample (irradiation 49a), the DC supply capacitor was charged to +60 kV, at which point there was audible corona from some portion of the setup. Current was about 0.1 ma, giving a drop or less than 1 percent over the isolation resistor. While the accelerator was being charged, but before it had been triggered, the cable punctured. An arc was struck to the window, holing it and venting the diode to atmosphere.

This sequence of events was noisy and somewhat unnerving; it instilled a sense of conservatism as regarding charging voltage on subsequent shots. For irradiation 50, the cable was charged to +10 kV; 51 and 52 were charged to +25 kV. All three of these samples were subjected to single pulses* and all three developed trees several inches long, running along the cable parallel to the conductor with branches wrapped around it, with a main stem eventually going down to the conductor.

It was concluded after these tests that positively charging the conductor was not effective up to 25 kV. It would appear, however, that higher bias is possible since the industry specified proof test for cable is 125 kVDC, and intrinsic dielectric strength is considerably higher.

*At 4.8 MV machine charging voltage with an 8 needle cathode.

4.2.3 Reduction of Dose per Pulse

a. Screening

It was theorized that if the charge injected per pulse were low enough, it would drop below the value needed to established break-down stress. Several techniques were therefore tried in an effort to reduce current density incident on cable samples. First of these was to overwrap with a layer of aluminum screening to intercept a fraction of the incoming electrons. The screen was manufactured from 10 mil diameter wire, 18 wires to the inch in one direction, and 16 to the inch in the other. Assuming complete opacity of the wires, the screen occluded approximately 30 percent of the surface area. One, two, and three layers were used on successive irradiations, with the results tabulated below. An irradiation consisted of a single pulse on RG17 A/U, and was made with an 8 needle cathode. Screens nominally reduced the dose to about 70, 40, and 20 percent for 1, 2, and 3 layers respectively. Trees were generated in all three cable samples. Results are shown in Table VIId.

TABLE VIId

Irradiation Number	Layers of Screen	Approximate Surface Area Occluded, %	Results
53	1	32	Treed in several places
54	2	59	Treed
55	3	79	Treed in two places. Trees emerged to the surface

Upon consideration it appears that screening may have actually been counterproductive; for the accelerating voltage being applied, electron range in aluminum should be about 1.0 gm/cm², or 0.14 in. (3.6 mm). Screen wires were, therefore, certainly not opaque, and their primary effect was to cause a portion of the beam to slow down, thus decreasing range. This is an undesirable effect, and is one which would be worsened by adding layers.

To successfully reduce dose, a mesh would have to consist of elements about 0.15 (3.8 mm) thick. Even if it were opaque to electrons, this would be a poor approach because of:

- * Inefficiency. Wastes energy.
- * Shadowing. Would need to mix the beam after the mesh. The transverse velocity so introduced would shorten range.
- * Heating. Would have to remove waste heat from the mesh in a production machine.

b. Cathode Modification

The preferred means of cutting down current density would be to choose a cathode design which spreads electrons over a larger area. Accordingly, a series of experiments was undertaken with the objective of building a cathode giving greater beam dispersal without sacrificing range. Approaches tried were to double the number of needles to 16 using a pair of side-by-side cathodes, and to use perforated metal of various lengths and diameters. Perforated metal was suggested by a comment found in a paper by Bradley et al⁽¹⁶⁾ to the effect that a cylindrical cathode could be made "from titanium sheet, perforated to produce an array of spikes". Bradley claims to have achieved a dose variation of less than 10 percent along the length of his tube (which was small, 7 cm long, 3 cm diameter). A commercial stainless steel perforated sheet having holes about 0.25-in. diameter was used, with sharp edges located on the interior of the cylinder. Initial tests were made with bare metal, but it was subsequently found that coating with graphite paint seemed to improve emission characteristics. Diameters of perforated metal cathodes were selected for convenience to coincide with either the inside or outside of rings used with needles cathodes, these rings being used for stress relief at the metal edges as shown in Fig.15

Because it was anticipated that diode impedance might be reduced when perforated metal was used (because of a larger number of emission sites), one such cathode was made short in an effort to compensate, and keep impedance up. Dimensions of the three metal cathodes were:

Diameter, Inches cm		Length, Inches cm	
8.25	21.0	10	25.4
11.0	27.9	10	25.4
8.25	21.0	4	10.2

Figure 15 illustrates a 16 needle cathode and three perforated cathodes.

8.25-in. diameter,
10-in. long perforated
metal

16 needles

8.25-in. diameter,
4-in. long
perforated metal

11-in. diameter, 10-in. long
perforated metal

Figure 15 . Cathode configuration tested.

At various times during the study, depth-dose profiles were measured for each cathode using cellophane interleaved between layers of 5 mil Mylar. From these profiles an extrapolated range was obtained, and this gave a measure of peak accelerating voltage, hence of impedance. According to Evans,^(19a) range and energy should be related (approximately by the expression

$$V = \frac{R + 0.106}{0.53}$$

where R is in gm/cm², and V in megavolts. Results of range measurements are summarized below, and estimated peak voltages are given.

TABLE VIId 5 MIL MYLAR SHEETS

Irradiation Number	Cathode Description	Extrapolated Range, gm/cm ²	Peak Voltage Estimated from Evans Formula, MV
56	3 needles	1.1	2.3
57	16 needles	0.8	1.5
67	perforated metal 8.25" dia x 10" long	0.75	1.7
73	perforated metal 8.25" dia x 4" long	0.85	1.8
75	perforated metal 11" dia x 10" long	1.05	2.2
128	perforated metal 11" dia x 10" long graphite paint	1.3	2.4

From this it can be seen that good penetration was achieved with the large diameter perforated metal cathode, particularly when its inside surface was coated with graphite. Every one of the new configurations diffused the beam to a greater extent than the 8 needles, but perforated metal seemed to give better beam spreading and uniformity. The large diameter metal cathode, however, was the only one which gave an impedance (peak voltage) similar to that of 8 needles.

First tests with the 16 needle cathode showed that it produced a region of high dose on the diode centerline, with low dose "wings" extending to either side. Irradiation 58 through 63 were conducted with RG17 at temperatures ranging from room temperature to 71°C, single pulses being delivered in each instance. Severity of treeing decreased as temperature rose; bubble formation was aggravated. Results are listed in Table VIId and are summarized below.

<u>Surface Temperature</u>	<u>Observation</u>
20°C	Treeing. Carbonized channels.
27°C	Treeing. Carbonized channels. Some bubbles.
43°C	Some small white trees. No carbonized channels. High bubble concentration.
52°C	No trees on center line. Small "star" trees in wings. Massive bubble concentration.
71°C	No trees on center line. Small "star" trees in wings. Massive bubble generation.

Irradiation 64 resulted in neither trees nor bubbles in the wings, suggesting that dose there might be below the treeing threshold. On test 65, therefore, a shadow ring was slipped over the sample to block off electrons in the central 1.87-in. (4.7 mm). This showed no bubbles and a very few white trees at the ends of the irradiation zone; these annealed away in the oil bath. Raising the temperature to 52°C and repeating gave a slightly higher density of white trees in the low dose region.

These findings suggested that a combination of reduced dose and temperature could be found which would allow single pulses to be made without treeing, hence attention was turned to the use of cathodes which would give better electron dispersion. Accordingly, the 8.25-in. (21 cm) diameter, 10-in. (25.4 cm) long perforated cathode was installed and used to irradiate RG17 A/U lengths (tests #69-72). Fewer and smaller trees were found than had been seen with needle cathodes; heating to 43°C eliminated trees characterized by heavily carbonized channels, but "bubble" trees remained. These could generally be annealed away.

TABLE VIId
RESULTS OF CATHODE STUDIES
(on RG17 A/U Cable, .25" (6.4 mm) wall)

Irradiation Number	Cathode Type*	Number of Shots	Cable Surface Temp., °C	Comments
58	16 needles	1	21	Trees in both high and low dose regions.
59	"	1	43	Some small white trees (bubble trails) in high dose region. No carbonized channels. All trees annealed away in oil at 230°F.
60	"	1	43	Small white trees (bubble trails) under c/l. Large bubbles under the centerline.
61	"	1	27	Trees in both high and low dose regions. Carbonized channels. Few bubbles
62	"	1	71	Small white "star" tree in low dose region (bubble trails). No trees on c/l. High concentration of bubbles under c/l.
63	"	1	52	Observations same as 62.
64	"	1	43	Repeat of 58. Small white trees under c/l. No carbonized channels. No bubbles in wings.
65	"	1	43	Center of cable shadowed by 1-7/8" long alum. tubing. No trees, no bubbles. A few "star" trees at end of irradiation zone. These annealed away.
66	"	1	52	Center of cable shadowed. Small white "star" trees in the wings.
69	8.25" dia 10" long PM	1	21	Many small unconnected trees going down to center conductor. Some bubbles near center of irradiated zone.

Table VIId continued
Results of Cathode Studies
(on RG17 A/U Cable, .25" (6.4 mm) wall)

Irradiation Number	Cathode Type*	Number of Shots	Cable Surface Temp., °C	Comments
70	8.25" dia 10" long PM	1	Room	Repeat of 69. Observations similar.
71	"	1	43	Many small "bubble" trees going to conductor.
72	"	1	27	Treed regularly all along radiation zone.
74	8.25" dia 5" long PM	1	Room	Many trees with carbonized channels.
76	11" dia 10" long PM	1	Room	One long carbonized tree coming to surface. No bubbles.
85	11" dia 10" long PM graphite paint	1	Room	No trees, and no bubbles.
87	"	3	Room	Treed. Carbonized channels.
88	"	3	38	A line of surface punctures along one side. Deep trees to conductor at ends of irradiation zone.

* PM = perforated metal

Irradiation 74 employed the 5-in. (12.7 cm) long perforated metal cathode at room temperature. This sample treed badly, and was immediately abandoned in favor of the 11-in. diameter, 10-in. long version (27.9 cm, 25.4 cm).

On test #85 a single pulse was put onto RG17 at room temperature without creating either trees or bubbles, using the large perforated metal cathode with a coating of graphite paint. This was followed by multiple pulses at one location, 3 shots being made on test #87 (room temperature) and #88 (38°C). Both treed, but it appeared that evidence had been obtained to suggest reduced current density might decrease the tendency to tree.

4.2.4 Effect of Shorting Line

During testing much difficulty was experienced with machine triggering, and a 25 ft. long helical shorting line was wound around the tube from the high voltage end to ground to short out the bushing during charging. This was done to prevent capacitive coupling across the trigger gap. When the gap discharged, the line provided timewise isolation for about 25 nano-seconds, then the pulse was shorted. This had the side effect of producing a voltage waveform which was approximately trapezoidal, rather than exponentially decreasing as before.

Although it was later shown that the line was not needed for good triggering, it was retained to increase mean accelerating voltage.

4.2.5 Experiments of Thin Walled RG Cables

Following tests with RG17 (0.25-in. wall), a lower voltage cable was irradiated whose insulation thickness was a smaller fraction of range. Results are reported in Table VIIe as irradiation test 117 through 120. In all of these irradiations, the 11-in. diameter coated cathode was employed.

It was possible to make 20 pulses into one location in RG8 without treeing (irradiation 118). Some bubbles accumulated along the solid conductor; it was felt that with a stranded conductor gas would either vent out the ends or accumulate between strands rather than form bubbles. One shot 120, therefore, a stranded version of RG8 was irradiated. After 5 shots no bubbles were noted. Small "spits" from the conductor were seen; these were attributed to asperities on the unshielded strands and it was hypothesized that a semi-conducting strand shield would eliminate them.

TABLE VIIe
RESULTS OF IRRADIATING THIN WALLED CABLE RG
(shots 114-120)

Irradiation	Cable Type	Total Wall Thickness,		Number of Shots	Cable Surface Temp., °C	Comments
		inches	mm			
117	RG 8 sol. cond.	0.10	2.5	1	Room	No trees, no bubbles
118	RG 8 sol. cond.	0.10	2.5	20	Room	No trees, a long bubble accumulated along the conductor. This vented through the cable end in oil
119	RG 8 sol. cond.	0.11	2.9	5	Room	One tree coming to surface at end of irradiation zone, some bubbles
120	RG 8U stranded cond.	0.10	2.5	5	Room	Four small "spits" from conductor. No bubbles.

4.2.6 Results of Pulsing Frozen* Cables

During the evaluation at elevated temperature, it was theorized that bubble formation could be suppressed by irradiating at very low temperature. The effect of chilling samples was investigated in irradiations 121 through 133 (see Table VIIe for details of results). While the motivation for trying this was to eliminate bubble formation, it soon became clear that freezing might be a means of eliminating trees.

First cable irradiated was a length of RG8 solid (0.1-in. wall, solid conductor), 5 shots being made after soaking to equilibrium in liquid nitrogen (LN_2). No treeing was seen when the cable warmed, but there were some bubbles along the conductor. The cable turned a very dark brown over its irradiated length, but this color annealed away with about 30 minutes warming. A second sample (122) was irradiated, left covered, and stored overnight in darkness to determine whether the annealing was thermal or light simulated. This sample annealed also; it was concluded that heat and not light was the agent. This was the hoped for result, as it means that color centers induced under an opaque jacket can be expected to disappear when the insulation returns to room temperature.

Formation of color centers in polyethylene at 77°K is not a new

* In this context, the term "frozen" means temperatures substantially below 0°C, ranging from 266°K (-7°C) to 77°K (-196°C), liquid nitrogen.

discovery; Charlesby noted it in a paper published in 1963⁽¹⁷⁾; Nikolskii et al⁽¹⁸⁾ also refer to this effect ("During low temperature radiolysis polyethylene becomes yellow-brown in color, and the color intensity increases with increase of dose"). These authors attribute color center formation to the stabilization of ions at low temperature, and report that annealing can be stimulated either thermally or by light (of sufficient quantum energy).

Following exposure of the two small cables, a segment of RG17, test #123 was irradiated. No treeing was seen after one shot at 77°K, so the sample was refrozen and pulsed three more times, initiating a tree which came to the surface at one end of the irradiation zone. It was felt that this surface-going tree might have been triggered by surface defects, therefore, the remainder of the work was carried out with power cable segments with extruded insulation shields.

With irradiation test #124 and 125 first 1 and then 5 shots were put onto 15 kV (.275") cable samples cooled in liquid nitrogen; no treeing was observed. Upon stripping the outer shields off, it was noted that discoloration was less prominent than it had been in RG17.

TABLE VIIe (cont'd.)
RESULTS OF IRRADIATING "FROZEN" CABLES
(Shots 121 through 133)

Irradiation Number	Cable Type	Total Wall Thickness,		Number of Shots	Cable Temp., °C	Comments
		inches	mm			
121	RG8 solid	.1	2.5	5	LN ₂	No trees. Bubbles on conductor. Insulation turned brown, but bleached.
122	RG8 solid	.1	2.5	5	LN ₂	No trees. Let sit overnight in dark. Color centers annealed away.
123	RG17 A/U	.25	6.4	4	LN ₂	Large carbonized tree coming to surface at one end of irradiation zone.
124	*Power cable #4	.275	7.0	1	LN ₂	No trees.
125	*Power cable #4	.275	7.0	5	LN ₂	No trees.
126	*Power cable #4	.275	7.0	20	Room	Treed at both ends of irradiation zone. Many bubbles appeared in PE after heating.
127	*Power cable #4	.275	7.0	20	LN ₂	No trees.

* See complete cable description in Table

Table VIIe continued
Results of Irradiating "Frozen" Cables
(Shots 121 through 133)

Irradiation Number	Cable Type	Total Wall Thickness,		Number of Shots	Cable Temp., °C	Comments
		inches	mm			
129	Power cable #4	.275	7.0	20	LN ₂	No trees or bubbles.
131	Power cable #3	.275	7.0	20	LN ₂	No trees.
132	Power cable #3	.275	7.0	20	Room	Large tree near center of irradiation zone.
133	Power cable #3	.275	7.0	40	LN ₂	No trees. No bubbles.

To verify that it was cooling and not the use of power cable which was responsible for the result observed, about 20 shots were made on samples at room temperature (126) and after cooling in liquid nitrogen (127). The room temperature sample treed at both ends of the irradiation zone; no trees were found in the frozen cable. In subsequent irradiations a 20 shot sample was prepared (129) and it was found that 40 shots could be accumulated without treeing (133). In this last instance, the cable was recooled after the first 20 shots.

Irradiation tests 128 and 130 were used to record depth dose profiles. These were measured for a thick roll of cellophane and Mylar (128) and for cellophane rolled between 5 mil polyethylene sheet sized to match the thickness of a 15 kV cable. Results are plotted in Figure 16. Note the substantial difference near the conductor location, where back scattering from the aluminum appeared to help to fill in the curve.

Dose profiles were measured for 10 shots. It is estimated that 20 shots on 15 kV cable (.275") test #129 should have produced a surface dose of 12.9 Mr and a dose at the conductor of 8.2 Mr.

DEPTH DOSE PROFILE FOR
11 INCH DIAMETER
PERFORATED METAL CATHODE

418 MV CHARGING
10 SHOTS TOTAL

Cooling was further examined on irradiation test #144 and 146 through 152. On test #144, a 15 kV cable was cooled to 77⁰K (liquid nitrogen) and pulsed 40 times. It was then sought to determine whether freezing as a pretreatment might be as effective as irradiating cold samples. Accordingly, cable test #146 was soaked in liquid nitrogen and then allowed to heat up to room temperature before pulsing; the delay was 18 hours. Trees were found when the shield was stripped, hence it was concluded that the effect of cooling is immediate and reversible upon warming. Low temperature does not introduce residual changes which are ultimately responsible for suppressing trees.

An attempt was made to determine if cooling to 77⁰K was necessary, or whether some higher temperature might be adequate. This was done on irradiation test #147 through 150 by first cooling cable segments, then delaying the start of irradiation by progressively longer periods to allow the average temperature to increase.

This procedure was not very precise because temperature varied with location in the insulation and with time during the course of irradiation. A rough thermal analysis was made by measuring the surface temperature history of a sample as it warmed, then making a Gurnie-Lurie analysis. This indicated that, after 5 minutes warming, the conductor is approximately 17⁰C cooler than the surface. A difference of this order persists for about 12 minutes of warming, when the two temperatures begin to converge. Very rough "average"* temperatures were estimated as a function of preirradiation delay; these averages were:

*Over space and time

Warming Time, Min.	Arithmetic Mean Temperature During Irradiation, °C
5	-59
10	-27
15	- 7

No trees were observed in any of the samples treated in this way, leading to the conclusion that deep cooling may not be required. Test #149 suggests that irradiation at temperatures near -7°C may be sufficient to suppress treeing. Table VIIf summarizes irradiation tests 144-150.

While low temperature processing of power cable may not be economically feasible, the test results suggest that radiation crosslinking of thick walled polyethylene can be accomplished without treeing. Other techniques more adaptable to cable manufacture are discussed in the sections which follow.

TABLE VIIf
SUMMARY OF CABLE IRRADIATIONS FROM 144 TO 150

Irradiation Number	Cable* Type	Total Wall Thickness,		Cathode Type	# Shots	Cable Temps.	Comments
		inches	mm				
144	power cable #4	.275	7.0	PM	40	LN ₂	No treeing.
145a	power cable #4	.275	7.0	PM	-0-	>melting	Heated 1 hour. Insulation melted.
145b	power cable #4	.275	7.0	PM	10	50°C	Jacket bubbled up. Large dark patches under these bubbles. Cable treed.
146	power cable #4	.275	7.0	PM	20	RT	Initially frozen, then allowed to reequilibrate with room. Irradiated 18 hours after cooling. Trees and bubbles.
147	power cable #4	.275	7.0	PM	20	LN ₂ (+ 5 min)	Soaked in LN ₂ , then delayed start of irradiation for 5 minutes while cable warmed. No trees. Some bubbles when placed in hot oil.
148	power cable #4	.275	7.0	PM	20	LN ₂ (+10 min)	Soaked in LN ₂ , then delayed start of irradiation for 10 minutes. No trees, some bubbles when placed in hot oil.
149	power cable #4	.275	7.0	PM	15	LN ₂ (+15 min)	Soaked in LN ₂ , then delayed start of irradiation 15 minutes. Some triggering problems. Window developed pinholes. No trees.
150	power cable #4	.275	7.0	PM	3	LN ₂ (+15 min)	Attempted to repeat 149, getting 20 shots. Machine refused to trigger after 3 shots.

* See Table IX for detailed description.

4.2.7 Tree Resistant Compounds

A possible means of preventing the development of trees is to formulate polyethylene with a tree resistant additive. Accordingly, several samples of 35 kV cable with thermoplastic TREBAN 100* insulation were evaluated. Although it was felt that the insulation was too thick (.415", .97 gm/cm²) for good penetration, samples were tested anyway, and some shots were made without the appearance of trees. A 25 kV (.335", .75gm/cm²) cable was next irradiated which, with its thinner insulation, showed no treeing in room temperature irradiations with up to five sequential pulses at one location. Details of experiments with 25 and 35 kV cable samples are given in Table VIIg.

Samples of 35 kV TREBAN cable were first irradiated with single pulses (134 and 135) and no evidence of treeing in either sample was found. Five pulses were then tried (136); a single heavy tree running through the exposed area was noted. Freezing 35 kV cable by soaking in LN₂ and then pulsing 5 times (137) was not helpful. The sample shattered as if it had been made of ceramic. Fracture surfaces appeared to be typical of brittle failure.

To test the possibility that freezing alone could produce this result, a 35 kV segment was prepared in identical fashion, soaked in liquid nitrogen, and allowed to warm to room temperature. It did not break up, hence fracture must be induced by mechanical or electrical forces accompanying irradiation.

*Tree resistant resin; Du Pont trade name.

In test #139 through 143, a 25 kV TREBAN cable with a wall thickness of .335" (8.5 mm) was studied and it was shown (140) that at least five successive pulses could be applied at room temperature without inducing trees. This led to trying 20 shots at room temperature (141) and after soaking in liquid nitrogen (142); both of these samples showed heavy treeing. Samples heated to a surface temperature of approximately 54°C followed by 10 pulses also treed (143).

The success with TREBAN 35 kV and 25 kV cable samples (1 and 5 room temperature pulses without treeing, respectively) suggested that additional dose might be imposed at elevated temperature without treeing, if a means of suppressing bubble generation could be found. This is accomplished in thermal curing systems by externally pressurizing to several hundred psi with steam or nitrogen, but this solution requires a thick walled pressure vessel not suitable for efficient electron transmission. It was proposed that a similar clamping effect could be achieved by internally pressurizing cable through the stranding. Internally pressurizing a thick walled cylinder produces biaxial stresses which are tensile in the hoop and radially compressive, with maximum compression occurring at the inside radius and being equal to the internal pressure⁽¹⁹⁾. This is the location where bubbles were most frequently seen to aggregate when cables were heated to transparency in oil.

TABLE VIIg
IRRADIATION OF ANTI-TREEING COMPOUNDS

Irradiation Number	Cable* Type	Total Wall inches	mm	Number of Shots	Cable Temp.	Comments
134	power cable #1 TREBAN 100	.415	10.5	1	Room	No trees.
135	power cable #1 TREBAN 100	.415	10.5	1	Room	No trees.
136	power cable #1 TREBAN 100	.415	10.5	5	Room	One long heavy tree running through the irradiation zone just over the strand shield.
137	power cable #1 TREBAN 100	.415	10.5	5	LN ₂	Cable shattered as if it were a ceramic.
139	power cable #7 TREBAN 100	.335	8.5	1	Room	No trees. Outer shield removed.
139 continued	power cable #7 TREBAN 100	.335	8.5	4	Room	Many punctures coming to surface along a line.

* See Table IX for detailed description.

Table VIIg continued
Irradiation of Anti-Treeing Compounds

Irradiation Number	Cable* Type	Total inches	Wall mm	Number of Shots	Cable Temp.	Comments
140	power cable #7 TREBAN 100	.335	8.5	5	Room	No trees and no bubbles.
141	power cable #7 TREBAN 100	.335	8.5	20	Room	One long tree running whole length of irradiated zone. Came up to surface.
142	power cable #7 TREBAN 100	.335	8.5	20	LN ₂	Heavy treeing along length of irradiated zone. Cable fractured in several places.
143	power cable #7 TREBAN 100	.335	8.5	10	54°C	Trees. No bubbles.

* See Table IX for detailed description.

Accordingly, on irradiation number 151(a), a 25 kV TREBAN cable was heated to a sheath temperature of 63°C and pressurized internally with 50 psig of dry nitrogen. The sample was subjected to 20 pulses and held at room temperature for 24 hours following irradiation before examination in oil. Neither trees nor bubbles were detectable to the naked eye.

Test #169 (TREBAN) was heated, then pressurized to 50 psig and pulsed 40 times. During the irradiation a pinhole developed in the window and diode pressure rose; at completion it was about 500 torr (usual operating pressure is 5×10^{-4} torr). It can be expected that discharging the cathode into high pressure could cause crowbarring, beam dispersion, ragged emission, and reduction of mean electron energy. Any one of these effects would probably disrupt the irradiation; massive treeing was found in the cable.

A second attempt was made to irradiate 25 kV (TREBAN) cable on test #170. The sample was pulsed 20 times while heated and pressurized; at one point a sound was heard which could have been an early discharge to the diode during the charging cycle. This cable displayed a single long tree down the length of the irradiated zone.

To monitor the nature of discharges like the one heard on test #170, a ratemeter was set up at the control console to test for production of X-rays. In this way uncommanded events which switched to the diode could be identified and recorded as possible low voltage shots, i.e. where electrons would have insufficient range to reach the conductor.

A series of irradiations were then made on samples of 15 kV cable, not TREBAN. Samples were all irradiated at room temperature with no grounding foil over them; 20, 40 and 60 shots were tried to give a spread in dose which it was thought would encompass the value needed to achieve good crosslinking. Each segment was wrapped with blue cellophane to indicate the magnitude and location of surface dose. Irradiations 188 and 189 were carried to 20 and 40 shots respectively; these cable lengths were cut in half at the centerline of the irradiated zone and immersed in oil; no radiation-induced defects were seen, except bubbles which appeared as the insulation warmed. This phenomena has been discussed earlier and is not considered to be a problem. See Table VIIh summarizing irradiation tests 188-192.

Irradiation tests #190 and #191 were given 60 shots. In both cases surface punctures through the sheath were observed. Test #190 was put in oil to verify that it had treed. The dose profile measured on #187 (see Figure 17) shows that good penetration was achieved, but on both sequences of 60, several prefires were experienced, the machine self-firing at low voltage. In an effort to counter this effect, irradiation test #192 was conducted in three steps of 20 shots each with pulsing periods spaced apart by 16 hours (overnight) and 8 hours. This sample appeared to be sound, based on the absence of punctures on the cable surface.

FIGURE 17. DEPTH-DOSE PROFILE
MEASURED ON
IRRADIATION TEST # 187

20 Shots at 4.8MV Charging
5 Mil Mylar
.375" Aluminum Mandrel
"Pineapple" Cathode
Reported for ICT-106 Calib.

TABLE VIIh SUMMARY OF RESULTS

Irradiation Number	Cable Type	Total Wall Thickness,		No. Shots	Surface Dose*, Mr	Observations
		inches	mm			
187	Depth-Dose	--	--	20	6.8	- - - - -
188	Power cable #8	.275	7.0	20	6.6	Appears defect free.
189	Power cable #8	.275	7.0	40	13.2	Appears defect free.
190	Power cable #8	.275	7.0	60	17.7	Trees (pulse generator prefire)
191	Power cable #8	.275	7.0	60	15.6	Surface punctures (pulse generator prefire)
192	Power cable #8	.275	7.0	60	16.5	No surface defects

*Obtained from ICT-106 calibration curve.

Tests #172 through 185 involved radiation of TREBAN 100 insulated cables with four wall thicknesses ranging from .215" (5.5 mm) to .340" (8.6 mm). It was anticipated that this series of tests would give insight into the electron range for this tree-resistant polymer. Unfortunately, subsequent solvent extraction test results ranged from 71% to 100% showing that the samples were not crosslinked. The lack of crosslinking was attributed to a malfunction with the oil-filled bushing connecting the output of the generator to the diode. Following irradiation #185, it was decided to recondition the bushing.

4.3 Pulse Clipping with Gas Insulation

Generation of bubbles in the oil filled bushing attached to the pulse generator was a recurring problem throughout the work described to this point, requiring reconditioning the bushing after every 300 shots or so. To eliminate the need for this, a redesign was initiated to permit the replacement of oil with a 60 psia charge of SF_6 . Having made the change to SF_6 , it was found that flashover occurred, but that it was delayed long enough to give a pulse length of about 20 nanosecs. Measurements made with cellophane show that two or three times the number of shots were required to obtain a given dose with this bushing as were needed when oil was used. This pulse clipping leads to reduced dose per pulse, a result which appears to be beneficial. Irradiation test #199 on a 15 kV cable (power cable #8*, not TREBAN 100) indicated that at least 100 consecutive pulses could be made using the SF_6 bushing without inducing defects.

* See Table IX

4.4 Solvent Extraction Tests on Irradiated Power Cable Samples

The majority of results reported thus far have related radiation defect vs. number of shots. On this basis irradiation tests #172-185 with 40 to 60 shots per test should have yielded reasonable crosslink density. This was not the case; extraction levels noted in Section 4.2.7, ranged from 71% to 100%. Hence, a test having had many shots, e.g. 60, while not inducing treeing or porosity, may not have been adequate for sufficient crosslinking.

In the final analysis, it must be possible to accomplish good crosslinking density at reasonable dose levels and without inducing defects. Table VIII includes 13 cable irradiation tests listing these critical parameters. Fig. 18 shows locations of solvent extraction sampling.

The following comments refer to Table VIII. Test #40 involved a special cable construction employing a high density jacket. The wall thickness: 350 mils (8.89 mm), $.82 \text{ gm/cm}^2$ was beyond the range of the irradiator, hence it was not surprising to find that extraction levels were unsatisfactory.

Test #41 treed even though it was within range, possibly because of a less than optimum diode configuration and high dose per pulse.

Tests #129 and #144 were without defects but required 25 Mrad to achieve marginal gel content in the inner zone and were performed at very low temperatures.

POWER CABLE SAMPLING FOR SOLVENT EXTRACTION

STRIPS OF PE WERE TAKEN BY TURNING CABLE SAMPLES IN A LATHE.
STRIPS WERE GENERALLY .014" THICK.

FIG. 18

Test #189 was conducted after converting the diode bushing from oil to SF6. This, along with modification to the cathode, yielded a reduced dose per pulse.

Test #190 achieved excellent extraction results at 17.7 Mrad. Treeing was noted, however, probably due to one or more low voltage shots.

Test #192 produced the best extraction levels with an incredible $\pm 3\%$ uniformity. This test is considered very meaningful in that it demonstrates the potential of radiation crosslinking.

Tests #194, 207 and 223 were also able to produce defect-free cable at room temperature, at reasonable dose levels, while achieving gel contents close to the desired range. Uniformity was considered excellent.

4.5 Voltage Endurance

Before the irradiated test specimen #223 was dissected for gel content and possible defects, it was exposed to a long term high voltage withstand test. The specimen was 52" (132 cm) long terminal-to-terminal, with approximately 25" (64 cm) under shield. The central 10" (25 cm) of the shielded length had been irradiated.

A voltage of 26.4 kV was applied to stress the insulation at 120 V/mil (4.7 kV/mm). This is approximately 300% of the rated voltage; see construction details for power cable #8 in Table IX. Voltage was maintained continuously for 3180 hours or 132.5 days. Subsequent

dissection revealed no electrical treeing attributed to radiation (see Fig. 19a and 19b). No conductor heating was involved. Final dissipation factor was .031% at the rated voltage of 8.7 kV-grd.

This voltage endurance test at high stress and long duration is thought to show that a conventional polyethylene insulated power cable can be irradiated sufficiently to achieve a reasonable crosslink density, without compromising its electric strength.

It is noted that the average extraction was 36% (@ $C_L A + 1''$) compared to a desired $\leq 30\%$. This is not considered significant; the slightly higher dose necessary to yield 30% extraction would not likely affect the results.

4.6 Summary of Test Results

Irradiation crosslinking of HMWPE power cable has been accomplished without inducing treeing or porosity. Internal pressure and temperature variation aids in reducing radiation defects. However, it has been shown that by elimination of prefires and by reducing dose per pulse to approximately 0.1 Mrad/pulse, it is possible to produce a uniform crosslink density with a toroidal diode under conditions amenable to cable manufacture. A voltage endurance test at 300% of rated voltage indicated that the dielectric was not adversely affected by radiation.

The successful results on prototype power cable suggest that work should proceed to develop radiation crosslinking capability for 138 kV and 230 kV rated cable.

IRRADIATED SECTION

Photographs of Irradiation Test #223 after voltage endurance: 3180 hrs. @ 120V/mil (4.7 kV/mm) in water filled conduit.

Photographs are at 75X magnification: .8 mils (.02 mm) per division.

Wafer specimens were taken from a section of cable which was 1-1/2" to 2" (3.8 to 5 cm) from the centerline of the diode during irradiation.

Largest bow tie is 9 mils (.22 mm) long, originating from a 1.7 mil (.04 mm) contaminant.

The Bowtie patterns are characteristic of water treeing and not related to radiation induced defects. Note similar treeing pattern on the non-irradiated section, fig. 15b.

Wafers were dyed with methylene blue.

Fig. 19a. Enlarged dissection from irradiated zone after long-term high voltage test.

NON-IRRADIATED SECTION

Photographs of Irradiation Test #223 after voltage endurance: 3180 hrs. @ 120 V/mil (4.7 kV/mm) in water-filled conduit.

Photographs are at 75X magnification: .8 mils (.02 mm) per division.

Wafer specimens were taken from the same cable as fig. 15a, except outside the zone of radiation. Specimens were sampled 10" to 10-1/2" (25 to 26 cm) from the centerline of the diode which was approximately 5" (13 cm) outside the zone of radiation.

The large ring-shaped contamination in lower photo is not identified -- note bow tie inside or underneath the ring.

Bow tie patterns are characteristic of water treeing and not related to radiation-induced defects. Note that the photographed section was not irradiated.

Wafers were dyed in methylene blue.

Fig. 19b Enlarged dissection from non-irradiated zone after long-term high voltage test.

TABLE VIII
SUMMARY OF CABLE TESTS COMPARING DOSE AND
SOLVENT EXTRACTION ON 15-35 kV CABLE

<u>Irrad. Test #</u>	<u>(1) Zone</u>	<u>(2) Depth</u>	<u>(3) Specimen Description</u>	<u>Ins or SC</u>	<u>Total Wall mils</u>	<u>Cable Thickness mm</u>	<u>Dose Mrad</u>	<u>% Sol. Ext.</u>	<u>Temp. °C</u>	<u>Tree</u>	<u>Gas</u>
40	C _L		Cable #2		350 ⁽⁴⁾	8.89			Room	Yes	No
		Jacket	DGDJ 2023	Ins			14	28.9			
		Outer	DFDA 6201	Ins			--	53.0			
		Mid	DFDA 6201	Ins			--	98.8			
		Inner	DFDA 6201	Ins			--	--			
	Cdr Sh		SC								
41	C _L A+1		Cable #3		225	5.72			Room	Yes	No
		Ins Sh	DXHD 6203	SC			13.8	16.1			
		Outer	NA 310-06	Ins			--	21.2			
		Inner	NA 310-06	Ins			--	28.6			
		Cdr Sh	DXHD 6203	SC			--	--			
41	C _L B+1		Cable #3		225	5.72			Room	Yes	No
		Ins Sh	DXHD 6203	SC			13.8	15.0			
		Outer	NA 310-06	Ins			--	20.6			
		Inner	NA 310-06	Ins			--	28.6			
		Cdr Sh	DXHD 6203	SC			--	--			
129	C _L A+1		Cable #4		225	5.72			Cold	No	No
		Ins Sh	DXHD 6174	SC			12.8	77.0			
		Outer	NA 310-06	Ins			--	51.6			
		Inner	NA 310-06	Ins			--	61.4			
		Cdr Sh	DXHD 6174	SC			--	--			

TABLE VIII (cont'd.)
SUMMARY OF CABLE TESTS COMPARING DOSE AND
SOLVENT EXTRACTION ON 15-35 KV CABLE

<u>Irrad.</u> <u>Test</u> <u>#</u>	<u>(1)</u> <u>Zone</u>	<u>(2)</u> <u>Depth</u>	<u>(3)</u> <u>Specimen</u> <u>Description</u>	<u>Ins</u> <u>or</u> <u>SC</u>	<u>Total Cable</u> <u>Wall Thickness</u>		<u>Dose</u> <u>Mrad</u>	<u>%</u> <u>Sol.</u> <u>Ext.</u>	<u>Temp.</u> <u>°C</u>	<u>Tree</u>	<u>Gas</u>
			Cable #5								
144	C _L A+1	Ins Sh	--	SC			25	--			
		Outer	NA 310-06	Ins			--	30.1			
		(6)	NA 310-06	Ins			--	32.5			
		(6)	NA 310-06	Ins	250	6.35	--	33.4	Cold	No	No
		(6)	NA 310-06				--	36.8			
		(6)	NA 310-06				--	40.5			
		Inner	NA 310-06	Ins			16.5	40.1			
		Cdr Sh	--	SC			--	--			
			Cable #5								
144	C _L B+1	Ins Sh	--				25	--			
		Outer	NA 310-06	Ins			--	35.5			
		(6)	NA 310-06	Ins			--	38.3			
		(6)	NA 310-06	Ins	250	6.35	--	40.1	Cold	No	No
		(6)	NA 310-06				--	43.1			
		(6)	NA 310-06				--	43.7			
		Inner	NA 310-06				--	55.8			
		Cdr Sh	--				16.5	--			

TABLE VIII (cont'd.)
SUMMARY OF CABLE TESTS COMPARING DOSE AND
SOLVENT EXTRACTION ON 15-35 KV CABLE

<u>Irrad.</u> <u>Test</u> <u>#</u>	<u>(1)</u> <u>Zone</u>	<u>(2)</u> <u>Depth</u>	<u>(3)</u> <u>Specimen</u> <u>Description</u>	<u>Ins</u> <u>or</u> <u>SC</u>	<u>Total Wall</u> <u>Wall Thickness</u> <u>mils</u> <u>mm</u>		<u>Dose</u> <u>Mrad</u>	<u>%</u> <u>Sol.</u> <u>Ext.</u>	<u>Temp.</u> <u>°C</u>	<u>Tree</u>	<u>Gas</u>
189	C _L		Cable #8								
		Ins Sh	6739	SC			13.2	--			
		Outer	310-6	Ins			--	40.2			
		Mid	310-06	Ins	275	6.99	--	40.6	Room	No	No
		Inner	310-06	Ins			--	39.7			
		Cdr Sh	6739	SC			--	--			
190	C _L		Cable #8								
		Ins Sh	6739	SC			17.7	--			
		Outer	310-06	Ins			--	29.6			
		Mid	310-06	Ins	275	6.99	--	25.6	Room	Yes	No
		Inner	310-06	Ins			--	25.0			
		Cdr Sh	6739	SC			--	--			
191	C _L		Cable #8								
		Ins Sh	6739	SC			15.6	--			
		Outer	310-06	Ins			--	58.9			
		Mid	310-06	Ins	275	6.99	--	58.9	Room	Yes	No
		Inner	310-06	Ins			--	57.4			
		Cdr Sh	6739				--	--			
192	C _L		Cable #8								
		Ins Sh	6739	SC			16.5 ⁽⁵⁾	--			
		Outer	310-06	Ins			--	29.6			
		Mid	310-06	Ins	276	6.99	--	29.9	Room	No	No
		Inner	310-06	Ins			--	28.6			
		Cdr Sh	6739	SC			--	--			

TABLE VIII (cont'd.)
SUMMARY OF CABLE TESTS COMPARING DOSE AND
SOLVENT EXTRACTION ON 15-35 kV CABLE

<u>Irrad.</u> <u>Test</u> <u>#</u>	<u>(1)</u> <u>Zone</u>	<u>(2)</u> <u>Depth</u>	<u>(3)</u> <u>Specimen</u> <u>Description</u>	<u>Ins</u> <u>or</u> <u>SC</u>	<u>Total Cable</u> <u>Wall Thickness</u>		<u>Dose</u> <u>Mrad</u>	<u>%</u> <u>Sol.</u> <u>Ext.</u>	<u>Temp.</u> <u>°C</u>	<u>Tree</u>	<u>Gas</u>
			Cable #8								
194	C _L (A)	Ins Sh	310-06	SC			28	44.2			
		Outer	310-06	Ins			--	33.7			
		Mid	310-06	Ins	275	6.99	--	36.8	Room	No	No
		Inner	310-06	Ins			--	38.0			
		Cdr Sh	6739	SC			19	37.1			
			Cable #8								
194	C _L (A)+1"	Ins Sh	6739	SC							
		Outer	310-06	Ins				32.6			
		Mid	310-06	Ins	275	6.99	--	34.8	Room	No	No
		Inner	310-06	Ins				38.5			
		Cdr Sh	6739	SC							
			Cable #8								
194	C _L (B)+1"	Ins Sh	6739	SC							
		Outer	310-06	Ins				40.8			
		Mid	310-06	Ins	275	6.99	--	44.5	Room	No	No
		Inner	310-06	Ins				46.5			
		Cdr Sh	6739	SC							
			Cable #8								
207	C _L (A)	Ins Sh	6739	SC			?	35.3			
		Outer	310-06	Ins				27.3			
		Mid	310-06	Ins	275	6.99		31.9	Room	No	No
		Inner	310-06	Ins				35.3			
		Cdr Sh	6739	SC			?	36.2			

TABLE VIII (cont'd.)
SUMMARY OF CABLE TESTS COMPARING DOSE AND
SOLVENT EXTRACTION ON 15-35 kV CABLE

<u>Irrad. Test #</u>	<u>(1) Zone</u>	<u>(2) Depth</u>	<u>(3) Specimen Description</u>	<u>Ins or SC</u>	<u>Total Cable Wall Thickness</u>		<u>Dose Mrad</u>	<u>Sol. Ext.</u>	<u>Temp. °C</u>	<u>Tree</u>	<u>Gas</u>
			Cable #8								
207	C _L A+1"	Ins Sh	6739	SC				--			
		Outer	310-06	Ins				29.9			
		Mid	310-06	Ins	275	6.99		33.6	Room	No	No
		Inner	310-06	Ins				37.5			
		Cdr Sh	6739	SC				--			
			Cable #8								
207	C _L B+1"	Ins Sh	6739	SC				--			
		Outer	310-06	Ins				32.4			
		Mid	310-06	Ins	275	6.99		36.2	Room	No	No
		Inner	310-06	Ins				40.3			
		Cdr Sh	6736	SC				--			

TABLE VIII (cont'd.)
SUMMARY OF CABLE TESTS COMPARING DOSE AND
SOLVENT EXTRACTION ON 15-35 kV CABLE

<u>Irrad.</u> <u>Test</u> <u>#</u>	<u>(1)</u> <u>Zone</u>	<u>(2)</u> <u>Depth</u>	<u>(3)</u> <u>Specimen</u> <u>Description</u>	<u>Ins</u> <u>or</u> <u>SC</u>	<u>Total Cable</u> <u>Wall Thickness</u>		<u>Dose</u> <u>Mrad</u>	<u>Sol.</u> <u>Ext.</u>	<u>Temp.</u> <u>°C</u>	<u>Tree</u>	<u>Gas</u>
			Cable #8								
223	C _L A	Ins Sh Outer Mid Inner Cdr Sh	6739 310-06 310-06 310-06 6739	SC Ins Ins Ins SC	275	6.99		36.0 41.9 41.4	Room	No	No
			Cable #								
223	C _L A+1	Ins Sh Outer Mid Inner Cdr Sh	6739 310-06 310-06 310-06 6739	SC Ins Ins Ins SC	275	6.99		30.1 39.3 38.5	Room	No	No
			Cable #								
223	C _L B+1"	Ins Sh Outer Mid Inner Cdr Sh	6739 310-06 310-06 310-06 6739	SC Ins Ins Ins SC	275	6.99		35.7 40.4 45.1	Room	No	No

Footnotes to Table VIII

- (1) Sample zone at centerline of diode or distance from centerline in inches.
- (2) Depth of solvent extraction specimen: outer (next to insulation shield), middle, or inner (next to conductor shield).
- (3) See cable descriptions in footnotes.
- (4) Exceeded gm/cm^3 range of irradiator. Special cable construction with high density insulating jacket; no SC insulation shield.
- (5) Time interval between shots. See Section 4.3.
- (6) Samples at regular radii intervals from outer (next to insulation shield) to inner (next to conductor shield).

TABLE IX
POWER CABLE DESCRIPTIONS
15-35 kV CABLE

		Total <u>mils</u>	Wall <u>mm</u>	Thickness <u>gm/cm²</u>
Power Cable #1	35 kV UD Cable			
	.020" Alathon PE 6736			
	.345" TREBAN-100 HMW PE insulation	415	10.05	.97
	.050" Alathon PE 6736			
Power Cable #2	Special Cable Construction			
	1/C 750 kcmil (61W) Aluminum conductor			
	.030" DHDA 7704 SC PE cond. shield			
	.220" DFDA 6201 HMW PE insulation	350	8.89	>.82
	.100" DGDJ 2023 HD PE jacket (insulating) (6)			
Power Cable #3	15 kV UD Cable			
	1/C 1/0 AWG solid Aluminum conductor			
	.020" DXHD 6203 SC PE cond. shield			
	.175" NA 310-06 HMW PE insulation	225	5.72	.53
	.030" DXHD 6203 SC PE insulation shield			
Power Cable #4	15 kV UD Cable			
	1/C 1/0 AWG solid Aluminum conductor			
	.020" DXHD 6173 SC PE cond. shield			
	.175" NA 310-06 HMW PE insulation	225	5.72	.53
	.030" DXHD 6174 SC PE insulation shield			

TABLE IX
POWER CABLE DESCRIPTIONS
15-35 kV CABLE

		Total <u>mils</u>	Wall <u>mm</u>	Thickness <u>gm/cm²</u>
Power Cable #5	15 kV UD Cable			
	1/C 1/0 AWG solid Aluminum			
	.020" SC PE unidentified strand shield			
	.175" NA 310-06 HMW PE insulation	225	5.72	.53
	.030" SC PE unidentified insulation shield			
Power Cable #6	UD Cable			
	1/C 1/0 AWG (19W) Aluminum			
	.025" Alathon PE 6736	145	3.68	.34
	.162" to .195" TREBAN-100 HMW PE insulation	to 238	6.05	.56
	.018" Type 3621 SC EPR heat-shrink tube			
Power Cable #7	25 kV UD Cable			
	1/C 1/0 AWG (19W) Aluminum			
	.025" Alathon PE 6736			
	.260" TREBAN-100 HMW PE insulation	335	8.51	.75
	.050" Alathon PE 6736			
Power Cable #8	15 kV UD Cable			
	1/C 1/0 AWG (19W) Aluminum			
	.020" Alathon PE 6739			
	.220" NA 310-06	275	6.99	.64
	.035" Alathon PE 6739			

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PART II - INDEX

Page

1.	Design of 7 MV Machine	
1.0	Summary	140
1.1	Introduction	141
1.2	Preliminary Design of 7 MV Machine	141
1.2.1	Selection of Pulser System	141
	Marx Generator with FEC	142
	Marx Generator with Transfer Capacitor and FEC	144
	Marx Generator with Peaking Capacitor and FEC	144
1.2.2	Circuit Modeling	147
1.2.3	Diode Length Versus Pulse Rate Tradeoffs	168
1.3	Marx Charging Circuit	173
1.4	Design of Marx Trigger Generator	178
1.5	Main Marx Bank Design	191
1.5.1	Design Criterion for Oil	192
1.5.2	Main Bank Capacitor Spacing	196
1.5.3	Modeling of Marx Inductance	198
1.5.4	Marx Generator Charge Isolation	198
1.5.5	Limiting Energy into a Faulted Main Bank Capacitor	202
1.5.6	Misfire of Output Switch	203
1.5.7	Practical Specification of Isolation Components	204
	Resistors	204
	Inductors	207
1.5.8	Mounting Scrap Length	210
1.5.9	Estimate of Radiation Dose in Front End Capacitor	212
1.5.10	Marx Switch Design and Life Tests	213

	<u>Page</u>
1.5.11 Spacing Between Isolation Inductors and Tank Top	226
1.5.12 Marx Tank Material Study	231
1.6 Peaking Capacitor	233
1.6.1 Initial Peaking Capacitor Sizing	233
1.6.2 Stripline Configurations	235
1.6.3 Geometry Tradeoffs	235
1.6.4 Mechanical Stability	239
1.6.5 Design of Peaking Capacitor Outer Conductor	248
1.6.6 Electrical Losses in the Peaking Capacitor	250
1.7 Preliminary Design of 7 MV Output Switch	256
1.7.1 Insulating Gas	256
1.7.2 Gap Length	259
1.7.3 Electrode Diameter	260
1.7.4 Envelope Length	260
1.7.5 Envelope Inside Diameter	260
1.7.6 Electrode Materials	261
1.8 Output Bushing	262
1.8.1 Design Criterion for Vacuum Flashover	262
DC	262
Pulsed Flashover	264
Design Practice in Pulsed Tubes	266
1.8.2 Preliminary Bushing Design	272
1.8.3 Testing of Oil Filled Concept	284
Length of Vacuum Tube	284
Cathode Shank Diameter	286
Tube Dimensions	288

	<u>Page</u>
Availability of Parts and Material	289
Results of Testing	289
1.8.4 Alternate Diode Concept	293
1.8.5 Final Bushing Design	301
1.8.6 Bushing Heating	306
1.8.7 Radiation Damage to Insulators	307
1.9 Field Emission Diode Sizing	308
1.10 Oil	321
1.10.1 Oil Storage System	321
1.10.2 Radiation Testing of Transformer Oils	321
1.10.3 Oil Temperature Rise	329
1.11 Facility Site and Cable Handling	331
1.12 Shielding	335
1.12.1 Radiation Protection Standards	335
1.12.2 Methods of Dose Reduction	338
1.12.3 Radiation Sources	338
Electrons	339
Neutrons	339
Bremsstrahlung Photons	341
1.12.4 Preliminary Shielding Design	341
1.13 Cable Crosslinking with a Bremsstrahlung Machine	343
1.13.1 Bremsstrahlung Experiments on FX-35	343

APPENDICES IN PART II

Page

1.14 References

350

<u>Appendix A:</u>	Blue Cellophane Calibtation Data Calorimetric Verification of Blue Cellophane	353
<u>Appendix B:</u>	Calculation of Charging Circuit Efficiencies Alternate Charging Circuits	362
<u>Appendix C:</u>	Selection of Isolation Component Values	389
<u>Appendix D:</u>	Energy Dissipated in a Faulted Capacitor	399

LIST OF FIGURES

PART II

Figure No.	Title	Page
1 - 19a	See Part I	
20	Output Pulse Shape of Marx Generator System Without Transfer or Peaking Capacitor	145
20a	Circuit Diagram of System for Computer Modeling	148
21	Open Circuit Voltage	153
22	Voltage on Peaking Capacitor and Load for SF ₂ Closure at 300 ns	154
23	Voltages on Peaking Capacitor and Load for SF ₂ Closure at 325 ns	155
24	Voltages on Peaking Capacitor and Load for SF ₂ Closure at 350 ns	156
25	Open Circuit Voltage, Calculated for Best Estimate of Final Machine Parameters	157
26	Voltages on Peaking Capacitor and Load, Calculated for Best Estimate of Final Machine Parameters	158
27	Output of New and Old Circuits	160
28	Effect of Reducing Marx Inductance	161
29	Effect of Reducing Output Resistance	162
30	Effect of Reducing Output Inductance	163
31	Effect of Peaking Capacitor Impedance Increase While Capacitance is Constant	164
32	Effect of Increased Peaking Capacitance with Constant Impedance	165
33	Marx Voltages and Current	166
34	Views of Charging Supply	177
35	Trigger Generator Cutaway	179
36	Trigger Generator Electrical Schematic	180
37	Photograph of Trigger Generator	181
38	Switching Range in CO ₂	184
39	Switching Range in N ₂	185

PART II
LIST OF FIGURES

Figure No.	Title	Page
40	Switching Range in 80% N ₂ - 20% O ₂	186
41	Evolution of Trigger Generator Gaps	187
42	Switching Range of Improved Gap in N ₂	188
43	Fractional Marx Charge as a Function of Current Limiting Impedance	189
44	Marx Generator Schematic	193
45	Summary of Inductance Modeling	199
46	Test Setup for Switch Life Studies	215
47	Variation of Self-Breakdown Voltage with Number of Discharges	216
48	Marx Switch	217
49	Test Setup for Triggered Switch Life Studies	219
50	Composite Photograph of Switch and Capacitor Test Setup	220
51	Single Stripline Peaking Capacitor	236
52	Dual Stripline Peaking Capacitor	237
53	Dual Stripline Peaking Capacitor, Alternate Design	238
54	Peaking Capacitor Options	249
55	Preliminary Output Switch Design	257
56	Conventional Vacuum Bushing	273
57	Summary of Breakdown Data	276
58	Oil Filled Bushing	278
59	Proposed Modification to FX-35	285
60	Oil Filled Bushing in Place on FX-35	290
61	Alternate Diode Concept	294

LIST OF FIGURES
PART II

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
62	Depth Dose Profiles Obtained from Side-to-Side Diode	246
63	Open Shutter Photographs of Diode Showing Grading Ring Emission	300
64	Final Bushing Design	302
65	Stepped Bushing Design	304
66	HD Polyethylene Test Fixture	305
67	Anode-Cathode Geometry for Impedance Studies	310
68	Impedance History for Cylindrical Diode	311
69	Variation of Diode Impedance in Cathode-Anode Diameter Ratio	315
70	Impedance Data from FX-35 Experiments	319
71	Oil Storage Tanks being Installed Outside XTU Vault	322
72	"Tank Farm", January, 1977	323
73	Tank Contents vs. Pressure Indication	325
74	Gallons of Oil vs. Indicated Pressure	326
75	Cable Guide	334
76	Location of Dosimeters for FX-35 Bremsstrahlung Experiment	347
77	Blue Cellophane Calibration Data	355
78	Resistive Charging	375
79	Inductive Charging	376

LIST OF FIGURES
Part II

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
80	Inductive Current Limit in the Primary	379
81	Circuit Configuration, Phase Control Ramp Generator	383
82	Circuit Configuration, Tap Changing SCR Generator	384
83	Output Current	387
84	Circuit Use	388
85	Faulting Capacitor Energy Limiting	401
86	Equivalent Circuit for Faulted Capacitor String	402

LIST OF TABLES FOR PART II

TABLE	TITLE	PAGE
I - IX	See Part I	
X	Circuit Parameters for Preliminary Output Calculations	151
XI	Circuit Parameters for Design Calculations	152
XII	Synopsis of R-C Charging Methods	176
XIII	Summary of Resistor Testing Results	208
XIV	Switch Self-Breakdown as a Function of Pressure for Two Gap Spacings	221
XV	Characteristics of Some Existing Switches	258
XVI	Insulators Investigated by Milton	267
XVII	Flashover Strength of Some Tube Materials as a Function of Pulse Duration	268
XVIII	Summary of Design Stresses for Vacuum Diodes of Large Accelerators	271
XIX	Summary of Data from Impedance Measurements Experiments with Cylindrical Diode on FX-35	314
XX	Summary of Impedance Experiments	318
XXI	Summary of TLD Readings	348

PART II

1.0 SUMMARY

This portion of the report describes development of a preliminary irradiator design and presents results of engineering studies conducted to determine details of the final design. On the basis of circuit calculations, it was concluded that an output waveform having peak voltage above 7 megavolts could be obtained by ringing a Marx generator into a peaking capacitor, and discharging this system through an overvolted output switch. To house these components, as well as a radiation source and output bushing, an oil filled tank approximately 40 feet long, 15 feet high, and 15 feet wide will be needed. To store the 40,000 gallons of insulating oil which will be required, four 10,000 gallon tanks were purchased and located in a group near the machine construction site. Other major acquisitions included an 11 foot diameter by 6.75 foot long peaking capacitor, Marx capacitors and switches, and a 480 kilovolt trigger pulse generator to initiate Marx erection. Several bushing designs were evaluated, leading to the selection of a segmented cylindrical unit which will be capacitively graded and which will mate to a cylindrical radiation source, extending equal distances to both sides of the source. The bushing will be about 4 feet in diameter and 15 feet overall length. Assuming that emission current is space-charge limited in the source, cathode and anode diameters of 30-inches and 6-inches should give the desired load impedance for a one foot long emitter.

Section 3

DESIGN OF 7MV MACHINE

1.1 Introduction

In addition to building, testing, and evaluating a 360 degree irradiator, the first six months of the program included a parallel effort to produce a preliminary design for the full scale 7MV pulser. A number of tradeoffs were considered, and sensitivity of the machine to circuit parameters was studied. This preliminary design work led to the configuration which was described in Section 1, and was followed by a detailed design effort in which individual parts of the machine were developed and specified for procurement. In this section, preliminary design tradeoffs are reviewed and then constituent parts of the system are considered more closely. The latter discussion has been organized so as to follow the general direction of power flow through the machine from low voltage input to the application of 7MV to the diode.

1.2 Preliminary Design of 7MV Machine

1.2.1 Selection of Pulser System

Among pulser systems which might be used in this machine the most promising are:

- (1) A Marx generator directly connected to a field emission cathode (FEC).

- (2) A combination of Marx generator, transfer capacitor, and FEC.
- (3) A combination of Marx generator, peaking capacitor, and FEC.

An energy store which was excluded from consideration is the LC generator or resonant Marx; while it can be compact and therefore of lower inductance than an equivalent Marx generator, all stages must employ triggered switches. For a system with many stages, it was felt that difficulties in maintaining proper switch sequencing and in providing adequate switch reliability would lead to an unacceptably short mean time between failures in an LC generator and would increase servicing requirements.

In the following an effort is made to analyze advantages and disadvantages of each of the three approaches listed above.

Marx Generator with FEC

This system has the advantage of requiring no output switch, transfer capacitor, or peaking capacitor. A disadvantage, however, is the need for a large number of stages and larger stored energy to achieve an output voltage of 7MV. If it is assumed that a ringing type waveshape should be avoided, then the lowest allowable stored energy corresponds to the capacity which will give critical damping. In this case the output voltage is 73.5% of "n" times the

stage voltage, where "n" is the number of stages, and is further reduced by series resistance of the generator, R_S .

With a stage voltage V_S of 80 kV, a series resistance R_O of $15\text{m}\Omega$ per stage, a load R_L of 100 ohms, and a desired output voltage V_O of 7 MV, the necessary number of stages is

$$V = 0.735 n V_S \cdot \frac{R_L}{R_L + n R_O}$$

or

$$n = \frac{V_O R_L}{.735 V_S R_L - V_O R_O} \cong 121$$

The minimum capacitance per stage is then given by the relation for critical damping,

$$2 \sqrt{\frac{L}{C}} = R_L + R_S$$

If inductance L is equal to n times the stage inductance L_O , and if the inductance per stage is 150 nH, the capacity C_O per stage must then be

$$C_O = \frac{4 L_O n^2}{(R_L + n R_O)^2}$$

For $n = 121$, C_O is equal to 847 nf. The minimum stored energy would then be equal to 328 kJ.

A Marx generator of 328 kJ is large and expensive and

would require a very slow pulse repetition frequency to yield the average power required. This slow pulse repetition frequency would mean that a long window would have to be built; in addition, the pulse length would be rather long, as is shown in Figure 20. This could lead to flashover problems in the vacuum bushing.

Marx Generator with Transfer Capacitor and FEC

In this system, the entire stored energy of the Marx generator would be transferred onto a coaxial line or Blumlein. The purpose of this transfer is to upgrade quality of the energy source from one with a relatively large inductance to one with a small inductance.

A disadvantage is that the switch connecting transfer capacitor and FEC must be discharged at a point of zero dV/dt , and must consequently be a triggered switch. The required transfer capacitor is rather large and expensive.

Marx Generator with Peaking Capacitor and FEC

This is the system which has been selected. It allows stored energy to be reasonably small and permits operation of the output switch at a point where voltage across it changes very rapidly; consequently an overvolted switch can be used. The peaking capacitor has the advantage of being smaller and less expensive than a transfer capacitor. Time required to charge the peaking capacitor is shorter

Figure 20. Output Pulse Shape of Marx Generator System Without Transfer or Peaking Capacitor.

than that required to charge a transfer capacitor and the output switch is therefore stressed for a shorter time, which increases reliability and reduces inductance.

Capacity of the peaking capacitor is determined by Marx inductance and desired load current. Proper operation of the peaking capacitor occurs when the impedance $Z = \sqrt{\frac{L}{C^1}}$ is equal to the load impedance.

$$\text{Here } C^1 = \frac{C \cdot C_P}{C + C_P}, \text{ with}$$

C = Marx generator capacitance

C_P = capacitance of peaking capacitor

For a generator inductance of 15 μH and load impedance of 100 ohms,

$$C^1 = \frac{L}{R_L^2} = \frac{15 \times 10^{-6}}{10^4} = 15 \times 10^{-10} = 1.5 \text{ nf}$$

The capacitance of the peaking capacitor would then be equal to 2 nf for $C = 6 \text{ nf}$, or 2.5 nf for $C = 4 \text{ nf}$.

The maximum number of stages is determined by impedance of the peaking capacitor. If it is assumed that the peaking capacitor has the form of a coaxial line with an outside diameter of 335 cm (11 ft.), inside diameter of 245 cm (8 ft.), and that it is insulated in oil, an approximate impedance of 10 ohms results. To obtain an output voltage of 7 MV it is therefore necessary to charge the peaking

capacitor to $V_P = V_O \frac{R_L + Z_P}{R_L} = 7.7 \text{ MV}$. Assuming a stage voltage of 80 kV, the necessary number of stages is then

$\frac{7.7 \times 10^6}{8 \times 10^4} = 96$. For the preliminary design calculations this number was set to 100. In a lossless Marx, this corresponds to a fully erected voltage of 8 MV.

If the optimum combination of peaking capacitor to Marx generator is chosen, the effect of Marx inductance on the output waveshape is eliminated and a pulse shape with very fast risetime (corresponding to the inductance of the output switch) and exponential decay can be achieved. To study the effects of various combinations of Marx capacity, peaking capacity, and switch closing time on output pulse stage, a series of computer simulations was made.

1.2.2 Circuit Modeling

For initial calculations the system was modeled by the circuit shown in Figure 20a. Several computational sequences were run, the first using a trial set of design parameters for the Marx and assuming an erected voltage of 8 MV.

Based upon results of these initial computations, Marx capacity was increased by about 50 percent (this corresponds to the use of 120,000 pF stage capacitors) and charging voltage was reduced from 80 to 60 kV to give a fully erected no loss output of 7.2 MV. Using this higher capacity, a second set of computations was made

C_1 = Marx capacity (nominal 3.3 nf)

L_1 = Marx inductance (nominal 25 μH)

C_2 = Stray capacities in Marx (estimated to be 0.25 nf)

L_2 = Stray inductances in Marx (estimated to be 3 μH)

Z = Peaking capacitor impedance (nominal 10 Ω)

S_1 = Marx switches

S_2 = Output switch

C_3 = Tube and load capacity (nominal 0.2 nf)

L_3 = Tube and load inductance (nominal 1 μH)

R = Load impedance (nominal 100 Ω)

Figure 20a. Circuit Diagram of System for Computer Modeling.

under the assumption that internal losses in the Marx drop the actual voltage to 7.0 MV.

Circuit parameters for the two sets of analyses are listed in Tables X and XI. Cases indicated in the first table were designed to yield the voltage waveform of an open circuited Marx in which the output switch, S2, is not closed (Case 3978-1), Fig. 21, followed by additional cases with S2 closing at various times after initiation of Marx erection. Output voltage on the peaking capacitor and at the load (cylindrical diode) are plotted in Figure 22 through 24 for these cases. Switching times in Figures 22, 23 and 24 are 300, 325, and 350 nano-seconds, corresponding to 80, 85, and 90 percent of peak voltage. For simplicity it is desirable to employ an overvolted rather than triggered output switch; breakdown delay makes it necessary to design for a firing voltage lower than the peak value to assure that switching will occur at or near the peak. The table below gives maximum load voltage as a function of switch closure time for each of the three cases examined; it can be seen that load voltages in excess of 7 MV can be

Switch Closure Time, ns (Measured from Marx Switch Closure)	Percent of Peak Open Circuit Voltage	Maximum Voltage on Load, MV
300	80	6.8
325	85	7.3
350	90	7.6

achieved provided switching occurs at the 85 percent point or later (but before peak voltage is reached).

Results of the second set of computations (for which component values are summarized in Table XI) are plotted in Figures 25 and 26. These figures assume that switching occurs at the 90 percent point, and that the Marx is 97 percent efficient. Under these conditions, voltage applied to the load should reach a peak value of about 7.6 MV. Designing for this figure provides a margin in the event that system losses are larger than expected.

As the program developed and detailed design studies produced better estimates of electrical parameters, initial computations were repeated and supplemented by a sensitivity study to determine the effect on output voltage of varying certain electrical parameters. In general, results confirmed the original computations and showed that output voltage should be less sensitive to Marx inductance, peaking capacitor impedance, and load impedance than was thought.

An improved estimate of Marx inductance was arrived at by measurements on scale models as reported in Section 1.5.3. The value obtained was 37 microhenries, somewhat higher than the 25 μ h employed in our first computation. Sensitivity calculations show that time for the output switch to fire is dependent on Marx inductance, but output voltage is insensitive to Marx inductance changes.

TABLE X. CIRCUIT PARAMETERS FOR PRELIMINARY
OUTPUT CALCULATIONS.

Component	Case Number			
	3978-1	3978-2	3978-3	3978-4
C_1 , nf	2.0	2.0	2.0	2.0
L_1 , μ H	25.0	25.0	25.0	25.0
C_2 , nf	0.25	0.25	0.25	0.25
L_2 , μ H	3.0	3.0	3.0	3.0
t , Ω	10.0	10.0	10.0	10.0
C_3 , nf	--	0.21	0.21	0.21
L_3 , μ H	--	1.0	1.0	1.0
R , Ω	--	100.	100.	100.
S_1 Closure Time, ns	Open Circuit	300.	350.	325.

- Initial conditions: (1) S_1 closes at $t = 0$, Marx erects
instantaneously
(2) Erected voltage of Marx is 8 MV

TABLE XI. CIRCUIT PARAMETERS FOR
DESIGN CALCULATIONS

Component	Case Number	
	3978-5	3978-6
C_1 , nf	3.3	3.3
L_1 , μ H	25.	25.
C_2 , nf	.25	.25
L_2 , μ H	3.0	3.0
t , Ω	10.	10.
C_3 , nf	0.21	0.21
L_3 , μ H	1.0	1.0
R , Ω	100.	100.
S_2 Closure Time, ns	Open Circuit	365.

Initial conditions: (1) S_1 closes at $t = 0$, Marx erects
instantaneously

(2) Erected voltage of Marx is 7 MV

CASE 3978-1

Figure 21 Open Circuit Voltage.

Figure 22, Voltages on Peaking Capacitor and Load
for S_2 Closure at 300 ns.

Figure 23. Voltages on Peaking Capacitor and Load for S₂ Closure at 325 ns.

Figure 24. Voltages on Peaking Capacitor and Load for S_2 Closure at 350 ns.

Figure 25. Open Circuit Voltage, Calculated for Best Estimate of Final Machine Parameters.

Figure 26. Voltages on Peaking Capacitor and Load, Calculated for Best Estimate of Final Machine Parameters.

Peaking capacitor parameters are based on a construction with cylindrical center conductor and 8 sided outside; this shape (see section 3.6) developed as a practical compromise in tank design. The impedance of that configuration has been estimated at 12 ohms and the total capacitance at .8 nanohenry. Sensitivity calculations show output voltage to be insensitive to peaking capacitor impedance when total capacitance is held constant, but output voltage decreases when capacitance is increased with constant impedance. Increased capacitance at constant impedance translates physically to a peaking capacitor with the same cross section but longer length. Increased impedance with constant capacitance translates to a capacitor with a relatively smaller diameter inner conductor and length adjusted to maintain constant total capacitance.

Model circuits used are shown in Figures 27 thru 33. The peaking capacitor is modeled as a four section, lumped constant delay line. Each simulation consists of two calculations. The first is with the output switch open, and essentially shows charging of the peaking capacitor. In the second, the output switch is considered to close when the peaking capacitor voltage reaches 90% of its peak value, and the mode voltage and branch currents at that point are used as initial conditions. Initial condition on the Marx capacitance is 7 megavolts in all cases.

Conclusions from this work are that changes as machine

FIGURE 28.

EFFECT OF REDUCING MARX INDUCTANCE

8/25/76 CS

Vout MV

FIGURE 29.

EFFECT OF REDUCING OUTPUT RESISTANCE

8/25/76 CS

FIGURE 31.

EFFECT OF PEAK C Z_0 INCREASE WHILE CAPACITANCE IS CONSTANT

9/25/76 CS

FIGURE 32.

EFFECT OF INCREASED PEAKING CAPACITANCE WITH CONSTANT Z_0

8/25/76

FIGURE 33. MARX VOLTAGES + CURRENT

8/25/76 CS

design evolved had not caused significant perturbations on expected output waveform, and that some leeway exists as regards Marx dimensions (inductance) and diode design. It was originally thought that Marx inductance and diode impedance would have to be held within close tolerances to assure a satisfactory output. The lack of sensitivity to diode impedance is particularly helpful, since design of this element of the system is based upon extrapolation from much smaller configurations than the full scale machine will require.

Within the limitations of validity of the simulation used, and for circuit values in the neighborhood of those used, detailed results were as follows:

- (1) The machine with best present estimates of Marx inductance and peaking capacitor parameters has an output essentially the same as previous estimates; see Fig. 27 for a comparison. Output voltage in the first 50 nanoseconds is slightly higher for the updated circuit parameters, but peak output is the same. Late in the pulse, voltage is lower than was estimated earlier.
- (2) Changing Marx inductance changes the time before the output switch closes, but has little effect on output voltage. See Figure 28.
- (3) Sensitivity of output voltage to load resistance variation is only .25. That is, if load resistance is

reduced 20%, output voltage goes down only 5%.

See Figure 29.

(4) The change in output voltage as load inductance is changed is small and is primarily in the first 25 nanoseconds. See Figure 30.

(5) When peaking capacitor impedance is changed but total capacitance held constant, output voltage is unchanged except for the timewise position of the minor peaks associated with capacitor (line) length. See Figure 31.

(6) When peaking capacitor impedance is held constant and total capacitance (length) is increased, output voltage decreases. Sensitivity is about - .25.

See Figure 32.

1.2.3 Diode Length versus Pulse Rate Tradeoffs

The basic design parameters for the machine are operating voltage and cable processing rate; relationships between linear cross-linking rate, pulse frequency, and diode geometry are considered here. Tradeoffs involved are the following:

- Repetition rate can be kept low and the Marx asked to deliver an energetic pulse into a long diode.
- Frequency can be increased, energy per pulse made

smaller, and the diode shortened.

For a fixed processing rate the average power which must be delivered will be a constant, independent of the strategy followed with respect to frequency, so that questions of heat dissipation in the Marx are in no way altered nor is there a change in the number of coulombs switched per unit time. Capacitor service life might benefit from lower pulsing rates.

In the diode, cost and design problems are directly related to length, and perhaps to length raised to some power greater than one. Longer length means greater surface area, hence more metal to fabricate and support, and it also means more volume, hence a larger pumping system for equivalent evacuation periods. A window of longer span is required as length is increased. It is also likely that lengthening the diode will decrease impedance and therefore go in the direction of reducing voltage delivered to the load, thus making a higher voltage Marx necessary. Finally, emission may prove to be ragged and nonuniform if cathode surface area is forced to become large. So, from the viewpoint of the diode, it would appear desirable to keep length to a minimum, i.e. to keep repetition rate high.

An idea of the range within which active diode length must fall can be obtained by demanding that dose per pulse not exceed some limiting value, and then proportioning stored energy of the Marx over a cable length whose mass is commensurate with this limit. This

gives

$$h = \frac{\eta E}{\rho A D} \quad (6)$$

where

h = diode length

E = stored energy per pulse

ρ = density of polyethylene

A = cross sectional area of the insulation

η = overall efficiency of energy transfer from Marx to cable, including losses due to absorption in the center conductor and backscattering from the surface

D = limiting dose/pulse

By asking that crosslinking be accomplished in a series of 10 pulses, and assuming that 10 megarad total dose provides adequate crosslinking, dose per pulse can be about 1 megarad and consequences of a missed pulse are reduced to the 10 percent range.

Manipulating the expression for diode length and using these values for dose and number of shots, an equation for Marx frequency can be derived. Recognizing that stored energy is given by

$$E = \frac{r c V^2}{2}$$

c = stage capacity

V = charging voltage

r = number of stages

and substituting this in (6) yields

$$h = \frac{\eta r C V^2}{2 \rho A D} \quad (7)$$

Using the fact that frequency can be found from

$$f = \frac{m \dot{\ell}}{h}$$

m = number of shots to crosslink

$\dot{\ell}$ = linear throughput

and substituting the above relation for h yields

$$f = \frac{2 m \dot{\ell} \rho A D}{\eta r c V^2} \quad (8)$$

For any set of processing and Marx parameters, therefore, a design frequency can be computed.

The Marx defined earlier utilizes 120 stages with stage capacity of 0.4 μ f; if energy transfer is 10 percent efficient, if processing rate is 10 ft./min., and if the cable has 3.2 -inch outer and 0.8 -inch inner diameter, then the quantities necessary to compute frequency are the following:

$$m = 10$$

$$\dot{\ell} = 10 \text{ ft./min (5 cm/see)}$$

$$f = .93 \text{ 8m/cm}^3$$

$$A = 48 \text{ cm}^2$$

$$D = 1 \text{ megarad (10 joules/gm)}$$

$$\eta = 0.1$$

$$r = 120$$

$$c = 0.4 \text{ } \mu\text{f}$$

$$V = 60 \text{ kV}$$

Inserting these values produces 2.6 Hz as an estimate of optimum operating frequency. Design value has been set to 2 Hz because this would give a better compromise with head length if transfer efficiency exceeds 10 percent, an event considered to be highly probable. For additional insurance, and to provide flexibility in choosing processing rate, the Marx trigger circuit has been designed for frequencies from 1 to 5 Hz ; it could readily be modified for operation at lower frequency if necessary.

Although the trigger generator is capable of pulsing at 5 Hz, charging supply has been sized for maximum power corresponding to a Marx firing rate of 3 Hz. This step was taken because frequency is closely tied to energy transfer efficiency, a figure of merit which is not known but which, from the preliminary work done with PEBS (see Section 2.3) could be as low as 10 per cent. Higher efficiency will mean that lower frequency is desired; three Hertz therefore represents what should be an upper limit on pulse rate.

For a Marx storing 85 kJ and transferring 10 percent of this to the cable, minimum active diode length would be 17 cm. Actual length will probably be made at least twice this for reasons related to efficiency and maintaining proper impedance. The latter topic is discussed in detail in a subsequent section.

The Marx generator will operate by slowly charging a number of capacitors in parallel and then rapidly discharging them in series. For a bank consisting of 120 400 nanofarad capacitors charged to 60 kilovolts twice a second, the energy which must be delivered is

$$\begin{aligned}\text{power} &= \text{energy} \times \text{rate} \\ &= 2 \times 86.4 \times 10^3 = 173 \text{ kilowatts}\end{aligned}$$

If the charging system were 100 percent efficient, this would be the power which must be drawn from the electric service. In fact, the charging system is less efficient and some energy will be dissipated as heat.

In the case of a constant voltage supply charging a capacitor through a current limiting resistor, it can be shown that half the energy supplied to the circuit will be lost through joule heating of the resistor. This represents a worse case charging loss, and several schemes are available which would give significantly better efficiency.

Efficiency of the charging system is important for three reasons; first, energy drawn from service must be paid for and higher efficiency will reduce operating cost. Second, and most important, power wasted as heat in the charging system must be dissipated in order to keep machine components cool. Effectively removing 591,000 BTU per hour, as would be necessary with 50 percent charging efficiency,

is no small design job. The third motivation for considering efficiency is the size and cost of power switch-gear, transformers, and rectifiers needed to convert power line AC to the required 60 kilovolts DC. A 50 percent efficiency would require components have twice the rating of those required by a system with 100 percent charging efficiency.

In addition to efficiency, another factor which must be considered is the variation of power drawn from the power service over time; the ideal system would draw power at a constant rate. A less desirable system would draw high power over part of the charging cycle and low power over others. Switchgear, transformers, and rectifiers must be sized for peak as well as average power.

Perhaps the simplest charging system would use a constant voltage DC supply and resistive current limiting. The circuit suffers from poor efficiency and uneven power line draw, but is widely used in single shot machines and low power equipment where simplicity is important and efficiency is not. There are a number of charging schemes which offer better efficiency than that obtained by applying constant voltage to an DC network; one of these is to continuously adjust the supply during charging so that the difference between bank and supply voltage is always small. This could be done by SCR phase control or through the use of a tap changing transformer. Efficiency of several step charging schemes which might be based upon such hardware are compared to the use of constant supply voltage in Table XII. As the number of steps becomes large, the supply cycle approximates a linear ramp and efficiency approaches 100 percent.

Another alternative would be to substitute inductive for resistive current limiting and charge the bank resonantly; because capacitors and inductors are essentially non-dissipative, efficiency can be very high. For the

present application it appears an impractically large inductor would be required to do this, however.

A more complete discussion of alternate charging schemes, including calculation of efficiencies, is given in Appendix B. In view of the complexity of these high efficiency charging techniques, their cost, and the engineering development which would be required to implement them into the system, it was decided to employ constant supply voltage and accept the penalty of low efficiency. This minimizes the attention which must be paid to design of the charging circuit and should provide a system which is relatively inexpensive, failure free, and easy to maintain, although a means of disposing of waste heat will be necessary. Accordingly, specifications were drawn up for a 65 kV plus-minus supply (see Appendix B for details of these specifications). A photograph of the supply is given in Figure 34.

While this approach should be acceptable for feasibility demonstration, commercialization will require substitution of an improved charging circuit to give more favorable operating costs.

TABLE XII. SYNOPSIS OF R-C CHARGING METHODS.

Charge Voltage - All use Resistive Current Limit	Efficiency	Time Variation of Power from Line
A. Constant supply voltage	Essentially 50%	Exponential
B. N steps of equal voltage each and equal time each	Increases with N 75% for N = 3 87% for N = 7	Stepped exponential each step smaller than one before
C. N steps of equal time each voltage of each step increasing as square root of time	Increases with N for given N less than B. 70% for N = 3 83% for N = 7	Stepped exponential
D. Linear voltage increase with time (ramp)	Can approach 1 like B as $N \rightarrow \infty$	Approximately linear ramp with time

Figure 34. Views of the Charging Supply

1.4 Design of Marx Trigger Generator

Purpose of the trigger generator is to initiate switch closure on the initial stages of the main Marx generator. To minimize the possibility of misfires, trigger voltage was made several times the stage voltage. Since the stage voltage is 120 kV, trigger voltage of 480 kV into open circuit was selected.

Physical layout of the trigger generator is shown in Figure 35. In its main components it is comprised of an 8 stage Marx generator, power supply, output cable and associated control circuits. The Marx generator is comprised of 8 capacitors of 12.5 nf capacitance each rated at 60 kV; maximum stored energy is 180 joules. Inductance of the Marx is estimated at 2 μ H which would provide a 10-90% risetime of the output pulse into a 50 Ω cable of

$$T_L = \frac{2.2L}{R} = \frac{2.2 \times 2 \times 10^{-6}}{50} = 88 \text{ nsec.}$$

Because the variation in closure time (jitter) of the Marx switches will be only a few percent of this risetime, the generator is more than adequate for its task. Decay time of the trigger pulse is determined by the erected capacitance of the generator and its load impedance, which is mainly comprised of trigger isolation resistors. If it is assumed that trigger isolation is equal to 1000 ohms, the RC decay time constant is then 1.56 μ sec, which again provides ample time and energy to ignite

TRIGGER GENERATOR

Figure 35. Trigger Generator Cutaway

Figure 36. Trigger Generator Electrical Schematic

Figure 37. Photograph of Trigger Generator

the switches in the main Marx bank.

Power supply of the trigger generator is designed for 3kVA, which allows operation up to 5 Hz.

The overall circuit diagram is shown in Figure 36. In addition to the 8 stage Marx generator and power supply, the circuit which initiates Marx erection is shown. The initiating signal is created by first charging capacitors C-5 and C-6 through resistors R_2 , R_3 , R_4 , R_5 , and then closing the gap S-1. Capacitors C7 and C8 serve as coupling capacitor and provide dc isolation.

The trigger generator is housed in a pressure vessel of 32" inside diameter and 78" length. Nitrogen at pressure up to 45 psig will serve both as insulating and switching medium. The generator will be located in back of or along-side the main Marx and the two will be connected through a high voltage polyethylene cable.

Figure 37 shows a photograph of the assembled unit.

To test the generator, a dummy load consisting of a 1000 Ω series-parallel resistive cable termination was built and immersed in an oil filled enclosure, and the machine was then put on life test at a repetition rate of 5 Hz. This is 2.5 times the design frequency of the main Marx, and allowed us to conduct an accelerated program while overtesting the machine thermally. During an initial period of experimentation the generator was conditioned and triggering characteristics were determined with a number of filling gases, including the

following:

- . nitrogen
- . carbon dioxide
- . 50 - 50 and 80 - 20 mixtures of CO_2 and N_2
- . 2.5 percent Freon - 12, balance N_2
- . 2.5 percent SF_6 , balance N_2
- . artificial air (80% N_2 , 20% O_2)

Self-breakdown voltage and triggering range were measured in CO_2 , N_2 , and artificial air; results are plotted in Figures 38 through 40. In each of these figures the upper curve is the charging voltage at which self-erection of the Marx occurred, while the lower is the smallest voltage at which triggering would take place. Triggering range is the difference between the two curves; it is desirable that range should be large in order that reliable triggering can be obtained over a span of voltages, and so that performance will be stable over long periods of operation, even with some gap erosion.

Design of the first set of spark gaps used in the machine is illustrated in the top photo of Figure 41. After a little more than 1,100,000 shots had been made with these gaps, operation became ragged; at this time it was decided to modify the design to reduce corona, simplify fabrication, and to make the gaps more readily

FIGURE 38 - SWITCHING RANGE IN CO₂

Figure 39. Switching Range in N_2

Figure 40. Switching Range in 80% N₂ - 20% O₂

Original Gap Design

electrode
midplane
electrode

Improved Gap

adjustable electrodes
diminished corona

insulator
electrode
midplane
electrode

Present Gap

greater field
intensification

insulator
midplane
electrode
electrode

Figure 41. Evolution of Trigger Generator Gaps

Figure 42. Switching Range of Improved Gap in N_2

adjustable. The result was the "improved gap" shown in the center of the figure. Switching range measured in nitrogen for this design was substantially larger than that of the original gap; at 40 psig it increased from 34 percent of selfbreakdown to 49 percent. Figure 42 gives switching curves for this gap in nitrogen.

A further redesign of the switch was made after approximately 460,000 shots were accumulated on the "improved" version. This became necessary because threads on screws securing electrodes to the switch frame eroded badly, and electrodes loosened. The lower photograph of Figure 41 depicts the final version of the switch. In addition to shielding the mounting screws, the midplane bar was reoriented to increase field intensification. This last design was run successfully for more than a million shots.

During this testing, capacitors accumulated almost 2,500,000 shots and remained in excellent condition.

Current limiting for the trigger generator is provided in part by a resistor bank located external to the pressure vessel in the primary circuit of the power supply. This approach allows most of the heat evolved during charging to be dissipated at a location where cooling is easily provided and component damage cannot result. Resistance in this bank controls the charging time constant; too large a value will result in the Marx being erected at less than full voltage. Figure 43 plots the percentage of full voltage reached as a function of primary

resistance for operation at two frequencies. "Full voltage" was determined by charging the Marx and holding it without triggering. As a result of this study, we have set the primary resistance to 2.5Ω , which causes the Marx to reach about 90 percent of supply voltage when operating at 5 Hz. At 2 Hz, it should come to full voltage.

Several component failures were experienced; all were minor. The monitor resistor intended to read Marx voltage failed after about two hundred thousand shots. This resistor was designed for service in oil and was overstressed when operated in three atmospheres of nitrogen. The monitoring function was eliminated; this in no way affects Marx performance.

It was found that the lowest ground-side charge resistor (R_{17} in Figure 36) was not adequately heat sunked. The Delrin rod supporting it melted and was replaced. A redesign of the mounting points cured this problem.

1.5 Main Marx Bank Design

The Marx bank has been designed as ten independently removable modules, each consisting of 12 capacitors, 6 Marx switches, and associated isolation components. Modules are suspended by straps from cross beams running across the top of the tank; individual modules will be interconnected by mechanical switches to put all ten in series. To reduce stress on charging components, capacitors are charged

alternately plus and minus 60 kV. Figure 44 shows one module in schematic form.

It is planned to initiate erection by externally triggering the six stages nearest ground using the trigger generator described in Section 1.4, the remainder being fired by tying switches into the output obtained by one or more stages below them. All sixty main Marx switches will be midplane spark gaps of the same design, details of which are described later in this section.

1.5.1 Design Criterion for Oil

Early in the machine design it was necessary to establish guidelines for working voltage stress level in the insulating oil. Design stress is important to reliability, size, and cost of the machine. If the working voltage stress is too high, voltage breakdown and sparking will result, causing machine malfunction and, possibly, component failures. With working stress lower than necessary, the machine will be larger and therefore more costly to construct than need be. In the peaking capacitor, for example, design requirements for characteristic impedance establish the ratio of inside diameter to outside diameter. The voltage stress is then proportional to diameter, but volume is proportional to the square of diameter. Since cost is proportional to volume, a 10% reduction of stress in the peaking capacitor will cause an increase of both volume and cost by about 21%. For this reason, the working voltage stress must be chosen carefully to insure reliable

— Are High Discharge Current Lines.
10 Similar Stacks are Used.

Figure 44. Marx Generator Schematic.

operation on the one hand but suitable size and cost on the other.

Because voltage breakdown in oil depends on the duration of applied voltage, the machine has two areas where voltage stress levels must be considered separately. The Marx generator is subject to slow charging and certain parts must have insulation essentially suitable for DC operation. The peaking capacitor and higher voltage parts of the Marx are subjected only to fast pulses, and a different design voltage stress is therefore appropriate. Fast pulse insulation requirements are considered here.

There are two primary sources of information on allowable stress in oil for fast pulses. One is the work of the team at AWRE, Aldermaston, England, and the other is the large electrode work carried out in U.S. facilities associated with the design phases of large pulse power systems. The tests at AWRE indicate oil breakdown for fast pulses can be estimated by:

$$F = \frac{.5}{t^{1/3} A^{1/10}} \quad (9)$$

where

F = breakdown stress in megavolts/cm

t = effective pulse time in microseconds

A = stressed electrode area in square centimeters

For the peaking capacitor t is 0.2 microseconds and A is about 1.58×10^5 square centimeters, so the breakdown stress predicted by (9) is

258 kilovolts per centimeter. Tests made on early scale models of the Aurora pulsed electron beam generator with voltage application times and electrode areas similar to those of the peaking capacitor found breakdown levels between 288 and 311 kilovolts per centimeter. The AWRE formula is based on data taken at essentially single shot conditions. Aurora testing was also single shot. Little experimental evidence is available to describe the effects of repetitive pulsing on breakdown stress levels. One test, done by Ameen at Ion Physics with small area electrodes, indicates breakdown levels may degrade to 85% of single pulse values at 2 pulses per second, and to 75% at 5 pulses per second.

Based on the information above, a design voltage stress level of 200 kilovolts per centimeter for fast pulse areas of the machine has been chosen. That is in line with breakdown predictions between 258 and 311 kilovolts per centimeter and the proven design level of 200 kilovolts per centimeter used on the Aurora machine.

Several other qualitative points relating to the fast pulse insulation of oil are indicated below.

Electrode surface finish has little effect on breakdown, so polishing is not required. Temperature variation of 15°C has little effect. Large volume tests have shown little influence of solid contaminants in the oil, but the tests were done single shot and repetitive pulsing may cause particle alignment as in dc machines. Plastic coating of electrodes can increase breakdown strength about 10%, but the

improvement may not be worth the cost of application and uncertainty of long term adhesion. Small bubbles, as well as dissolved water, have little impact on breakdown in large volume machines. A conditioning effect has been reported where breakdown occurs at a lower level for the first few pulses than it does for subsequent pulses.

1.5.2 Main Bank Capacitor Spacing

In the initial Marx design, vertical spacing between capacitors in a column was 5.08 centimeters and the maximum voltage was 240 kilovolts. With an enhancement due to corners or sharp edges of two, this arrangement gave a stress of 95 kilovolts per centimeter. Similarly, the horizontal space between capacitor columns was chosen to be 15.25 cm, and the maximum voltage was expected to be 1,440 kilovolts. Using an enhancement of 2, this resulted in a stress of 190 kilovolts per centimeter. Spacings in the Marx generator section therefore gave fields less than 200 kilovolts per centimeter. When computer modeling suggested an increase in bank capacity from 2 to 3.3 nf (erected) component spacing was reviewed. In this design, as the Marx rings with the peaking capacitor, voltage between taps of adjacent capacitor columns will reach a peak value of 1.8 MV (assuming inductance is uniformly distributed throughout the Marx). Based upon a six inch column spacing, this corresponds to a

uniform field stress of 118 kV/cm. With enhancement due to unshielded components or mechanical misalignment, stress could reach values in excess of the 200 kV/cm specified as a design criterion.

Spacing was therefore increased by 2-inches to give a total of 8-inches between columns at the point of highest potential difference. Corresponding field is about 88 kV/cm.

In oil insulated Marx generators which IPC has built in the past to produce 300 kV by 50 μ sec pulses, a stage spacing of 0.5 - inches was used for 60 kV; the same equipment utilized 3-inches of oil to hold off 300 kV from ground at the output end. Design field strength was therefore in the range 40-50 kV/cm, assuming uniform field conditions.

Because erection time of the Marx generator will be relatively short, on the order of a microsecond, it is anticipated that higher stresses can be supported than were carried in the design cited above. Scaling by the inverse cube root of peak duration to obtain an estimate of strength for a 1 μ sec pulse gives

$$F = \left(\frac{50}{1} \right)^{1/3} 40 \left(\frac{\text{kV}}{\text{cm}} \right) \sim 150 \frac{\text{kV}}{\text{cm}}$$

With spacing now yielding a stress of about 90 kV/cm over an 8-inch main bank gap, adequate margin against sparkover should exist. To assure that this is the case, stress shields will be employed on the uppermost stages of each column.

1.5.3 Modeling of Marx Inductance

Two models of the Marx generator were built, one based upon a scale of 0.5-inch equals one foot and the other upon 1-inch equals one foot. Each model was tested with wire shaped to include interconnects and gaps, but excluded inductance in the capacitors themselves. Wire sizes used were 0.032-inches and 0.064-inches.

Measured inductances were:

large model with large wire: 0.2818 μ H/section

small model with small wire: 0.1405 μ H/section

It appears that inductance scales directly with linear dimension. Using this premise to estimate inductance of the full sized Marx gives

$$(0.282 \mu\text{H/section}) \cdot (10 \text{ sections}) \left(12 \frac{\text{inches}}{\text{inch}}\right) = 33.8 \mu\text{H}$$

$$(120 \text{ capacitors}) (25 \text{ nh/capacitor}) = 3 \mu\text{H}$$

$$\text{total inductance} \quad 36.8 \mu\text{H}$$

Original output calculations assumed that Marx inductance could be held to 25 μ H; results of modeling suggested that this was somewhat low, and output computations were updated using 37 μ H (see Section 1.2). Fig. 45 is a summary of inductance modeling.

1.5.4 Marx Generator Charge Isolation

It is necessary to provide isolation impedance between capacitors, subject to the conditions that not too much power is dissipated during charging or during erection and discharge.

Figure 45 . Summary of Inductance Modeling.

Isolation elements must be sized so that there will be no catastrophic failures of isolation or Marx capacitors in the event of machine faulting.

There are at least two basic approaches to charging the Marx; capacitors may be charged in series so that all current flows through the isolation impedance of the first, or capacitors in a stack can be charged in series with charging lines connected to a bus providing isolation between pairs of stacks (see below).

For a long Marx operated repetitively, series charging puts a high average power requirement on charge isolation components in the early portions of the chain. For this reason a bus arrangement has been used.

For isolation within a stack, a reasonable impedance is in the neighborhood of 4.8 k ohms in series with 3.8 mH. A typical 5K, 200 watt wirewound resistor has inductance of about 1 mH. To achieve the desired values, options considered were to (1) have special resistors made, (2) build special resistors, or (3) build an inductor to put in series with a standard resistor. In all cases, preliminary calculations indicated components would have physically reasonable dimensions and could be built to withstand a capacitor short or an output switch misfire.

For isolation impedance between stacks, use of an inductor appears to be the best choice. A value of about 70 mH is appropriate. The inductor must hold off 1.5 megavolts; damping to below critical is provided by the stack isolation resistance. A 70 mH inductor made as a solenoid with # 16 wire close wound would be 18 inches in diameter and 36 inches long. It is planned to place these inductors above the Marx capacitors.

Discussion supporting these conclusions can be found in Appendix C.

1.5.5 Limiting Energy Into a Faulted Main Bank Capacitor

Should a capacitor in the Marx short, all the energy in the other 59 capacitors being charged to the same polarity would be discharged through it. The worst case is a capacitor which shorts after all are charged to full voltage but before the Marx is fired. It can be shown^{*} the energy into the fault is never worse than $(1 + \frac{nr}{R})$ times the energy stored in each capacitor, where n is the number of capacitors external to the fault, r is the fault resistance, and 2R is the isolation resistance between capacitors.

At Los Alamos, the SYLLAC program designs to limit energy to 25 kJ in 1.85 μ fd 60 kV Aerovox capacitors, and scaling to our physical size suggests a safe limit of 15 kJ. Therefore the minimum isolation resistance, R, is 3r. If r equals 1, then R must be at least 3, and 30 would be better.

Because fault resistance would be measured in milliohms, it appears that isolation specified to limit droop will be more than adequate to prevent dissipation of excessive energy in a shorted capacitor. Protection against capacitor fault conditions, therefore, requires no additional components beyond those present to provide isolation.

*

See Appendix D

1.5.6 Misfire of Output Switch

If the output switch fails to close and the fully erected Marx is not connected to the diode, then the Marx will be damped through the isolation resistors and all the stored energy will be dissipated in them. This results in a circuit configuration where, for most locations, the energy stored in four capacitors is shunted through six resistors. Most resistors will have to dissipate about $2/3$ of the energy stored in a single capacitor, but a greater demand is placed upon the resistor nearest ground. This component is required to shunt some portion of the current from all upstream capacitors, and will therefore be required to handle a power loss equal to 1.75 times unit stored energy, or 1.26 kJ.

Published data show that an R5-10 wire wound 10-watt resistor can safely take from 27 to 80 joules, depending upon resistance. Extrapolating from this by assuming that a reasonable figure of merit for estimating energy handling capacity is 5 joules per watt of rated power, then it might be anticipated that a standard 200 watt wire wound resistor would carry 1 kJ successfully. If this is the case, then it seems reasonable to expect that a larger specialty resistor could be designed which would safely take 1.26 kJ. To determine energy handling ability of various commercially available resistors, tests described in the following subsection were conducted.

1.5.7 Practical Specifications of Isolation Components

Resistors

Desired value is between 2 k with 5 mH inductance and 5 k with 3 mH to limit Marx discharge during erection to 1 percent of stored energy. Options for obtaining the desired components are to build, buy a standard resistor, or buy a special. The preference is to buy, and this appears to be possible, based upon evaluation of several types in pulsed tests.

Normal operating parameters for charge isolation resistors are 250 kilovolts peak for about 3 microseconds each half second, and a heating current of 0.35 amps RMS. Occasional fault conditions may require resistors to discharge a capacitor equivalent to .0167 microfarad charged to 240 kilovolts, an energy of 480 joules.

Measurements of impedance and pulse response at low voltage show that two industry standard 200 watt wire wound resistors in series will give acceptable charge isolation; a 1.0 kilohm resistor has inductance of about 0.3 mH, and 2.5 kilohm has inductance near 0.5 mH. Inductance is somewhat lower than calculations indicate will be required, but calculated values were based upon a pessimistic estimate of Marx erection time. If erection is faster than was assumed, less inductance will be needed.

Several resistor manufacturers were contacted about building

resistors with higher than normal inductance. Because special tooling is required in the manufacture of high power wire wound resistors, it appears that such a part would be prohibitively expensive if made in anything but a standard size.

To test commercially available components, standard $1\text{ k}\Omega$ wire wound resistors were purchased from each of the following manufacturers:

Clarostat

Dale

Charles T. Gamble

Milwaukee

Ohmite

Ward-Leonard

Resistors of two lengths were supplied by Charles T. Gamble, 10.5 and 12.5 inches.

Test circuit was that sketched below; effective resistance was nominally $1\text{ k}\Omega$.

This circuit was used to terminate the trigger generator cable during life testing. Resistors initially used were Clarostat VK-200, 10.5 inches long. These operated satisfactorily for more than 1,500,000 pulses, gave no problems, and all read 1 k Ω upon removal.

Bulk of the pulsing was done at a trigger generator charging voltage of 45 kV, which should correspond to an output voltage of about 320 kV. Energy dissipated in a pair of series elements is no more than 90 joules (half the energy stored in the generator).

In the analysis given earlier it was argued that isolation resistors would have to carry voltage up to 240 kV and that should a misfire of the output switch occur, resistors could be required to dissipate as much as 1.26 kJ. The setup overtested for voltage standoff (320kV versus 240 kV required), but did not yield data on ability of resistors to withstand fault energies. Successful operation thus gives confidence that components will be adequate for normal functioning of the Marx, but additional testing would be needed to verify fault performance. It may be possible to obtain this verification with a relatively simple rig consisting of a capacitor, overvoltage switch and the resistor to be evaluated. As of this writing, however, such testing has not been carried out.

Clarostat resistors were run successfully at charging voltages higher than 45 kV, up to 55 kV, giving about 360 kV over the chain. It therefore appears that a pair in series will have substantial voltage

margin for normal Marx operations.

A summary of test results is given in Table XIII. Length of normal run was (somewhat arbitrarily) set at 400,000 shots, and policy was to exchange resistors at the first convenient point after this number had been accumulated. With one exception, each of the four resistor types tested to date have performed well. It thus appears that selection of an acceptable resistor from those commercially available will be possible.

Inductor

An inductance in the range 20 to 90 mH will be required, exact value depending upon Marx erection time and allowable energy loss from the bank during erection. Minimum conductor size is limited by the RMS charging current (3.5 amps). The present Marx layout will permit inductors which are up to 15 inches in diameter and 24 inches long.

A preliminary design was made using #22 wire and irradiated PVC insulation with .010 wall thickness. This wire was close wound on a 15 inch diameter form over the 24 inch length. Resulting inductance was calculated to be 33 millihenries with resistance of 26.6 ohms and dissipation of 326 volts at 3.5 amps RMS.

A quarter scale (approximately) model of this inductor was fabricated by winding number 22 stranded wire on a short length of

TABLE XIII
SUMMARY OF RESISTOR TESTING RESULTS

Manufacturer	Resistor Designation	Nominal Resistance, Ω	Length, Inches	Number of Shots	Comments
Clarostat	VK200	1000	10.5	1,500,000 +	No problems. All read 1 k Ω upon removal. OK.
Dale	HL-225-042	1000 $\pm$ 5%	10.5	409,000	No problems. OK.
C. T. Gamble	---	1000	12	~2,000	Local flashing, shedding of ceramic coating. This did not condition with continued pulsing.
C. T. Gamble	---	1000	10.5	500,000 +	Initially, local flashing and shedding of coating. This conditioned and resistors are now performing well. OK.

Test Conditions

oil immersion
 ~320 kV per resistor pair
 ~90 joules per pulse per pair
 pulse frequency, 5 Hz

14 inch diameter PVC tubing. Coil length was about 4 inches, and measured inductance as 3.4 millihenry; ends were not shielded. This was put in parallel with a resistor array being evaluated with the trigger generator, and pulsed for several hours (about 40,000 shots) at which point it began to break down between windings at several places. Upon removal and examination it was found that severe pitting of the PVC had occurred at these locations and insulation had been removed from the wire.

A second inductor was then wound using a Lucite form and solid 22 gage wire. Coil diameter was 11.5 inches and length 4 inches; inductance was 2 mh. Ends of this coil were also unshielded. This design accumulated in excess of 650,000 shots without indication of damage.

1.5.8 Mounting Strap Length

The Siege II program included an investigation of support strap flashover as a function of stress per unit length; tests used a pulse with 50 μ sec decay, quite a bit longer than our present machine, and were all single shot. Straps were nylon, 3 inches wide, 3/8 inches thick, in oil. Results of those tests(20) give some guidelines for our strap length. It was found that number of breakdowns increased rapidly with stress but, below 65 kV/cm, there were none. At 65 kV/cm, only one out of a total of 3500 test shots led to flashover.

Using 65 kV/cm as a standard for maximum stress (or minimum length), and considering that computer simulations show peak voltage of 9.6 MV on the peaking capacitor, it is concluded that at least 54 inches of strap length will be required for both the peaking capacitor and the last Marx module.

Peaking capacitor strap length as now designed is 63 inches, and should be adequate. Straps for the last section of the Marx bank are not so conservative, and may require redesign.

Options to give increased strap length include the following:

- drop the highest voltage Marx module toward the bottom of the tank

- put some of the high voltage stages inside the peaking capacitor, thus cutting the height of the last module and increasing strap length in oil
- eliminate some capacitors from the last module

The last solution is probably the most practical one. Dropping four capacitors would give several additional feet of immersion; the cost of this would be about 3.3 percent in peak voltage and stored energy.. These figures were arrived at from:

$$V = Nv$$

$$v = \text{stage voltage}$$

$$N = \text{number of capacitors}$$

$$c = \frac{C}{N}$$

$$c = \text{stage capacity}$$

$$U = \frac{1}{2} CV^2 = \frac{1}{2} \frac{C}{N} (Nv)^2 = \frac{1}{2} cv^2N$$

and then

$$\frac{dN}{N} = \frac{dV}{V} = \frac{dU}{U}$$

This shows that the change in output voltage, V , and stored energy, U , varies directly with the percent change in number of capacitors. Loss of energy does not pose a problem because the machine is considerably overdesigned in terms of potential processing rate. Calculated output voltage is about 7.4 MV peak (Figure 27 with some smoothing); dropping

this 3.3 percent brings it down to a little below 7.2 MV. These numbers neglect losses in the system, which would have to be held below 3 percent if 7 MV were to be achieved with 116 capacitors. It is not clear that this can be done.

Resolution of strap length at the last Marx module was still up in the air at contract's end. Final decision will necessarily have to consider the placement of isolation components, as insulation of the last stage inductor may also be a problem.

1.5.9 Estimate of Radiation Dose in Front End Capacitors

Capacitors nearest the source are shielded from it by 15 feet of oil, sufficient to provide an attenuation of 2×10^6 in the radiation dose. Even so, dose rate due to direct photons will be about 11 rads/hr (copper target) at full voltage; with buildup, this could be as high as 20 rads/hr. From REIC-44⁽²¹⁾ 1 megarad is required before the reliability of paper and oil capacitors is effected. At 20 r/hr, it should be possible to operate for 50,000 hr before reaching this level, so that problem should develop in the present installation. In a commercial unit, capacitors could be rotated on a fixed schedule, replaced at standard intervals, or shielded by (for example) filling the peaking capacitor with suitable material.

1.5.10 Marx Switch Design and Life Tests

Among the most critical components of the Marx are the 60 main switches. Marx switches of the type needed here have previously not been operated over long periods of time and at relatively high frequencies. Consequently, a test setup as shown in Figure 46 was built and a preliminary switch design was tested under the following conditions.

Charge Voltage:	80 kV
Capacitance:	260 nf
Max. Current:	70 kA
Stored Energy:	830 J
Charge Transfer:	20 mC
Gas Pressure:	3 psig of N ₂
Rep Rate:	.3 pps

This first switch was overvolted; as the Marx design evolved through its early stages it became clear that a triggered unit would be needed to initiate erection, and subsequent testing was conducted on such a model. Of primary concern at program outset was the need to determine electrode erosion rates and the effect on holdoff voltage of depositing erosion products as walls of the housing. A sputter shield was included to act as a collector for deposits.

Variation of self-breakdown voltage as a function of the number of discharges was recorded on a strip chart and is shown in Figure 47. From this figure it can be seen that self-breakdown voltage remained constant after an initial burn-in period. Gas was not changed during testing; at the time the tests were terminated (192,500 discharges) the switch was still operating satisfactorily.

After opening the switch, shown in Figure 48, a strong blackening of the metal parts, but not of the lucite enclosure was observed, which indicated that the sputter-shield provided the expected protection. The anode, cathode and midplane all showed signs of erosion, and by measuring indentations, the following erosion rates were determined.

	<u>Material</u>	<u>Rate</u>
Cathode	Brass	.035 mm ³ /C
Anode	Brass	.020 mm ³ /C
Midplane	Elkonite	.010 mm ³ /C

From these results it appeared that reliable switch performance could be obtained without the need for continuous flushing and without resulting to exotic electrode materials. From the self-breakdown data it also appeared that prefire could be eliminated by operating the switch at less than 70% of self-breakdown voltage.

Subsequent to this initial work the switch was upgraded to operate at a higher frequency, giving electrode heating rates more nearly equal to those expected in the full scale machine, and provision for switch

Figure 46. Test Setup for Switch Life Studies.

Figure 47. Variation of Self-breakdown Voltage with Number of Discharges.

Note: Dimensions are in inches.

Figure 48 . Marx Switch.

triggering was added. It was also recognized that switch testing presented an opportunity to obtain operational data on main bank capacitors. To this end, a 300 nf 80 kV capacitor, typical of units specified in the preliminary Marx design, was used as the energy discharge element.

A block diagram of the triggered switch test setup is shown in Figure 49 and a composite photograph is given in Figure 50. The energy storage capacitor could be resistively charged from a 200 milliamp power supply to any level up to its 80 kilovolt rating. The switch was triggered with a small Marx generator similar to ones sold as standard products by IPC. The trigger Marx consisted of 6 stages, each with 8.1 nanofarads rated at 40 kilovolts. Various charge levels for the trigger Marx were used, and 26 kilovolts was found to be effective. The Marx is triggered by a low level pulse generator which has variable repetition rate from 0.5 to 5 pulses per second. Periodically, tests on switch holdoff voltage were made to check for degradation due to deposits. In order to test switch holdoff at levels at 120 kilovolts and beyond, the energy storage capacitor and the 200 MA charging power supply were disconnected and the test was made with a low current supply which can go to 180 kilovolts (each switch must operate to 120 kilovolts in the final machine design, where it holds off the voltage of two 60 kilovolt capacitors.) The test switch was designed for 120 kV service but was run at 80 kilovolts due to

Charge Voltage: 80 kV
 Stored Energy: 960 Joules
 Charge Transfer: .024 Coulombs/Pulse
 432 Coulombs/Hour
 Rep Rate: to 5 pps

Figure 49. Test Setup for Triggered Switch Life Studies.

Switch under Test

100 kV
Trigger Generator

100 kV, 20 Kilowatt
Power Supply

Load Resistor

Figure 50. Composite Photograph of Switch and Capacitor Test Setup.

equipment limitations in this setup. The test gave accurate information on switch wear due to electrode erosion and deposition of contaminants because these are proportional to total charge transfer, or coulombs, rather than applied voltage.

The first switch tested had a total anode-to-cathode spacing of one inch. Gas used to pressurize was carbon dioxide; the voltage holdoff characteristic as a function of gas pressure is shown in Table XIV. Since the self-breakdown was not adequate for 120 kilovolt service without going to high pressure, the spacing was increased to 1.7 inches. Result of this is also shown in Table XIV

TABLE XIV. SWITCH SELF-BREAKDOWN AS A FUNCTION OF PRESSURE FOR TWO GAP SPACINGS.

psig of CO ₂	5	10	15	20
self-breakdown, 1 inch space, kV	60	71	80	89
self-breakdown, 1.7 inch space, kV	70	78		

Note: Switch geometry per drawing of W. Nightingale, 3 Nov. 75, 1089-004.

Tests have shown a very good triggering range for the switch (trigger range is the ratio of self-breakdown voltage to the minimum anode-to-cathode voltage which can be reliably triggered). A wide range is desirable so that triggered operation is repeatable with anode-to-cathode voltages well below self-breakdown. This condition prevents self pulsing while assuring reliable operation if the switching range should decrease in service. The operating trigger range was better than 4 to 1 for all test conditions.

The first triggered switch tested aggregated just over 500,000 shots at voltage levels from 50 to 80 kV at which point it was opened, inspected, and modified to correct problems which were found. Material lost from the electrodes was measured and erosion was about $0.029 \text{ mm}^3/\text{coulomb}$ on the cathode and $.026 \text{ mm}^3/\text{coulomb}$ at the anode. It was difficult to estimate total material lost from trigger rods, but there was no impairment of function and such impairment was not imminent.

Concerning materials, results largely agree with tests on the overvolted switch. Nylon was found to be unacceptable in the gas or for the gas hose to the switch. Delrin is better than nylon, but eventually crumbles away on the outside. O-rings show cracks on the side exposed to gas and the Lucite envelope shows crazing; this was worst at the ends near the O-ring.*

Detailed observations on the switch are catalogued below.

* O-ring material was Buna-N.

- (a) light blue green powder all over except adjacent (within 1/4 in) to spark area, where coating was black
- (b) nylon screws holding sputter shield were dark green, fuzzy, weakened, and cracked
- (c) Delrin plug-spacer on sputter shield stud was crumbly, white on outside
- (d) the elkonite rod termination with brass slug brazed to its end, and those secured in the sputter shield with set screws, seemed to hold up well
- (e) acrylic ring has deep cracks near O-ring on ends
- (f) have about 1/8 tsp of brown scale loose inside
- (g) O rings show surface cracks where exposed to gas.

Leaving the basic switch as it stood, details were redesigned to provide improved mounting of the sputter shield and electrodes, and testing was resumed.

Early versions of the Marx design called for a 0.3 μ f 80 kV capacitor, of which two were purchased from Aerovox and used in the switch testing setup. Both of these capacitors failed in service, suffering from internal tracking which, once initiated, rapidly progressed to severe internal heating and mechanical damage. Conditions under which these capacitors were operated are listed below:

Capacitor	Type	%Voltage Reversal	Charging Voltage, kV	Shots to Failure
1	0.3 μ f 80 kV	75	70-75	200,000
2	0.3 μ f 80 kV	50	70-75	800,000

Following the second failure, Aerovox dismantled and examined the capacitor, concluding that failure was a result of excessive voltage reversal (the capacitor was specified for 20 percent reversal).

It is Aerovox experience that life is an inverse power function of reversal; our data show that dropping reversal by a third increased lifetime 4-fold. Aerovox capacitors have been pulsed in the SYLLAC facility at Los Alamos to shot totals in excess of a million, according to Hutzler, without damage of the sort precipitated by our test.

Accordingly, the setup was modified to reduce reversal below 20 percent, and a third capacitor was installed. This was a 0.4 μ f 60 kV device taken from amongst the 122 capacitors purchased from Aerovox for service in the main bank. Specifications call for a 10 million shot life at reversal less than or equal to 20 percent, 60 kV charging voltage and operation at 5 Hz or less for one eight hour shift per day. The setup was reconfigured to operate strictly within these

specifications, and at termination of the testing program, the capacitor had been discharged 5,217,635 times, showing no signs of degradation. During the course of testing the redesigned switch was opened twice for inspection. The first opening occurred in May, 1976, after 1,383,168 shots. At this time, main electrode spacing was reduced by 1/4 inch to prevent discharges to the sputter shield. The switch was opened again in June, 1976 (after 2,315,031 shots) for inspection prior to finalizing switch design and ordering production parts. Erosion measured at this time indicated that a life of 10 million shots should be possible. Based upon results of the June examination, several minor changes were made in the production switch design. These changes were intended to impart better survival characteristics, and have consisted of (1) reshaping electrodes to increase surface area under the discharge, and (2) increasing diameter of the trigger bars to provide additional material as a hedge against erosion. Testing was resumed without making these changes in the prototype.

At this same time, the setup was given a final upgrading by adding a second capacitor. The two were charged plus/minus to place 120 kV peak over the switch, thus simulating service stress.

As of late October 1976, shots on the switch and capacitors had reached the following totals:

Switch

at 60 kV	3,162,805
at 110 kV	1,519,013
<hr/>	
Total	4,681,818
Positive Capacitor	5,217,635
Negative Capacitor	1,628,425

Testing was terminated here as we had become satisfied that the switch design is adequate and that capacitor lifetime will be sufficiently great.

Following this conclusion, castings, rods, and housing materials necessary to fabricate 60 switches were ordered. At contract's end we were prepared to assemble pending delivery of sputter shield castings.

1.5.11 Spacing Between Isolation Inductors and Tank Top

The electrical stress between isolation chokes and the top of the tank is high. As originally conceived, all Marx sections would be at equal depth and stress above the top of the last one is about 330 kV/cm, or 1.65 times the design goal of 200 kV/cm in oil.

If the last Marx module were lowered to equalize space on the top and bottom, stress would be reduced to about 260 kV/cm. Since the area is small, this may be acceptable.

The stress was calculated with the simplifying assumption of a cylinder over a plane, shielding influence of the nearby peaking capacitor will reduce it somewhat.

If it proves that there is still a problem, another possible solution is the following:

Since the last section is the high stress one and since it has the smallest charging current, the charging scheme for that segment could be changed to reduce or eliminate the charging inductance and therefore increase insulation space.

Details of computations of stress over the inductor are given in the following pages.

Figure a

General Formula :

$$\text{Max Stress} = \frac{2V}{\ln \frac{s + (s^2 - a^2)^{\frac{1}{2}}}{s - (s^2 - a^2)^{\frac{1}{2}}}} \times \frac{a + (s^2 - a^2)^{\frac{1}{2}}}{a(s - a)}$$

Figure b.

Results:

Figure a. {	x inches	24	24	30	30
	dia. inches	36	48	48	60
Figure b. {	s cm	107	122	137	152.4
	a cm	46	61	61	76.2
Stress kV/cm		328	326	262.5	262.4

Maximum Stress for Infinite
Cylinder Near Infinite Plane

The fields between a cylinder and a plane can be found by the method of images if the cylinder is considered as a line charge with q coulombs/unit length.

$$(1) \quad \text{where } q = \frac{4 V \pi \epsilon_0}{\ln R_1/R_2}$$

$$(2) \quad R_1 = \frac{D}{2} + \left(\frac{D^2}{4} - a^2 \right)^{\frac{1}{2}}.$$

$$(3) \quad R_2 = \frac{D}{2} - \left(\frac{D^2}{4} - a^2 \right)^{\frac{1}{2}} \quad D = R_1 + R_2$$

See: Plonsey and Collin, Principles and Applications of Electromagnetic Fields, McGraw-Hill, 1961, p. 71.

The image diagram is:

The voltage, v , at any point, z , between the left cylinder and the plane is found by the images technique as:

$$(4) \quad v = \frac{q}{4 \pi \epsilon_0} \ln \left(\frac{r_1}{r_2} \right)^2$$

where q was found from (1), the ratio $\frac{r_1}{r_2}$ can be expressed in terms of R_1 , R_2 , and Z

$$(5) \quad \frac{r_1}{r_2} = \frac{R_1 - Z}{Z - R_2}$$

So, from (1), (4), and (5)

$$(6) \quad v = \frac{2V}{\ln \frac{R_1}{R_2}} \ln \frac{R_1 - Z}{Z - R_2}$$

The voltage stress at Z is $\frac{\partial V}{\partial Z}$ which is found from (6)

$$(7) \quad \frac{\partial v}{\partial Z} = - \frac{2V \left[2Z + R_1 - R_2 \right]}{\left(\ln \frac{R_1}{R_2} \right) (R_1 - Z) (Z - R_2)}$$

This is maximum when $z = a$ using (2) and (3) and making $s = \frac{D}{2}$

$$(8) \quad \frac{\partial v}{\partial Z} (z = a) = \frac{2V}{\ln \frac{s + (s^2 - a^2)^{\frac{1}{2}}}{s - (s^2 - a^2)^{\frac{1}{2}}}} \frac{a + (s^2 - a^2)^{\frac{1}{2}}}{a (s - a)}$$

1.5.12 Marx Tank Material Study

An alternative to the fabricated steel Marx tank shown in Figure 1 of Part I could be a poured concrete housing. There are several advantages to such an approach; these are:

- . potential cost saving due in part to less expensive material, but contributed to by reduced shielding thickness.
- . flexibility in locating ground planes.
- . reduced span for overhead structural members needed to carry shielding against vertical radiation.

Some disadvantages are also noted, principally an absolute lack of mobility which would require construction of a new tank if the unit were to be relocated at contract's end. Consideration of "life cycle" costs, including cost to dismantle the machine and return the facility to its present configuration, would also appear to favor a steel tank. Finally, steel would provide "no cost" shielding against radio frequency emissions which will be generated by switching and discharge. Some protection against these emissions should be provided to assure that operation does not disrupt local communications, aircraft movements into local airports or interfere with other plant operations.

A design study was made to evaluate construction costs for

steel and concrete tanks, and it was concluded that specifying concrete would result in approximately 30 percent greater expense. This follows from the need for additional site preparation. cost of forms, and expense of sealing or lining the vessel. Accordingly, the primary reason for considering concrete, to obtain a cost advantage, appears to have no force, and the extra cost buys little or nothing in view of the arguments raised above in favor of steel. It was therefore concluded that steel is the material of choice.

1.6 Peaking Capacitor

The peaking capacitor was originally viewed as consisting of a cylindrical inner housed in a cylindrical tank which would form the outer conductor. Tradeoffs were made to evaluate various stripline configurations, but cylindrical geometry appeared to be the most effective. On the basis of cost, however, it was found that a tank of rectangular cross section would be preferred. A compromise outer was designed by inserting fillets to make the tank octagonal in the region of the capacitor.

Design impedance was 10 ohms; it was desired that this should be a small fraction of the load to prevent significant voltage drop over the capacitor. Sensitivity studies section 1.2 showed that the effect of higher peaking capacitor impedance on output should not be great, and a compromise was reached which has impedance between 12 and 13 ohms.

The following pages review initial sizing estimates, present a discussion of stripline configurations, and give some mechanical considerations.

1.6.1 Initial Peaking Capacitor Sizing

A cylindrical electrode geometry was chosen for the peaking capacitor because it has good volumetric energy efficiency. The capacitor size is determined by desired characteristic impedance and electrical length, in addition to voltage stress. Characteristic impedance must be much less than expected electron source impedance to get good voltage transfer from the Marx and peaking capacitor to the load (electron source). Electron source impedance is expected to be about 100 ohms, so peaking capacitor impedance must be in the neighborhood of 10 ohms. Peaking capacitor diameter is then determined by:

$$F = \frac{V}{r \ell \ln p} \quad \text{where } p = \frac{R}{r}$$

R = radius of inner surface of outer conductor in same units as r

r = radius of inner conductor

F = maximum voltage stress in units of V and r
 ℓn = natural log

$$Z_o = \frac{60}{\sqrt{\epsilon}} \ell n p$$

Z_o = characteristic impedance of peaking capacitor in ohms
 ϵ = relative dielectric constant of insulator
 = 2.2 to 2.4 for insulating oil

A choice of R of 6 feet and r of 4.5 feet gives a voltage stress of 203 kilovolts per centimeter and a characteristic impedance of 11 ohms; both are in the desired range.

Electrical length determines mechanical length. Preliminary computer simulations showed electrical length of 9 nanoseconds to be adequate. Mechanical length is found by:

$$L = \frac{T}{1.016 \epsilon}$$

L = length in feet
 T = electrical length in nanoseconds
 ϵ = relative dielectric constant
 = 2.2 to 2.4 for insulating oil.

The resulting dimension is six feet. The peaking capacitor was therefore, initially established as cylindrical, 6 feet long, 9 feet diameter inside conductor, and 12 feet diameter outside conductor.

Subsequent computer work indicated that voltage on the capacitor would be higher than the 8 MV originally thought, and it was resized for 9 MV. Tradeoff studies were carried out to examine the effects on oil volume of altering parameters of a cylindrical capacitor. Possibility of utilizing a stripline configuration was also considered. Design has been fixed upon a

cylindrical shape with diameter of 11 feet 1-inch and effective length of 6 feet 9-inches. Diameter of the outer conductor (tank) was increased to 14.5 feet.

1.6.2 Stripline Configuration

Peaking capacitors of coaxial construction are large; in an effort to find a more compact configuration, the dimensions of single and dual striplines were calculated. Unless there is some advantage to a tall slim or short fat configuration, striplines do not appear to be attractive. They are too large and dimensions are such that mating to the Marx generator and diode would require awkward transitions. Sketches of three possible stripline designs are given in Figures 51, 52 and 53.

1.6.3 Geometry Tradeoffs

Calculations have been made to determine whether significant savings on tank volume could be made by altering peaking capacitor dimensions somewhat from those given above.

If the diode impedance can be designed to a sufficiently high value, characteristic impedance of the capacitor can increase above 10 or 11 ohms. The result would be a longer capacitor of smaller diameter. For a simple coaxial capacitor, size is determined when the applied voltage, design stress, capacitance, and characteristic impedance are given. Volume is determined from diameter and length. In the final system, total volume is more dramatically impacted by capacitor diameter than by its volume because diameter determines overall tank dimensions.

Nominal design conditions for the peaking capacitor are:

$$C = 0.9 \text{ nfd}$$

Z_0 = Characteristic impedance, 10 or 11 ohms, the lower the better (Choosing Z_0 equal to 11 gives the dimensions quoted above.)

$$F = \text{Stress} = 200 \text{ kV/cm} = 6096 \text{ kV/foot}$$

Long dimension may be horizontal or vertical

$$Z_o = 10 \text{ ohms}$$

$$C = 900 \text{ pf}$$

$$\text{Peak } V = 9 \text{ MV}$$

$$\text{Stress} = 200 \text{ kV/cm}$$

Figure 51. Single Stripline Peak Capacitor

$Z_o = 10 \text{ ohms}$
 $C = 900 \text{ pf}$
 $\text{Peak } V = 9 \text{ MV}$
 $\text{Stress} = 200 \text{ kV/cm}$

Figure 52. Dual Stripline Peak Capacitor

$Z_o = 10 \text{ ohms}$
 $C = 900 \text{ pf}$
 Peak V = 9 MV
 Stress = 200 kV

Figure 53. Dual Stripline Peak Capacity,
Alternate Design

E = Total applied voltage = 9 MV

ϵ = Relative dielectric constant = 2.1 for oil

Changes in these parameters result in the following approximate relationships:

- If Z_0 is increased by 10 percent and other parameters remain constant, tank depth and width will decrease 7 percent and capacitor volume will decrease 10 percent.
- If applied voltage E , increases 10 percent and other parameters remain constant, tank depth will increase 10 percent and capacitor volume will increase 20 percent.
- If allowed stress, F , is increased 10 percent and other parameters remain constant, tank depth and width will decrease 10 percent and capacitor volume will decrease 20 percent.

Savings in oil and tank fabrication costs on the order of 10 to 20 percent could therefore be realized by designing a high impedance capacitor or by choosing a design stress greater than 200 kV/cm. It was our judgement that these savings did not justify the increased risk of breakdown which would follow from increasing design stress. Furthermore, since the peaking capacitor and diode represent series impedances, it is desirable to keep capacitor impedance low to minimize voltage drop over it. This provides some margin for achieving design voltages on the diode if system losses are greater than predicted or load impedance proves to be lower than nominal.

1.6.4 Mechanical Stability

Because it is intended to handle the peaking capacitor and output switch as a unit, the switch being bolted to a flange on the capacitor, it is necessary to include both items in considerations of stability.

(a) Mechanical stability if suspended by straps at the forward and aft frame rings.

Component weights for steel construction have been determined to be as follows:

switch: 820 lbs.

aft torus and ring; 331

capacitor forward of aft framing ring; 2041 lbs

With these weights, center of gravity of the switch and capacitor system is located about 15 inches to the switch side of the capacitor center line when the assembly is suspended in air and is dry. To determine this:

In oil, there will be a net buoyant force on the switch, and CG will shift toward the center line. The switch displaces 16.6 ft³ of oil,

resulting in 955 lbs lift; net loading under oil is therefore 135 lbs buoyancy.

Installed CG will therefore fall at

$$x = \frac{(331)(44) - (135)(54) - (204)(6)}{3192}$$

$$x = -1.4 \text{ inches,}$$

ie, 1.4 inches to the Marx side of the centerline. This is ideal, for it means that straps will carry balanced loads, and if strap creep occurs, it will be uniform.

Handling in air could be awkward, as the straps nearest the switch will carry most of the load. Using the schematic below, strap loadings in air work out to 1120 and 2072 lbs respectively.

This means that the unit will require some effort to balance when lifted in a sling; this could be corrected by ballasting, but at the expense of

nonuniformly loading straps when the capacitor is submerged. Since service life will be primarily in oil, it seems well advised to leave the system unballasted, and compensate when lifting by proper rigging.

(b) Expulsion of oil from the capacitor at removal

If no provision is made for bleeding the capacitor body as it is lifted from the Marx tank, oil will be trapped in the lower half of the capacitor below the lip of the axial opening. A rough estimate suggests that this trapped oil could weigh as much as 15,000 lbs and occupy a volume of 265 ft³. Such an addition to the unit weight would be likely to precipitate strap failure or creep or to cause structural damage to the skin of the capacitor. To circumvent this, it will be necessary to drain the capacitor as it is lifted free of the tank to assure that a significant oil volume does not build up inside it.

An estimate of the drain area needed to accomplish this can be made in the following way. Volume flow through an orifice is given by:

$$Q = kA \sqrt{2gh} \quad \text{ft}^3 / \text{sec}$$

where A is the orifice area

k is a factor which accounts for "pinching" of the jet cross section as it emerges from the orifice

h is the liquid head over the orifice.

Recognizing that Q is the rate of change of volume leads to

$$\frac{dv}{dt} = kA \sqrt{2gh}$$

If the capacitor cross section is idealized into a parallelepiped of equivalent volume (see sketch),

then

$$wl \frac{dy}{dt} = kA \sqrt{2gy}$$

Integrating and solving for flow area gives

$$A = \frac{wl}{kt} \sqrt{\frac{2h}{g}} \quad \text{ft}^2$$

For our system h , w , and l are roughly 5 ft., 6 ft., and 7 ft. respectively; if k is taken equal to 1 and draining time is required to be 10 minutes, then the drain area needed is

$$A = \left(\frac{54}{600} \right) \left(\sqrt{\frac{10}{32}} \right) = 0.05 \text{ ft}^2$$

$$A = 7.2 \text{ in}^2$$

Because k is a number less than 1, actual area required would be somewhat larger, probably on the order of 11 in². This corresponds to a single hole of diameter about 3.75 inches, or to 55 half inch diameter holes.

This calculation assumes that the capacitor will be removed from the Marx tank with a full load of oil, then drained; in practice this would never be allowed because of the likelihood of structural damage. A more reasonable removal strategy would be to lift the capacitor at a constant rate such that a small head of oil was present and volume changes due to lifting and draining are kept in equilibrium. Then the time required to lift free would be

$$t = \frac{V}{Q} = \frac{V}{kA\sqrt{2gh}}$$

and area required for a given lifting time is

$$A = \frac{V}{kt\sqrt{2gh}}$$

Here V is the total volume of oil to be drained and h is understood to the equilibrium head. This quantity would be selected in such a way that the oil loading imposed on the straps is reasonable, but non zero. If h is set to a foot, then the drain area required for a ten minute lift is

$$A = \frac{265}{(0.67)(600)\sqrt{(2)(32)(1)}} = 0.083 \text{ ft}^2$$

$$A = 12 \text{ in}^2$$

This equates to 60 half inch diameter holes. If 20 such holes are used, the lifting time will be increased to half an hour.

Final design incorporates 12, 1.5 inch diameter holes, 6 at each end of the capacitor, and 26, 0.5 inch holes situated in two rows along the bottom. The half inch holes are 22 inches above capacitor bottom. The large holes will quickly clear oil to the 22 inch level. Time required to drain remaining oil will be roughly 12 minutes.

(c) Sinking the capacitor

To submerge the capacitor to the point where oil can begin to flow into it through the axial opening requires displacing about 250 ft³;

this represents a bouyant force of 14,300 lbs. Since this is four times the assembly weight, it is clear that the capacitor will not sink unless arrangements are made to fill the central cavity. This can be done by pumping it full or by bleeding it up through the drain holes. A combination of these offers the fastest means of getting the capacitor under oil.

(d) Mechanical loading exerted on capacitor by output switch

The switch loads the capacitor most heavily when the assembly is in air, in which case a force of 820 lbs acts through the switch CG. This means that the mounting flange must carry 820 lbs, plus a moment of about 1250 ft lbs (the switch is 3 feet long). If the support structure is idealized as shown below, and if it is assumed that only the uppermost angle carries the switch, then we have created a very severe worst case. The angle

is loaded in tension by 820 lbs; cross sectional area is 2.11 inches (from Machinery's Handbook), so that the stress is a little less than 400 lbs/in². This should provide for a safety factor of at least ten.

Assuming that the moment created by cantilevering the switch generates a couple acting on the upper and lower framing angles, then there is a force acting on each angle to deflect it as an end loaded cantilever. This force is

$$F = \left(\frac{1.5}{2.7} \right) (820) = 455 \text{ lbs}$$

Deflection of a simply loaded cantilever with fixed end is

$$y = \frac{Fl^3}{3EI}$$

y = Deflection

F = Force

l = Length of Cantilever

In steel, $E = 3 \times 10^7$ psi; 3 x 3 x 3/8 angles have inertia equal to 1.8 in⁴ (both values from Machinery's).

Then

$$y = \frac{\overset{+2}{(4.55)} \overset{+3}{(3.9)}}{\underset{+7}{(3)(3)(1.8)}} = 1.67 \times 10^{-3} \text{ in}$$

Therefore deflection should be less than 2 mils, hence distortion of the capacitor body will be negligible.

The capacitor framing has been very conservatively designed, and the unit should therefore be mechanically sound.

1.6.5 Design of Peaking Capacitor Outer Conductor

In preliminary designs the peaking capacitor was shown as a coaxial arrangement consisting of inner and outer cylinders. Because the Marx tank will be rectangular in cross section, provision for a cylindrical outer requires the addition of tank fillets in the vicinity of the pulse shaper. For reasons of cost, it appears advantageous to use fillets made of straight segments rather than parts shaped to a cylindrical configuration. Doing this will increase impedance of the peaking capacitor, however.

Figure 54 shows schematic cross sections of the capacitor and tank for three arrangements which were considered. In the first, four cylindrical fillets would be employed, a coaxial configuration would result, and impedance would be equal to 11.4 ohms. This value is a compromise; 10 ohms would be preferred, but this has been allowed to grow in order that stresses on the capacitor could be reduced, providing additional safety margin against breakdown from inner to outer.

If no fillets were employed (Figure 54C), impedance would be increased to 13.6 ohms, a value which is thought to be unacceptably high. By adding four straight fillets as in 54A an octagonal outer is formed which

(a)

STRAIGHT FILLET
(4 Required)

(b)

CYLINDRICAL FILLET
(4 Required)

(c)

NO FILLETS

Figure 54. Peaking Capacitor Options

approximates a coaxial configuration and should have an impedance of 12 to 12.5 ohms. Fabrication problems are greatly simplified with this arrangement; for this reason it has been adopted as a cost saving compromise.

If fillets are extended beyond the peaking capacitor in both directions, several benefits accrue. These are (1) they can be terminated against the tank ends, thus eliminating the need for carefully rolling them off to prevent regions of high stress, (2) significant savings in oil volume can be made, and (3) inductance should be reduced somewhat. Accordingly, it was decided to carry tank fillets from the forward wall to the break point in the tank at the front end of the Marx generator.

1.6.6 Electrical Losses in the Peaking Capacitor

The peaking capacitor will have electrical losses due to resistance of conductors and losses in the oil. Based on oil dissipation factor measurements made on irradiated samples, and using several simplifying assumptions, it is possible to estimate the magnitude of these losses. These were computed to be in the neighborhood of a few percent of total machine power, or perhaps 5 kW. If this is correct, losses are acceptably small and heat load in the peaking capacitor region will be small.

It is expected that losses will be small even with poor oil because stress is present for such a small percentage of time.

The following pages give the analysis supporting these conclusions.

There are two frequencies of interest:

- (1) The relatively long charge-discharge cycle.
- (2) The relatively short transit time ringing.

Loss parameters to be estimated are:

R = series resistance/unit length

G = shunt conductance/unit length

$$R = \frac{1}{2} \left(\frac{\rho f \mu}{\pi} \right)^{\frac{1}{2}} \left(\frac{1}{a} + \frac{1}{b} \right)$$

$a + b$ in meters

ρ = resistivity in ohm meters

μ = henries/meter

$$G = T_L \omega C$$

T_L = loss tangent of insulating medium

Charging time is ~ 435 nsec

$$\text{That is } \frac{1}{2} \text{ cycle of } \frac{1}{2 \times 435 \text{ nsec}} = 1.149 \text{ m Hz}$$

$$\text{So low frequency charge } \omega = 7.22 \times 10^6$$

high frequency is wavelength like 2 x cap length

$$\text{that is } f = \frac{984}{\sqrt{2.1} \times 2 \times 6.17} = 55 \text{ m Hz}$$

$$\omega = 345.7 \times 10^6$$

Dissipation factors (DF) in irradiated oil were determined to be

	<u>Irradiated</u>	<u>Unexposed</u>
DF @ RT	0.112%	0.054%
DF @ 40 °C	3.070%	--
DF @ 60 °C	8.150%	0.320%

DF is the ratio of equivalent series resistance to reactance.

$$DF = \frac{R}{X} = \cot \theta$$

Loss tangent or tangent of loss angle of a capacitor is the power loss divided by units of reactive power at a sinusoidal voltage of specified frequency. Loss tangent of a dielectric includes effects of finite conductivity as well as effects of polarization damping forces. The loss angle is the dielectric angle subtracted from 90°.

$$\text{So } \tan \delta = \frac{R}{X} = \cot \theta = DF$$

$$G = T_L \omega C$$

$$C = 800 \text{ pf or } 425.6 \text{ pf/m}$$

$$G = .0307 \times 7.22 \times 10^6 \times 800 \times 10^{-12} = 1.773 \times 10^{-4} \text{ mho}$$

or

$$G = 9.434 \times 10^{-5} \text{ mho/m}$$

$$G = .0307 \times 345.7 \times 10^6 \times 800 \times 10^{-12} = 8.49 \times 10^{-3} \text{ mho}$$

or

$$G = 4.517 \times 10^{-3} \text{ mho/m}$$

$$R = \frac{1}{2} \left(\frac{\rho f \mu}{\pi} \right)^{\frac{1}{2}} \left(\frac{1}{a} + \frac{1}{b} \right)$$

$$= \frac{1}{2} \sqrt{f} \left(\frac{\rho \mu}{\pi} \right)^{\frac{1}{2}} \left(\frac{1}{a} + \frac{1}{b} \right)$$

Using the values for aluminum

$$\rho = 2.62 \times 10^{-4} \text{ ohms/m}$$

$$\mu = 4\pi \times 10^{-7} \text{ henries/m}$$

$$a = 1.6764 \text{ meters}$$

$$b = 2.2098 \text{ meters}$$

$$R = 5.37 \times 10^{-6} \sqrt{f} \text{ r/meter}$$

$$\text{Length} = 1.8796 \text{ meters}$$

$$R = 1.082 \times 10^{-2} \text{ ohms}$$

or

$$R = 5.756 \times 10^{-3} \text{ ohm/m}$$

$$R = 7.49 \times 10^{-2} \text{ ohms}$$

or

$$R = 3.982 \times 10^{-2} \text{ ohm/m}$$

The line inductance is $L \approx Z_o^2 C = 12.3 \times 425.6 \times 10^{-12} = 6.439 \times 10^{-8} \text{ h/m}$

$$\omega L = .4649 \cdot \Omega/\text{m}$$

$$\text{or } 22.26 \Omega/\text{m}$$

$$\omega C = 3.073 \times 10^{-3} \text{ v/m}$$

$$\text{or } 1.471 \times 10^{-1} \text{ v/m}$$

NOTE:

$$\omega L = \begin{cases} .4649 \\ \text{or} \\ 22.26 \end{cases} \gg R = \begin{cases} 5.756 \times 10^{-3} \\ \text{or} \\ 3.982 \times 10^{-2} \end{cases}$$

and

$$\omega C = \begin{cases} 3.073 \times 10^{-3} \\ \text{or} \\ 1.471 \times 10^{-1} \end{cases} \gg G = \begin{cases} 9.434 \times 10^{-5} \\ \text{or} \\ 4.517 \times 10^{-3} \end{cases}$$

Now attenuation $= \alpha = \frac{R}{2Z_o} + \frac{G}{2} Z_o \text{ nepers/unit length}$

$$8.14 \times 10^{-4} \text{ Np/m for charge frequency}$$

$$\alpha = \text{or}$$

$$2.78 \times 10^{-2} \text{ Np/m for capacitor length transit frequency}$$

Since the peaking capacitor length is 1.8796 m,

Loss is $\begin{cases} 1.53 \times 10^{-3} \text{ Np for charge frequency} \\ 5.23 \times 10^{-2} \text{ Np for capacitor length transit frequency} \end{cases}$

Charge frequency goes through one cycle for each pulse, but the transit frequency goes through about 10 cycles per pulse, so loss per pulse is:

$$\text{loss} = \begin{cases} 1.53 \times 10^{-3} \text{ Np for charge frequency} \\ 5.23 \times 10^{-1} \text{ Np for capacitor length transit frequency} \end{cases}$$

Amplitude of the charge pulse is the full peaking capacitor charge voltage, but that of the length transient is shown by computer simulation to be only about 14 percent of full charge voltage or about 2 percent of full charge energy. So loss per pulse, weighted for the relative amplitude of the two signals, is:

$$\begin{aligned} \text{loss} &= 1.53 \times 10^{-3} \text{ Np for charge frequency} \\ &\quad \frac{1.046 \times 10^{-2}}{1.53 \times 10^{-3}} \text{ Np for length transient} \\ &\sim 1.2 \times 10^{-2} \text{ Np total} \end{aligned}$$

A loss of 1.2×10^{-2} Np implies an input to output power ratio of:

$$\frac{P_i}{P_o} = e^{2 \text{ Np}} = 1.024$$

So, about 2.4 percent of pulse energy is lost in metal resistances and oil conductance.

Some of the assumptions used above are:

- The oil DF does not change with frequency.
- The aluminum capacitor structure has no joint resistance.
- Pulse voltage applied to the peaking capacitor can be described with only two frequencies.

1. 7 Preliminary Design of 7 MV Output Switch

Basic design parameters and shape of the output switch have been selected. Factors to be considered in the design were:

- Size gap length, electrode diameter, and envelope diameter and length for conservative voltage stress
- Keep size no larger than necessary to hold down inductance and cost
- Design for long rep rate life
- Provide for cooling
- Provide for way out in the design is grossly off and the switch must be altered.

It was established early in the program that the output switch would not be triggered; this results in a substantial reduction in complexity, cost, and uncertainty in extrapolating performance from existing switches. A sketch of the design is shown in Figure 55; considerations leading to it are detailed in the following paragraphs.

1. 7. 1 Insulating Gas

To reduce size and inductance, the insulating gas used most often for switching is high pressure sulfur hexafluoride (SF_6), whether alone or mixed with other gases. Some characteristics which must be considered are:

- Gas taken from nearly empty cylinders may have significantly lower breakdown properties, even though the pressure is up. Tucker⁽²²⁾ at Sandia and Champney at Physics International both reported this in the early 1970's

Note: Dimensions are inches.

Materials

Electrodes - copper skirts, brass caps
Housing - crosslinked polystyrene
End plates - aluminum

Fill gas - SF_6 to 200 psig
Tie rods - Delrin

Figure 55 . Preliminary Output Switch Design

Table XV. Characteristics of Some Existing Switches

Self Breakdown of Some SF₆ Switches

Switch	Hydra Orig. (Bradley)	Hydra #2 (Tucker)	Hydra Final (Tucker)	Neptune B Switch 3	Gamble I Switch I (IPC)	Gamble I Switch II (IPC)	IPC Laser Triggered Switch	Martin Rule of Thumb
Gap Length, cm	3.1	6.9	4.45	1.9	10.16	11.4	7	---
Gas	SF ₆	SF ₆	SF ₆	N ₂ + 3% SF ₆	N ₂ + 20% SF ₆	N ₂ + 50% SF ₆	N ₂	SF ₆
Pressure (PSIG)	160	100	160	175	80	155	150	High
Voltage MV	1.76	3.2	3.3	.770	1.8	3	2	Several
Stress (simple) kV/cm	568	464	742	400	180	263 no brk- down	286 no brk- down	500
Charge	pulse	pulse	pulse	pulse	pulse	pulse	DC	pulse

- Breakdown strength of SF_6 gas goes down as temperature increases at constant pressure. Clark reports a 40 percent decrease from 20°C to 100°C

1.7.2 Gap Length

Some information about past switches is shown in Table XV. Hydra switches used SF_6 and showed self breakdown of over 500 kV per centimeter at 160 psig. The Neptune B switch 3 went to 400 kV per centimeter with 175 psig of N_2 with only 3 percent SF_6 . These examples, at 3 MV and below, seem to indicate 500 kV/cm is reasonable in 160 psig of SF_6 .

J. Martin, at the EPRI switch workshop in March 1976, suggested a design rule of thumb of 500 kV/cm for high pressure SF_6 that is pulse charged. He further suggested that the length of walls need not be much longer than the gap itself.

At Sandia, T. Martin's empirical equations for pulse breakdown in SF_6 and some geometrical considerations were used to derive an equation for SF_6 switch breakdown. Compared to pressure versus voltage for the switch labeled Hydra #2 in Table XV, Tucker showed that the formula under predicts breakdown voltage below 100 psig and over predicts at high pressure. The formula is:

$$d = \frac{V^{1.2}}{577 \left(\frac{\rho}{\rho_0}\right)^{0.6}}$$

d = gap length in cm

V = applied voltage, kV

$\frac{\rho}{\rho_0}$ = density relative to standard

Summarizing, Hydra switches show 560 to 746 kV/cm in 160 psig SF_6 , Martin suggests 500 kV/cm in high pressure, and the formula above says 380 kV/cm at 140 psig. Strength will also depend on stress grading and

therefore on geometrical factors other than gap length.

Selecting a design value of 500 kV/cm gives a 16 cm gap for 8MV; a slightly longer gap has been specified.

Designing the envelope to operate at pressures up to 200 psig SF₆ provides a safety margin against poor gap grading, and will assure that the switch operates under nominal conditions which are well below maximum standoff. For switching at voltages below 8 MV, reduced SF₆ pressures can be used or a gas substitution can be made. Gap length adjustments within the switch can also be employed to adjust the switching point.

Approximate inductance of the arc, neglecting electrodes and flanges, will be 240 mH (assuming 15 mH per cm).

1.7.3 Electrode Diameter

Electrode diameter should be greater than gap length in order to provide a reasonable area of uniform stress thus spreading erosion. Choosing diameter equal to three times gap length gives 48 cm (or 18 inches).

1.7.4 Envelope Length

Martin claims envelope length need not be too much greater than gap length in pulse charged switches, but his experience has been with single shot conditions. We can count on a buildup of debris. Tucker suggests an envelope-to-gap length ratio of 4.6. Earlier, Mulcahy, T. H. Martin, and others had suggested ratios up to 7. A ratio of 6 has been chosen here, giving an inside envelope length of 36 inches.

1.7.5 Envelope Inside Diameter

Conservative design calls for the equivalent of a gap length between electrode and envelope wall; Tucker suggests that less space is needed. We have chosen the conservative approach and have specified an inside diameter for the envelope of 30 inches (18 inch electrode diameter plus twice the interelectrode gap of 6 inches).

1.7.6 Electrode Materials

Electrodes can be standard dished heads of brass. Electrode bodies (sides) should be a good electrical conductor, a good heat conductor to carry gas heat out to the end plate, and the material must be weldable to the brass end. Copper was used as the material. The sides can be flared to give slightly less inductance and more heat transfer surface area to the gas. They may be rolled from flat material.

The envelope must be an insulator. Previous results were good with crosslinked polystyrene in megavolt switches designed for IPC's Neptune series machines and for switches supplied to the Gamble accelerators at the Naval Research Laboratory. Nylon is used for many of the SYLLAC switches at Los Alamos. In Sandia's Hermes machine, nylon switch housings were found to fail after short service lives. Best choice for the housing appears to be crosslinked polystyrene.

Temperature of the gas may become a problem. Hopefully, enough heat will be conducted out the end plates to keep the gas cool. On Marx switches run on life test under this program, gas was cooler when the sputter shield support ring was brought out to contact the oil.

1.8 Output Bushing

The output bushing must provide a vacuum envelope within which the field emission diode can operate. It must insulate about 7 MV from ground. Several possible designs were considered and models of some were built and operated on FX-35 in conjunction with efforts to irradiate cable specimens. Discussion in this section begins with a review of vacuum flashover data, then gives details of preliminary design studies and testing, and closes with a description of the bushing as it had evolved at the point where work was suspended.

1.8.1 Design Criterion for Vacuum Flashover

Data on vacuum flashover under pulsed and DC voltages have been compiled in an effort to establish guidelines for design of the output bushing. General practice in the construction of vacuum diodes for other large accelerators was also reviewed. While it is well known that initiation of flashover is time dependent and that higher stresses can be carried in short pulses, DC data are of interest because a bushing sized to hold off continuously applied voltage equal to the maximum expected should represent an upper limit on the necessary dimensions.

Shannon, et al⁽²³⁾ examined several insulators in various geometries including glass frusta placed between uniform field electrodes. For Corning 7070 and 7740 glasses with a frustum half angle of 45 degrees, flashover strengths in hard vacuum were found to be about 50 kV/cm for first

sparking. With conditioning, this could be increased to 80 kV/cm; with right circular cylinders of the same materials and lengths (2.5 and 5 cm) flashover initiated at about 25 kV/cm.

The authors were careful to create good stress conditions at the interface between glass, metal, and, vacuum, and therefore obtained holdoffs which were 1-1/2 to 2 times greater than those reported by earlier workers.

Gleichauf⁽²⁴⁾ experimented with Pyrex rods 1.3 cm in diameter by 2.25 cm long between uniform field electrodes; no extraordinary precautions were taken to grade triple points or to bond glass to the electrodes. Flashover was found to occur at 15 kV/cm.

In a subsequent paper,⁽²⁵⁾ he examined a number of additional materials in similar geometry, with the results listed below.

Material	Flashover Gradient, kV/cm
Fused Quartz	28
7740 Pyrex	20
7740 Pyrex (oiled)	25 - 32
Soda Lime Glass	18
Rutile	18
Polystyrene	33
Teflon	22
Barium Titanate	5.3

While stresses were substantially lower than those achieved by Shannon, et al, the measurements showed that polystyrene is superior to many other insulating materials.

J. Hugenin, et al⁽²⁶⁾ described a synchrotron injector tube employing porcelain rings which operated DC at gradients of 45 to 75 kV/cm after conditioning. In a two month life test the tube held off 60 kV/cm continuously with fewer than ten breakdowns per day.

At Ion Physics, Britton, et al⁽²⁷⁾ designed a resistively graded tube in which a 30 cm stack of 2.5 cm thick Pyrex rings with aluminum grading plates held off a megavolt; this corresponds to a stress of 33 kV/cm. This is approximately the value which has been set as a design goal for DC accelerator tubes at High Voltage Engineering Corporation.

Summarizing, it appears that DC gradients of 20 to 30 kV/cm can readily be obtained over short gaps; Shannon, et al, were able to hold off 50 kV/cm, and felt that 80 kV/cm should be possible with conditioning. Experience with full scale tubes at IPC and HVE suggests that a gradient of 30 kV/cm can be sustained with proper design, while at CERN, operation as high as 60 kV/cm has been demonstrated.

Pulsed Flashover

Design of output tubes for most pulsed accelerators now in use is based upon the work of Smith⁽²⁸⁾ at AWRE and Watson and Shannon⁽²⁹⁾ at

Ion Physics. Employing voltage pulses up to 4 MV in amplitude and 30 nsec long, Smith studied the flashover performance of insulating materials including Lucite, polyethylene, epoxy, tetrafluoroethylene, nylon, several filled epoxies, silicone rubber, and glass. Parameters varied were pressure (from 10^{-4} to 10^{-1} torr) and the angle between insulator and field. Some additional work was done with pulses slightly less than a microsecond in length at a peak voltage of 500 kV and with the addition of "coatings" of low vapor pressure liquids or gums, among these being silicone oils and greases, transformer oil, diffusion pump oils, unpolymerized resins, paraffin wax, sulfur, and soot.

It was found that breakdown strength is strongly dependent on angle, there being factors of four or more between maximum and minimum strengths for some materials. In general, an optimum angle was found and this was usually positive, positive angles being defined as opening away from the cathode. For polyethylene, epoxy, and Lucite the optimum angle was found to be near 45 degrees, where a gradient of about 200 kV/cm could be held off over small gaps. Epoxy showed a second relative maximum in strength at about -30 degrees, but the gradient which could be withstood was only half that for the optimum angle.

Rubber behaved somewhat differently, strength being maximized at small positive angles. One rubber supported 280 kV/cm under 30 ns pulses.

With liquid coatings it was almost always found that breakdown strength increased; "spectacular" improvement was obtained with soot and sulfur coatings on glass, where breakdown strength was doubled for a 10 degree cone.

Watson and Shannon⁽²⁹⁾ and subsequently Watson⁽³⁰⁾ developed a theory of flashover which assumes that positive surface charge grows by emission of electrons until returning electrons are given sufficient energy to initiate an avalanche through secondary mechanisms. In this hypothesis, formative time is controlled by thermionic emission while flashover is initiated by

secondary electrons. To obtain verifying data, urethane-epoxy resin, Lexan and two Pyrex glasses were loaded with 250 kV square waves about 150 ns long. Insulators were tested at both positive and negative angles; findings were similar to those of Smith. The maximum gradient which could be carried in glass occurred near 45 degrees and was equal to 250 kV/cm. Watson showed that his theory was in good agreement with experiment.

Milton⁽³¹⁾ has extended the work of Smith and Watson to include a number of additional dielectrics (see Table XV1 and has confirmed the dependence on angle noted by earlier investigators. Using 5 μ s pulses and 1.27 cm long specimens, Milton found that higher negative than positive gradients could be held by most materials, although several were relatively indifferent to polarity. These included teflon, boron nitride, and several rubbers. Best performers were Lucite, etched teflon, polystyrene, and cast nylon. Flashover strength of the last named could not be determined because of equipment limitations, but it was in excess of 240 kV/cm and was at least 20 percent higher than other superior materials.

Flashover data for several of the most widely used insulator materials has been taken from the above discussion and summarized in Table XV11. About a sixfold increase takes place when the time of application of voltage is reduced from continuous 5 μ s; smaller increases result from further pulse shortening.

Design Practice in Pulsed Tubes

Virtually all large pulsed electron beam accelerators use capacitively graded vacuum bushings consisting of 45 degree insulating rings alternating with aluminum plates. Rings are generally manufactured from plastic, most frequently Lucite or crosslinked polystyrene, occasionally epoxy.

TABLE XV1. INSULATORS INVESTIGATED BY MILTON

Insulating Material	Flashover Gradient, kV/cm*
Lucite	195
Polyethylene	180
Pyrex 7740 Glass	200
Teflon	175
Etched Teflon	195
828-DEA	175
828-B, Machined	175
828-B, Cast	160
SRIR	150
828-DEA, Mica Filled	120
Nylon Phenolic	120
Metal Iononics	125
Reynolds Al ₂ O ₃	100
Coors Al ₂ O ₃	80
Diallyphallate	40
Drill, FS-5	95
Boron Nitride	85
65-35 PZT	15
Epoxy Glass	140
Phenolic Glass	100
Polystyrene	195
Lexan	190
C-LEC Styrene	215
Lead Borate Coated Al ₂ O ₃	60
Cast Nylon MC901	> 240
Polyurethane Foam	30
SE9090 6E Silicone Rubber	85

*For cone angle of +45 degrees, 1.27cm frustum, and 5 μ s pulse.

TABLE XVII FLASHOVER STRENGTH OF SOME
TUBE MATERIALS AS A FUNCTION
OF PULSE DURATION.

Pulse Length	Flashover Strength, kV/cm		
	Lucite	Polystyrene	Glass
DC	--	33	30 (50)
5 μ s	195	195	200
150 ns	--	--	250
30 ns	200	--	--

The output tube of Ion Physics 10 MV flash x-ray machine, FX-100, employs 30 2-inch thick by 30-inch diameter Lucite rings; design stress is about 55 kV/cm.

At the U.S. Army's Harry Diamond Laboratory in White Oak, Maryland, the world's largest electron beam machine, Aurora, is housed. It has an output bushing consisting of a generally cylindrical envelope formed by forty Lucite rings, 4-inches thick and 10 feet in diameter. The tube is 15 feet long and carries a 15 megavolt, 125 ns pulse. This corresponds to a stress of 33 kV/cm.⁽³²⁾ Under most operating conditions the tube is stressed to no more than 11 megavolts; it has proved to be essentially trouble free over a lifetime of thousands of shots.

REBA (Relativistic Electron Beam Accelerator), a 4 MV accelerator operated by the Sandia Corporation,⁽³³⁾ employs a tube consisting of 18 Lucite insulators each 1.75-inches thick and 24-inches diameter. At a vacuum of 10^{-5} torr, the tube can withstand 70 kV/cm before flashing. For nominal output voltage of 4 MV, stress is 50 kV/cm.

A relatively new Sandia machine, HARP, is designed to produce 3 MV in a 25 ns wide pulse.⁽³⁴⁾ The tube is constructed from four 48-inch diameter by 2-inch thick Lucite rings; flashover strength is estimated to be 160 kV/cm at 3.3 MV. Design stress corresponding to the nominal 3 MV output is about 130 kV/cm.

In a paper published in 1975, Champney and Spence⁽³⁵⁾ describe a 9 MV accelerator producing a 75 ns long pulse. Output tube was fabricated

from 26 Lucite rings 80-inches in diameter and 4-inches thick, separated by 0.5-inch aluminum plates. Operating stress is about 30 kV/cm.

A final large machine, Hermes, is located at Sandia and generates voltages up to 15 MV. The Hermes tube uses crosslinked polystyrene rings 78-inches in diameter; the tube is approximately 15 feet long. At a megavolt per foot, this gives a design stress of 33 kV/cm.

Design stresses for these machines are summarized in Table XV111. They are generally on the order of stresses that can be achieved over small specimens under DC voltage although HARP has been designed to operate at a considerably higher gradient. Based upon this experience, it would appear that a design stress in the range 30 to 50 kV/cm should be a reasonable choice for machines having effective pulsewidth of 100 ns or so. Accordingly, a value of 35 kV/cm has been selected as the criterion for sizing the tube for this project.

To hold off the computed peak voltage of 7.5 MV will require a tube length of about 225 cm (7.5 feet).

TABLE
XVIII.

SUMMARY OF DESIGN STRESSES FOR
VACUUM DIODES OF LARGE ACCEL-
ERATORS.

Machine	Pulse Length, ns	Design Voltage, MV	Tube Design Stress, kV/cm
FX-100	30	10.	50
REBA	70	4.	50
HARP	25	3.	130
Pulserad 1480	75	9.	30
Aurora	125	15.	33
Hermes	100	15.	33

1.8.2 Preliminary Bushing Designs

Major concerns in bushing design are the following:

- inductance must be minimized
- should be designed against flashover and insulators must have a relatively long service life
- should be easy to assemble and install
- parasitic losses through shank emission should be minimized or prevented

In an effort to determine the optimum manner of satisfying these requirements, several tube designs were considered. First of these was a strictly conventional vacuum bushing similar to those employed on other large accelerators; Figure 56 shows a sketch of a bushing of this type as it might be fitted to the present pulser.

Figure 56. Conventional Vacuum Bushing.

To hold off 7.5 MV at an average stress of 35 kV/cm, the bushing would be 7.5 feet long; for good voltage grading, the ratio of length-to-diameter should be near 3/2, requiring a ring diameter of about 5 feet. Insulating rings would be cast from crosslinked polystyrene; the tube would require 22 such rings, each 3.75-inches thick and flared at a 45 degree angle away from the cathode. Insulators would be spaced apart by 3/8-inch aluminum grading rings.

Using the criterion of 200 kV/cm which was established in Section 3.5.1 approximately 40 cm of oil must lie between the tube wall and the outer housing. Inductance is determined by the ratio of cathode shank diameter to housing diameter; because housing size is fixed by the need to prevent breakdown in the oil, diameter of the cathode shank is the only variable which can be manipulated to reduce inductance, but this must be selected within the constraint that flash-over should not occur across the vacuum gap between the cathode shank and tube face. To minimize vacuum stress at the surface of the shank its diameter at this point should be 1/e times that of the tube, or about 1.8 feet. At the high voltage end of the tube, improved grading and a slight decrease of inductance would result from tapering the shank down from a larger diameter to this final value.

With a housing diameter of 8 feet and a 1.8 foot cathode shank, inductance would be

$$L = 0.2 \ln \frac{d_o}{d_i} \text{ u h/m}$$

where

d_o = outer diameter

d_i = inner diameter

or

$$L = 0.2 \log \frac{8}{1.8} = 0.3 \mu\text{h/m}$$

For a 7.5 foot tube (2.25 ns), this corresponds to an inductance of 0.68 μh .

This is somewhat less than the 1 μh which was assumed for tube inductance in the computer simulations described in Section 3.2.2, and implies a slightly smaller voltage loss between the peaking capacitor and diode than is predicted there.

It is expected, however, that detail design of the baseplate to provide for tube mounting rods and grading would required an increase in the housing diameter, and a corresponding increase in inductance.

Vacuum stress on the cathode shank opposite ground at the tube face can be found from

$$E = \frac{V}{r_i \ln \frac{V_o}{V_i}} = \frac{V}{r_i}$$

since the shank has been sized to give $\ln \frac{r_o}{r_i} = 1$. For 7.5 MV on the shank

(radius equal to 0.9 feet or 27 cm), stress at the surface would be almost 280 kV/cm.

Figure 57, a compilation of time dependent vacuum breakdown data for several electrode materials, suggests that for an aluminum shank and tube face under a 300 ns pulse, flashover would occur at a surface stress of about 300 kV/cm. Because the shank surface area is relatively large, about $4 \times 10^4 \text{ cm}^2$, this value should probably be derated somewhat. Doing this shows that the shank is very close to flashover threshold and suggests that, even if vacuum breakdown does not occur, electron emission from points other than the 360 degree head may shunt the diode and cause low output. This would be a serious shortcoming.

Figure 57. Summary of Pulsed Breakdown Data.

Summarizing, a conventional tube has the advantage of being straightforward to design and backed by a good deal of experience on similar bushings; it should give an acceptably low inductance. Disadvantages are that insulators and grading rings must be of relatively large diameter, therefore expensive, heavy, and difficult to handle. There was serious concern over the possibility of vacuum flashover and shank emission.

These considerations have led to the proposal of a second design in which the roles of oil and vacuum would be reversed; the tube would be oil filled and surrounded by a vacuum envelope. A sketch is shown in Figure 58. It would be built as a unit, oil filled on a stand outside the diode, then carried to the machine and installed by "plugging in". Length end-to-end would be greater than that of the conventional tube due to the need for both oil and vacuum bushings.

In this concept, the tube base would be isolated from ground through a cast polystyrene cylinder; length of this cylinder is determined by the spacing required to hold off 7.5 MV in oil. According to Roth⁽³⁶⁾, as long as the insulator is clean, flashover under AC conditions occur at the same stress as volume breakdown. Wellauer⁽³⁷⁾ reported flashover on textolite (fiberglass) under oil occurred at a stress 20 percent below volume breakdown when an impulsive voltage, rising in 1 μ sec and decaying to 50 percent of peak in 40 μ sec, was applied. In work done with oil containing dissolved gases and water vapor, Ameen⁽³⁸⁾ at IPC found the flashover stress of Lucite to be 140 ± 10 kV/cm under repetition rate conditions. Ameen's experiments employed coaxial geometry with radial Lucite spacers.

Figure 58. Oil Filled Bushing.

Using the most pessimistic of these criteria, Ameen's 140 kV/cm, length of the oil bushing must be 50 cm (1.6 feet) to hold 7.5 MV; for this design it was made 3 feet long to protect against degradation due to accumulation of debris on the top of the bushing from sedimentation.

Length of the vacuum bushing would be the same as that determined for the first tube type, 7.5 feet. Overall length from output switch to 360 degree head would therefore be 10.5 feet.

Requiring a maximum stress at the surface of the cathode shank of 200 kV/cm gives a radius of

$$r = \frac{V}{E \ln \frac{r_o}{r_i}} = \frac{V}{E}$$

if dimensions are chosen with r_o/r_i equal to e . For voltage of 7.5 MV, this computes to 39.5 cm, or a diameter of 2.5 feet. The result is a tube which is actually somewhat larger in diameter than the vacuum bushing, having a 5 foot shank and outer diameter of 7.5 feet. By shading the breakdown criteria to a slightly higher value, 230 kV/cm, and specifying that the ratio of tube to shank diameters should be 3/1, a configuration is produced which features a 1 foot shank and 3 foot outer. A tube of this size is attractive because considerable cost saving could be realized over the larger vacuum bushing described earlier.

Two points should be considered, however; first of these is the possibility of reducing dimensions of the vacuum bushing by re-designing for operation at a somewhat higher stress, thus achieving the same savings. This is probably not a practical solution. It would increase the probability of substantial shank emission currents, shunting the diode and reducing insulator life by electron bombardment. Furthermore, once initiated, a vacuum streamer would quickly develop into a full scale breakdown. In oil, on the other hand, the velocity of streamer propagation is relatively slow, and arcs may be unable to cross from shank to tube face within the time voltage is applied.

A vacuum bushing which proves to be underdesigned will therefore be nonfunctional at its rated voltage, while an oil filled tube could still function satisfactorily if streamers damped out in the dielectric.

This leads to the second point, which is the technical risk involved in using a stress of 230 kV/cm for oil at the shank surface, rather than the design criteria of 200 kV/cm established for the Marx and peaking capacitor in Section 1.5.1.

Calling upon the AWRE formula for time dependent stress in oil (Equation 9), nominal breakdown stress can be estimated from a knowledge of an effective time of voltage application and the shank area. For a 1 foot diameter shank which is 10 feet long, surface area is about $3 \times 10^4 \text{ cm}^2$. Effective time is defined as the period for which voltage exceeds 68 percent of peak; referring to Figure 27, the voltage pulse shape calculated by computer for our best estimate of machine parameters, effective time would appear to be about 100 ns (time above 5 MV). Using this value and an area of $3 \times 10^4 \text{ cm}^2$ in Equation (9) predicts a breakdown stress of 395 kV/cm. In view of this, it would seem that the risk involved in raising the design criteria to 230 kV/cm is small.

The oil-to-vacuum interface of this tube would consist of about 30 crosslinked polystyrene insulating rings 2-1/2-inch thick by 3 feet nominal diameter. Rings would be beveled at 45 degrees away from the 360 degree head on the vacuum side, and would be spaced apart by aluminum grading rings, approximately 0.5-inches thick.

At the diode end of this vacuum portion of the tube, diameter of the vacuum chamber should be about 9 feet. This would give a vacuum stress from tube to housing wall of about 200 kV/cm, well below the 300 kV/cm indicated by Figure 20 for aluminum electrodes under a 300 ns pulse.

If the vacuum envelope were continued at this diameter, then inductance per unit length of the tube would be approximately

$$L = 0.2 \ln \left(\frac{9}{1} \right) = 0.44 \mu\text{h/m}$$

Because the tube is 3.15 meters long (10.5 feet), overall inductance would be about $1.4 \mu\text{h}$.

This could be reduced somewhat by tapering the vacuum housing to reduce the ratio of r_o/r_i near the low voltage end of the insulator stack. The form which such a taper should take can be estimated in the following way. Nominal stress on the rings at the vacuum-oil interface is

$$E = \frac{V}{r \ln \frac{d}{r}}$$

where

r = tube radius, a constant equal to 3 feet

d = radius of vacuum housing

V = potential difference between tube wall and vacuum housing

By requiring constant stress at all points along the tube, the housing radius d can be solved for, and is found to equal

$$d = r e^{\frac{V}{Er}}$$

If it is assumed that the tube is perfectly graded, then voltage will decrease linearly from 7.5 MV at the cathode to 0 at the tube face, and

$$V = \frac{V_o x}{l}$$

where

x = distance along tube measured from ground end

ℓ = length of vacuum bushing

Using this in the expression for d gives

$$d = r \exp \left(\frac{V_o x}{E r \ell} \right) , \quad (2)$$

so that housing diameter should expand exponentially with distance along the tube to maintain constant stress at the tube surface.

Maximum value of the exponent occurs when $x = \ell$; for $V_o = 7.5$ MV, $E = 200$ kV/cm, and $r = 50$ cm, it takes on the value 0.75. Over most of the tube length it is considerably smaller. Equation (2) can therefore be approximated to within about 30 percent by the relation

$$d = r + \frac{V_o x}{E \ell} \quad (3)$$

Inductance of a transmission line with constant inner and outer expanding according to (3) can be estimated by integrating the form

$$\frac{dL}{dx} = 0.2 \ln \frac{d}{r}$$

to give

$$L = 0.2 \int_0^{\ell} \ln \left\{ 1 + \left(\frac{V_o x}{E \ell} \right) \right\} dx .$$

Result of performing the integration is

$$L = 0.2 \left[1 + (1 + a\ell) \left\{ \ln(1 + a\ell) - 1 \right\} \right]$$

where

$$a = \frac{V_o}{Er\ell} = 0.23 \text{ m}^{-1} \text{ when}$$

$$V_o = 7.5 \times 10^6 \text{ V}$$

$$E = 2 \times 10^7 \text{ V/m}$$

$$r = 0.5 \text{ m}$$

$$\ell = 3.2 \text{ m}$$

With these figures, overall inductance would be $0.35 \mu\text{h}$, a substantial reduction from the $1.4 \mu\text{h}$ of a straight walled housing. Although this analysis is approximate, it suggests that inductance of an oil filled tube could be held to $1 \mu\text{h}$ or less by properly tapering the vacuum envelope.

1. 8. 3 Testing of Oil Filled Concept

An oil filled bushing was fabricated and tested on FX-35; design philosophy and calculations for this bushing are outlined below. Ground rules for building this test bushing were:

- (1) Retain current and voltage monitors if possible so that impedance estimates could be made.
- (2) Keep nominal stresses near those which would be employed in the full scale machine.
- (3) Use existing hardware where possible.

It was intended to retain the present output bushing, oil fill it, and add a vacuum bushing external to the FX-35 face plate; See Figure 59.

Vacuum stress settled upon earlier for a design criterion was 35 kV/cm. If it is assumed that impedance of the 360° head will be large compared to the 40 Ω characteristic impedance of FX-35, then the tube would carry a potential which is essentially equal to the charging voltage, or 4.5 MV. This implies a length of

$$\frac{4500 \text{ kV}}{35 \text{ kV/cm}} = 129 \text{ cm (4.22 ft.)}$$

This length was too great to be accommodated easily in the standard A-tank appropriated for a vacuum envelope, therefore a compromise was needed. Resizing for 50 kV/cm (approximately the upper limit of nominal stress for which other pulsed tubes have been designed) gives a length of

$$\frac{4500 \text{ kV}}{50 \text{ kV/cm}} = 90 \text{ cm (3 ft.)}$$

At 35 kV/cm, a tube of this length would carry a voltage of 3.15 MV; a reasonable margin against flashover should exist.

Existing FX-35 Envelope

Figure 59. Proposed Modification to FX-35

Cathode Shank Diameter

Diameter of the cathode shank was determined by the requirements that stresses in the gas-side bushing be minimized. Inside diameter of the tube rings and faceplate was 19.7 cm (7.75-in.). Using the "e" rule this suggested a shank diameter of

$$d = \frac{19.7}{2.7} = 7.25 \text{ cm (2.86-in.)}$$

Diameter was reduced somewhat to get to a standard pipe size.

Assuming a voltage of 4.5 MV and shank diameter of 2.75-in., maximum stress would be

$$E = \frac{2 V}{d \ln \frac{D}{d}} = \frac{9,000 \text{ kV}}{(7) (1.04) \text{ cm}} = 1240 \frac{\text{kV}}{\text{cm}},$$

a number which is steep compared to the criterion of 230 kV/cm used to design the full scale output bushing. At 230 kV/cm, the highest voltage which could be supported on a 2.75-in. shank is

$$V = \frac{Ed}{2} = \frac{230 \frac{\text{kV}}{\text{cm}} (7\text{cm})}{2} = 0.8 \text{ MV}$$

Because FX-35 delivers a shorter pulse than is expected from the crosslinking machine and because surface area of the shank is small compared to that of the larger device, there is conservatism in the 230 kV/cm when applied to the present situation. To estimate a reasonable stress, we use the expression

$$F = \frac{500}{t^{1/3} A^{1/10}} \quad \text{kV/cm}$$

with

$$t = 0.04 \mu_s$$

$$A = (\pi) (7 \text{ cm}) (90 \text{ cm}) = 1.98 \times 10^3 \text{ cm}^2$$

$$t^{1/3} = (.04)^{1/3} = (40)^{1/3} (10^{-3})^{1/3} = 0.342$$

$$A^{1/10} = (1.98)^{.1} (10^3)^{.1} = (1.0705) (1.996) = 2.14$$

Then the equation above gives

$$F = \frac{500}{(.34) (2.14)} = \frac{500}{.73}$$

$$F = 680 \text{ kV/cm}$$

With a stress of 680 kV/cm, it should be possible to operate at voltages up to

$$V = \frac{Ed}{2} = \frac{\left(680 \frac{\text{kV}}{\text{cm}}\right) (7 \text{ cm})}{2} = 2.38 \text{ MV}$$

within the limitations imposed by available equipment.

Tube Dimensions

Dimensions of the vacuum tube were specified by the cathode shank and A-tank diameters. For minimum stress on the shank at the ground end of the tube, inside diameter of the grading rings should be the same as that of rings in the gas-side bushing, or 13.7 cm (7.75-in.). It was considered simplest to carry this diameter down the whole length of the tube, even though at the high voltage end the potential difference between shank and grading rings becomes smaller, and ring diameter could be decreased without raising stress above the value at the tube base.

Outside diameter of the tube should be about $1/e$ times the A-tank diameter (88 cm or 34.5-inches), or 32 cm (12.5-inches). With this diameter, vacuum stress at the high voltage end at 4.5 MV would be

$$E = \frac{(2) (4500) \text{ kV}}{(32) \text{ cm}} = 280 \text{ kV/cm.}$$

From voltage monitor to axis of the 360 degree head was a distance of about 135 cm (53-inches). Inductance was therefore about

$$L = 0.183 \ell \ln \frac{D}{d} \mu\text{h}$$

with l in meters,

$$D = 34\text{-in.}$$

$$d = 2.75\text{-in.}$$

$$l_n = 2.5$$

$$L = (.183) (1.35) (2.5)$$

$$L = 0.62 \mu\text{h}$$

Availability of Parts and Material

Insulators were fabricated from acrylic blanks drawn from dead storage. These blanks were originally intended for use as FX-100 spares. They are 1.25-inches thick and yielded insulators of a slightly smaller thickness. Eleven spare grading rings for the FX-35 bushing were located, and the tube was designed around these to minimize the number of rings to be fabricated.

A photograph of the completed bushing is shown in Figure 60 with and without the vacuum housing in place.

Results of Testing

Two malfunctions appeared as this bushing was operated over a period of many hundreds of shots. First of these was tracking and eventually chipping of acrylic insulating rings on the vacuum side, the effect being especially prevalent over midportion of the bushing. To correct this, rings were reworked to shield triple points on both cathode and ground sides of the rings. Shielding was accomplished by machining relief grooves which moved triple points about 0.25-inches toward the machine axis, as shown in the sketch below.

Oil Filled Bushing

A-Tank Installed Over Bushing
As Vacuum Envelope

Figure 60. Oil-Filled Bushing in Place on FX-35

With this change the problem of vacuum side insulator damage appears to have been solved; many thousands of shots have been accumulated on the reworked rings without sign of damage.

Second problem was flashover in oil down the existing machine-side bushing. This bushing was fixed by dimensions of the FX-35 and could not be changed without a major refabrication involving the machine itself. By virtue of its shorter length, this portion of the system was subjected to considerably higher stresses than the test bushing, nominally about 150 kV/cm in the oil. Imperfect grading may raise this by 25 percent, to something in the vicinity of 180 or 190 kV/cm, but stress was still lower than that which should be needed to cause flashover. For this reason, and because none of the noise or mechanical shock which would accompany oil switching were heard during testing, it is presumed that flashover was due to the presence of bubbles which could not be expelled during assembly. These tended to grow as pulses were registered until a sufficiently large amount of gas evolved to short the bushing from end to end.

Several steps were taken in an effort to prevent bubble formation and extend useful bushing lifetime; these included

- vacuum filling over a period of two days
- pressurizing the filled bushing with an atmosphere of dichlorodifluoromethane

Neither of these proved successful. This experience suggested that particular care would have to be taken to avoid a similar problem in the full scale machine, hence it was decided to return to the use of internal rather than external vacuum. Following pages elaborate on efforts to refine such a design.

Because FX-35 played an important part in the cable testing program, a bushing "fix" was needed to allow work to continue. This was accomplished by removing oil and pressuring internally to 45 psia with SF₆. The system is still not properly insulated and breaks down about halfway through the voltage pulse, but this happens very reproducibly and gives an acceptable waveform, although a larger number of shots is needed to accomplish equivalent cross-linking.

1. 8. 4 Alternate Diode Concept

At Lawrence Livermore Laboratories and Sandia, workers are apparently thinking in terms of modular cylindrical diodes with independent radial ground returns between segments to provide magnetic isolation. Arrangements of this type are most easily driven from a parallel plate transmission line or stack of lines. Bradley⁽³⁹⁾ made passing reference to a diode of this form, and Gerardo et al⁽⁴⁰⁾ have given a more explicit description. The concept probably would become unwieldy if extrapolated to high voltage because spacings required to prevent transmission line or diode breakdown would be large; however, it does suggest an alternative to the single, large diameter vacuum bushing designed earlier in this section. The alternative arrangement is sketched in Figure 61. Advantages would be a shorter cantilivered span and smaller overall machine length. An objection to the scheme as it is drawn is the need for twice as many insulating rings (have to isolate both sides of the cathode from ground instead of just one), but this would probably be compensated to some extent by the fact that rings could be smaller in diameter.

Two additional points in favor of the alternate approach are: (1) smaller vacuum volume and (2) lower inductance. This last is somewhat problematical since, for purposes of estimating inductance, it is necessary to consider the coaxial lines formed by the cathode shank and outer and the coax resulting from current returning to ground along the window or center conductor of the work-piece. Because the two sides of the diode are in parallel with respect to the shank current, effective path for inductance is half the diode length; sum of the shank length and half the diode may not be much different from the shank length we now have on our drawings.

Figure 61 Alternate Diode Concept

A preliminary layout of the diode shown in Figure 61 was made and it was concluded that the concept is mechanically feasible. It resulted in a decrease in overall machine length of about 8 feet, and would allow the diode to be housed in a simple extension of the main tank rather than a special tapered section.

Hardware necessary to test this side-to-side concept was fabricated for FX-35 and evaluated there late in the first year of the program.

Although it was ultimately intended to surround the shank and vacuum envelope with oil, initial experiments were conducted with 2 atmospheres of sulfurhexafluoride because of the ease of filling and certainty of trapping no air bubbles in the FX-35 bushing. The machine was first charged to 4 MV and voltage and current traces were recorded. It was noted that the diode seemed noisy. Output voltage consisted of a flat topped pulse about 20 ns long; mean impedance estimated from the traces was about 38 ohms, a relatively close match to the 45 ohms characteristic of FX-35.

This pulse shape was not typical of the machine in pure vacuum, where generally triangular pulses of 40 to 50 ns duration (baseline-to baseline) had been observed. For this reason flashover was suspected.

For 4 MV charging, maximum voltage indicated by the monitor was about 1.7 MV.

Using 7 layers of 10 mil Mylar sheet alternately wrapped with blue cellophane, a depth-dose profile was measured under the following conditions:

- 15 shots total
- 4 MV
- 8 needles
- 7.25 inch diameter tip circle
- 2 inch cathode shank
- 1 mil aluminum window
- 30 psia SF₆ in the bushing.

Results have been plotted in Figure 62. Seven layers were far less than the electron range in this instance; a relatively flat profile was obtained.

Figure 62. Depth-Dose Profiles Obtained From Side-to-Side Diode

Circumferential uniformity was checked by scanning cellophane strips and was found to be about ± 5 percent on the diode centerline and ± 15 percent at a point about 2 inches off center.

It was desired to establish shape of the tail of the profile and to determine electron range; therefore, the measurement was repeated with 25 layers of mylar sheet. Results of the measurement are also plotted in Figure 62. It was noted that the voltage monitor indicated a peak of 1.75 MV; peak voltage can also be estimated from range using the expression:

$$R = .53 V - .106$$

or

$$V = \frac{R + .106}{0.53}$$

Here R is range in gm/cm^2 and V is voltage in MV. The observed range of $.4 \text{ gm/cm}^2$ corresponds to a peak voltage of about 1 MV. This is a significant discrepancy.

In an effort to resolve this problem the bushing was charged to 45 psia SF_6 and a third profile was measured with charging voltage raised to 4.5 MV. At the voltage pulse shape remained flat topped; amplitude was equal to 2.0 MV. Note that the additional insulation appeared to raise the operating limit by 250 kV.

Measured range was about 0.65 gm/cm^2 corresponding to a peak voltage of 1.4 MV. The difference between this and voltage indicated by the monitor may be due to inductance between the monitor and cathode. A series of short circuit shots has been made to determine inductance of this span and it appears to be about $1.6 \times 10^{-7} \text{ h}$. Where the voltage pulse is flat topped, current is changing at an average rate of $2.4 \times 10^{12} \text{ amps/second}$. The monitor should therefore record a voltage which is about 0.4 MV higher than that on the cathode.

The fact that voltage reconciles, at least roughly, still left doubt as to whether flashover or breakdown was occurring. For this reason it was decided to oil fill the bushing in an effort to further increase operating voltage.

An estimate can be made of the level at which vacuum flashover from the cathode to ground would be expected. J. C. Martin (AWRE Report SSWA/JCM/713/157, March, 1971) has fit flashover data to the empirical formula $FA^{1/10}t^{1/6} = 175$

where F is in kV/cm, A is area in cm^2 , and time t is measured in micro-seconds. For our bushing and pulse shape, area is about 1240 cm^2 (one side) and t is roughly $0.03 \mu\text{sec}$. Using these figures and the bushing length of 19.4 cm, the formula predicts breakdown at a voltage of 2.9 MV. This corresponds to a linear stress of 150 kV/cm, a figure which is rather high but is on the order the design stress used by Sandia for their HARP machine.

Because voltage is measured with a capacitive divider, operating in oil gives an output signal which is higher than the vacuum level by a factor of about 2.2 (dielectric constant of oil).

Peak voltage read as a function of charging voltage was:

<u>Charging Voltage, MV</u>	<u>Monitor Reading, MV</u>
3.75	2.2
4.0	2.2
4.5	2.2

An inductive correction of about 0.4 MV is required to estimate cathode voltage, but it appears that voltage on the diode was roughly independent of driving voltage. This strongly suggested vacuum flashover, even though applied voltage was a megavolt less than Martin's formula suggests for the breakdown point.

To check for vacuum breakdown, a series of open shutter photographs of the diode interior were taken; examples are shown in Figure 63.

They showed copious fluorescence in general and brightspots on certain tube rings near the cathode. The diode was then disassembled and examined for evidence of tracking; this could be seen on surfaces of the insulators. It appeared that flashover initiated at the interface between the first grading ring and second insulator on both sides of the cathode.

Nominal linear stress at which flashover occurred was 93 kV/cm; this is more than 2.5 times the design stress level for the full scale diode (design stress is 35 kV/cm).

Figure 63 . Open Shutter Phtographs of Diode
Showing Grading Ring Emission

Test results indicated that a "side-to-side" diode could be built, and provided experience at assembling such a unit. Potential advantages of the side-to-side concept, particularly shorter tank length, were perceived as being great enough to make this the reference design, and engineering efforts were channeled in this direction.

1.8.5 Final Bushing Design

The final bushing design is similar to that shown in Figure 64. Basically it is a constant diameter polyethylene pipe divided into nine segments the division pieces being resistively graded. Field shaping electrodes deform the electric field so as to guide stray electrons away from the insulator surface. This is known to increase the voltage withstand of a bushing.^(41,42) The bushing design has been examined with a field plotting code and peak/mean electric field along the bushing kept to a maximum of 1.2. The anode inside the bushing will be conical, to ease mechanical constraints on cable guide rollers. The length of each segment is 10-inches including 1/2" electrode thickness, necessitating a slight recess in the tank wall. The electric field for 7 MV is thus reduced to a maximum of

$$\frac{7000 \times 1.2 \text{ kV/cm}}{9 \times 9\text{-}1/2 \times 2.54} = 38.7 ,$$

essentially equal to the 35 kV/cm criterion set for bushing design.

Tank Wall

Figure 64 . Final Bushing Design

In reaching this design the use of a stepped bushing (Figure 65) and materials other than polyethylene were considered for purposes of minimizing construction costs. Estimates of dollars required to fabricate each of several bushing types are listed below:

	Single Diameter Bushing	Stepped Bushing
cast acrylic	\$ 41,970	\$ 47,120
epoxy	37,870	46,770
high density polyethylene	22,980	30,620

Least expensive of the possibilities is that having a constant diameter polyethylene insulators; low cost arises largely from the fact that thick walled polyethylene pipe is commercially available in suitable diameters (about 4 feet). Cost (at this writing) would be about \$90 per foot (exclusive of cutting charges), inexpensive for a bushing although it may be dear for a sewer installation.

To evaluate the use of polyethylene as an insulator, the test fixture sketched in Figure 66 was built. Housing was made of loaded, black polyethylene obtained as a free sample cylinder, 16 inches in diameter, from M. L. Sheldon Plastics, 350 Lexington Ave, New York, New York. Immersed in oil and evacuated, its performance was studied, yielding the results below.

- Outgassing was reasonable. It pumped down to 8×10^{-6} torr overnight
- Did not conduct at high voltage, 25 kV over 4 inches, DC, led to < 0.2 ma
- Flashover strength O. K,
Mean fields of 27.5 kV/cm (1" gap) were withstood (2 μ sec pulse)
- No evidence of plastic degradation could be seen after 4 hours 1 pps pulsing in oil.

Figure 65 . Stepped Bushing Design

Figure 66.

H.D. POLYETHYLENE TEST
FIXTURE

The flashover study was not too rigorous. Bushing was close to 3/4 inch diameter rings, separated by 0.96". Approximately 60 kV was required to flashover from side of rings to the bushing. Peak fields along the bushing were probably ~ 20 kV/cm, but a field plot would be needed for exactitude. There was some evidence of fast ringing on the voltage pulse which could lead to premature breakdown.

From this the material seemed adequate, and was selected for the final design.

1.8.6 Bushing Heating

The bushing, holding off the cathode voltage from ground, has three sources of heating. These are

- Anode radiation
- Grading resistors
- Ion Bombardment

Cooling is by convective loss to the oil. The anode itself cannot exceed about 200 C without weakening; it is assumed that the anode will be cooled to at least this temperature. Power radiated from a 6 inch diameter by 15 foot long by 200 C blackbody would be

$$\pi 6 \times 15 \times 2.54^2 \times 12 \times (473)^6 \times 5.67 \times 10^{-12} \text{ watts}$$

$$= 6.2 \text{ kw}$$

Taking the hot anode length as only 2 ft., for equivalent heat loss the anode temperature would have to be over 500 ° C. The correction for reradiation is less than 20% in both cases.

Strictly speaking grading resistors should lose heat to the oil directly. However, they contribute a little by conduction and, by warming the oil locally, interfere with the cooling mechanism.

It is expected that they will take less than 5% of the total power, i. e. 8.65 kw.

To estimate heating by ion bombardment, use Langmuir, assuming a plane parallel nonrelativistic diode and an ion current limited by ion space charge. Ion current would be $\sqrt{\frac{1840}{2}} \times$ the

size of electron current (if the ions were hydrogen). In practice not all of this current has time to cover the gap between anode and cathode. Loss is 4.05 kw.

The total heating is 18.9 kW and is probably spread over 7 feet of the five foot diameter bushing; the extra length compensates somewhat for the finned nature of the structure. This is about 0.84 watt sq. in which will mean less than 10 C difference between bushing and oil. From this it is concluded that the use of low temperature materials, such as polyethylene, will be safe.

1.8.7 Radiation Damage to Insulators

The bushing, particularly the high voltage end, will be forced to operate in a relatively high X-ray field generated by Bremsstrahlung from stopping of electrons in the cable. All polymers eventually degrade under irradiation, but some are more resistant than others. Polyethylene is not among the better choices from this standpoint and, for long duration running, rings would have to be rotated from high voltage to ground or replaced altogether at regular intervals. Rings should have sufficiently long life to meet the testing and manufacturing requirements of this program but, were cost less of a consideration, significant improvement (order of magnitude or more) could be obtained by going to cross-linked polystyrene or glass (many orders of improvement).

1.9 Field Emission Diode Sizing

It is desirable to have a means of reliably estimating diode impedance, as this parameter will be the important one in determining output voltage. To this end, Langmuir's theoretical results for space charge limited cylindrical vacuum diodes have been employed, and data have been obtained from FX-35 testing for comparison.

(43)

Langmuir and Blodgett derived the following expression for current in a space charge limited cylindrical diode;

$$i = 14.7 \times 10^{-6} \frac{\ell V^{3/2}}{r\beta^2} \quad \text{amp}$$

where

ℓ = diode length, cm

V = Voltage

r = anode radius, cm

β^2 = a factor which depends on the ratio of anode to cathode radius

The quantity β^2 also depends upon the physical location of the cathode with respect to the anode; it is substantially greater when, for a given ratio of radii, the cathode is external to the anode. This is the case of interest, to us, and for it β^2 takes on the values tabulated below.

$\frac{r_c}{r}$	β^2
1.	0.
2.	0.845
4.	6.000
8.	24.805
16.	81.203
50.	450.23
200.	2946.1

Impedance can be computed from the relation for current by dividing through by V and inverting. This gives

$$Z = \frac{V}{i} = 6.8 \times 10^4 \frac{r \beta^2}{\ell V^{1/2}} \Omega$$

If Langmuir's analysis applies, impedance would be expected to decrease as the diode is made longer or as voltage is increased, and to become greater as the anode radius is made larger or as the ratio of cathode to anode diameter increases.

To verify these dependencies, a series of pulses were made on FX-35 with a cylindrical vacuum diode, varying r_c/r and diode voltage. Testing utilized a toroidal cathode with pins to act as emitting sites; this configuration is sketched in Figure 67. Number of pins was varied, and the diameter upon which pin-tips fell was increased or decreased to vary r_c . Voltage and current were measured with a capacitive divider and return current shunt respectively, both of which have been described in detail by Graybill et al.⁽⁴⁴⁾ Charging voltage was recorded with a generating voltmeter.

Figure 67. Anode-Cathode Geometry for Impedance Studies

Figure 68. Impedance History for Cylindrical Diode(8 pins, 4 MV charging, 7.4-inch pin tip diameter, 2-inch cathode shank)

Load impedance for FX-35 can be estimated from the ratio of load and charging voltages using transmission line theory. When the machine is discharged by closing one end of the Van de Graaff charged coaxial gas capacitor to the diode, right and left moving waves are excited, each having amplitude equal to half the charging voltage, or $V_c/2$. Wave moving onto the diode is transmitted according to

$$\frac{V_t}{V_i} = \frac{2 Z_t}{Z_t + Z_m}$$

Here V_i is voltage in the incident wave, and the subscripts t and m designate diode and machine impedance, respectively. Using the fact that V_i is equal to $V_c/2$, this expression can be solved for Z_t , with the result that

$$Z_t = \left(\frac{\frac{V_t}{V_c}}{1 - \frac{V_t}{V_c}} \right) Z_m .$$

In using this equation, V_t has been taken as maximum voltage indicated by the capacitive divider. This occurs at a time when the rate of current change is small and the contribution made to indicated voltage by shank inductance is negligible.

To check the approach described above, current and voltage traces for a typical pulse were analyzed to determine true diode voltage, and impedance was computed as the ratio of diode voltage and diode current. Results are plotted in Figure 68. At 10 ns, the point at which uncorrected voltage was a maximum, impedance was about 53Ω .

Using the equation given above (with characteristic impedance of the machine equal to $45 \Omega^{(45)}$), diode impedance was calculated to be 55Ω . Charging

voltage was 4.5 MV, voltage indicated on the diode was 2.2 MV. Agreement with the more exact approach is excellent, and indicated that a point on the impedance history can reliably be estimated using voltage ratios. Impedance estimated in this way tends to be near maximum; when the cathode has fully lighted, impedance drops to a value which is more or less constant and equal to about a third the maximum. Averaged over the whole pulse, impedance is about half the maximum value.

Langmuir's equation can be used to calculate impedance for each geometry and diode voltage listed in Table XIX. This was done to produce values given in the final column. Calculations assumed effective diode length equal to the axial dimension of the annular ring to which emitting points were attached; this corresponds approximately to mean width of the beam as it expands away from the needles. With this choice, impedance from theory values which roughly 80 percent of those measured. Observed trend in impedance with increasing radius follows that predicted by Langmuir, (see Figure 69); impedance falls off with voltage, but appears to decrease somewhat more rapidly than would be expected from the inverse square root. In general, however, accuracy appeared to be sufficiently good to allow an estimate of diode dimensions to be made by extrapolating with Langmuir's equation.

Marx and peaking capacitor have been sized for a diode impedance of 100Ω . If the window is to be 4-inches in diameter and the cathode 2-feet long, then β^2 must be at least

$$\begin{aligned}\beta^2 &= 1.4 \times 10^{-5} \frac{Z \ell V^{1/2}}{r} \\ &= \frac{(1.4 \times 10^{-5}) (10^2) (60) (2.6 \times 10^3)}{(5)} \\ &= 43.5\end{aligned}$$

Table XIX. Summary of Data from Impedance Measuring Experiments
with Cylindrical Diode on FX-35.

Runs	Number of Pins	Tip-to-Tip Diameter, in.	Charging Voltage, MV	Tube Voltage, MV	$\frac{V_t}{V_c}$	Measured Diode Impedance Ω	Impedance from Langmuir's Equation Ω
1	4	6.73	3.5	2.82	0.81	191	81
2	4	6.73	4.0	3.04	0.76	142	78
3	4	6.73	4.5	3.04	0.68	96	78
4	4	6.23	4.0	2.51	0.63	76	67
5	4	7.46	4.0	2.94	0.74	128	103
6	8	7.46	4.0	2.92	0.73	121	102
7	8	6.27	4.0	2.62	0.66	88	66
8	8	6.70	4.0	2.62	0.66	88	84
9	8	6.70	4.5	2.72	0.60	68	82
10	8	6.70	3.5	2.34	0.67	91	76

Figure 69. Variation of Diode Impedance with Cathode-Anode Diameter Ratio

This requires that the cathode diameter be eleven times that of the window, or 44-inches.

If the emitting length were shortened to 1-foot, this diameter could be reduced to 30-inches. One foot is the present design length, and inside diameter of the cathode has been set to 34-inches.

This cathode is large but not impossibly so; it fits readily into the tank and is actually smaller in diameter than the bushing. A concern, however, is that there may be a significant deviation from theory in large diodes; it was desired to extend earlier experiments to higher values of r_c/r_a to study such a possibility.

Using a 2-inch diameter window and fixed cathode ring with needle emitters on FX-35, it was only possible to obtain adjustment of the cathode-to-anode radius ratio, r_c/r_a , over the range 3.3 to 3.8. This was extended in a series of experiments whose objective was to make impedance measurements at radius ratios in excess of 10.

High ratios were obtained by substituting solid aluminum rods for the 2-inch window; rods having nominal diameters of 0.25, 0.50, 0.75, and 1.5 inches were used. In addition to varying anode diameter, diameter of the circle upon which needle tips fell was also adjusted, two positions being used. These corresponded to 6.45 and 7.35 inch diameter circles. In all cases 8 cathode needles were used.

When FX-35 was charged to voltages below 4.5 MV, output pulse shapes recorded by the voltage monitor indicated potentials in excess of charging voltage. From transmission line theory, maximum output voltage is

generated by switching onto an open circuit; in this case voltage equal to the charging voltage should be obtained. The observed result was attributed to failure of the needles to emit properly early in the pulse, followed by emission of electrons from the cathode shank. Accumulation of significant space charge about the shank will increase its effective diameter and alter calibration of the monitor. Unless significant current begins to flow, electrons leaving the shank will not be magnetically confined and may cross to the monitor where they can charge it; as with a change in calibration, this will result in indication of a voltage which is too high.

At 4.5 MV charging it appeared that satisfactory cathode performance was obtained, hence measurements were concentrated at this condition after an early period of exploration. Results are listed in table XX. Two values of impedance have been reported, the first calculated from peak voltage and transmission line theory and the second from ratio of peak voltage to current flowing at the time corresponding to voltage maximum. These are given in the final columns of the table.

In figure 70 electrical impedance (V/I) has been plotted as a function of r_c/r_a and compared to Langmuir's theory and to data obtained during initial experiments. It can be seen that measured impedances are essentially independent of r_c/r_a , agreement with theory being obtained only at ratios near 4. This behavior is characteristic of that which would be expected if the actual emitter consisted not just of the needles but of the whole cathode structure, including shank and ring.

Table XX. Summary of Impedance Experiments

Anode Diameter, Inches	Cathode Diameter, Inches	$\frac{r_c}{r_a}$	Charging Voltage, MV	Tube Voltage, MV	Transmission Line Impedance, Ω	$\frac{V}{I}$, Ω
.75	7.35	9.9	4.5	3.2	110	--
.50	7.35	14.6	4.5	3.6	169	94
.25	7.35	29.3	4.5	3.9	670	121
.75	7.35	9.9	4.5	3.6	169	117
.50	7.35	14.6	4.5	2.8	73	92
.25	6.45	25.7	4.5	2.8	73	97
.50	6.45	12.9	4.5	2.8	73	97
.75	6.45	8.6	4.5	3.0	91	108
1.50	6.45	4.3	4.5	2.8	73	91
.25*	6.45	25.7	4.5	3.4	142	87
.50*	6.45	12.9	4.5	3.4	142	81
.75*	6.45	8.6	4.5	4.1	455	105
1.50*	6.45	4.3	4.5	3.6	180	92

* For these shots a 2-inch diameter cathode shank was employed. In all other cases, shank diameter was 1-inch.

A similar finding was reported by T.H. Martin and R.S. Clark⁽⁴⁶⁾ who studied impedance of a 1.5 MV microsecond pulse generator at Sandia. The cathode used in their work consisted of a hemisphere suspended upon a cylindrical shank; it discharged to a disc shaped anode. They noted that "impedance of this geometry was dependent only on relative diameters of the (cathode) shank and conducting wall and relatively independent of the anode-cathode gap until the gap was very small, since almost all of the current was emitted along the cathode shank".

It appears, therefore, that unless shank emission can be suppressed, it is not possible to conduct an experiment which will show the dependence of impedance on gap geometry. This result also indicates the importance of eliminating shank emission in the full scale diode if impedance is to be predictable and controlled.

It should be noted that the final diode design for the full scale machines surrounds the shank with oil; this reduces surface stress and provides a physical barrier to emission, hence should eliminate cathode action from the shank.

1.10 Oil

1.10.1 Oil Storage System

Four 10,000 gallon storage tanks were placed in position on prepared footings; figure 71 gives several views of the tanks as they were being offloaded and mounted, and figure 67 shows the completed "farm". Tanks were sprayed internally with a layer of transformer oil prior to delivery and penetrations were sealed the day after installation.

Figure 71. Oil storage tanks being installed outside XTU vault.

Figure 72. "Tank Farm"

A complete oil storage and transfer system was designed and portions necessary to put the tankage into service were completed. This work was conducted to provide storage capacity required to sequester approximately 13,000 gallons of insulating oil for the generator.

To prepare the storage system it was necessary to sandblast tank interiors to remove a heavy wax coating, and to condition exteriors by removing rust and scale to the extent required to permit application of preservative paint. All four tanks were plumbed with vents, fill pipes, valving, and transfer lines, and plugs were welded in as needed to close up holes. Manways were reworked to allow them to function properly in the inverted position (tanks were located with manways on the top side rather than down, the design orientation). To act as inexpensive level indicators, pressure gages were installed on tank bottoms. Drain lines were placed in the tank bottoms to allow any water which might accumulate to be bled off.

Upon completion of modifications, each tank was pressurized with plant air to check for leaks, and all were found to hold pressure over a 24 hour period.

After the four tanks were loaded it was estimated that 12,500 gallons had been received. Oil was allowed to equilibrate between the tanks so that each contained about 3000 gallons.

A pair of figures (73 & 74) was drawn to aid in reading oil height and volume as a function of indicated head.

$$P = 62.36 \times .90 \times \frac{126}{1728} = 4.10$$

CAPACITIES Large Tank = 9930(length 15.3)
 Small Tank = 9670(length 14.9)

$$\text{VOLUME} = .66 HW + \frac{H^3}{2W}$$

$$A \times \text{GPCF} = 86.59 \times 7.48 = 648$$

$$9670 \div 648 = 14.92 \text{ ft. lg.}$$

$$9930 \div 648 = 15.32 \text{ ft. lg.}$$

Note: Quantity of oil rounded off to the nearest 10 gal.

Figure 73. Tank Contents Versus Pressure Indication.

<u>SMALL TANK</u>	<u>PSI</u>	<u>HEIGHT</u>	<u>LARGE TANK</u>
9670	4.10	10' - 6"	9930
9510	3.90	10' - 0"	9760
8830	3.51	9' - 0"	9070
7970	3.12	8' - 0"	8110
6830	2.73	7' - 0"	7010
5700	2.34	6' - 0"	5860
4570	1.95	5' - 0"	4690
3400	1.56	4' - 0"	3480
2280	1.17	3' - 0"	2340
1280	.78	2' - 0"	1320
470	.39	1' - 0"	480

Figure 74 . Gallons of Oil Versus Indicated Pressure

1.10.2 Irradiation Testing of Transformer Oils

Because it appears that the diode and bushing will require transformer oil to be located in relatively close proximity to a strong source of x-radiation, the literature has been scanned for data pertaining to radiation resistance of oil. Little of pertinence was found; Collins and Calkins⁽⁴⁷⁾ report that motor oil polymerizes above about 30 megarads. Recollection of engineers at High Voltage Engineering is that Shell conducted tests many years ago and found that transformer oil was unchanged after hundreds of megarads.*

To supplement this information, a series of electron irradiations were carried out with IPC's 300 kV PEBS machine; 10 to 20 mil thick layers of oil were subjected to average doses of 125, 600, and 1250 megarads. The latter corresponds roughly to the dose that would be collected in oil located at closest approach to the cathode over a 40 hour work week. In addition to examining oils for color and viscosity changes, breakdown strength was measured in a one-inch gap formed by two hemispheres.

Three oils were tested; these were

- oil from the switch testing tank, a mixture of unknown composition but probably consisting largely of Transcrest
- castor oil
- Hatcol-101, an oil substitute manufactured by the Hatco Division of W. R. Grace

Some general observations were that Transcrest became progressively darker and more viscous as dose increased, but it was considerably lighter and less viscous after 1250 megarads than an unirradiated sample of Sun XX cable oil.

Castor oil became rapidly lighter in color and polymerized at 600 megarads. Breakdown strength of Hatcol-101 was degraded by irradiation, whereas it appeared that little or no degradation in Gulfcrest took place.

Results of breakdown measurements are tabulated below.

Oil Type	Dose, Megarads	Breakdown Voltage in one - in Gap, kV	Comments
Transcrest (?)	0	46	
	125	--	
	600	44	
	1250	~50	
Castor Oil	0	~50	turned clear, polymerized
	125	~50	
	600	--	
Hatcol-101	0	~50	
	125	~50	
	600	33	
	1250	29	

It was concluded that transformer oil probably will not degrade significantly below 10^6 megarads. By circulating oil in the Marx tank, the volume subject to irradiation can be increased and the mean dose reduced to levels below 10^6 megarads.

Subsequent to this testing, survey of the literature produced a paper describing the results of exposing various oils to radiation from a nuclear reactor⁽⁴⁸⁾, where it was found that the effect of irradiation is to increase viscosity, a finding similar to that observed under this program.

1.10.3 Oil Temperature Rise

Oil temperature must be maintained at or below 40°C (104°F) for main bank capacitors to meet their specified life of 10^7 shots. This implies that, over the course of an 8 hour shift, temperature should not be allowed to increase by more than 20°C .

If the Marx tank is assumed to be adiabatic and if all energy dissipated in the oil goes into heating it alone (rather than heating components and structural elements which are immersed in it), then the rate of temperature rise can be found from

$$\dot{T} = \frac{Q}{c}$$

where Q = power dissipated

C = specific heat of oil.

Taking Q equal to 250 kW, something more than half the power delivered by the charging supply, and using a specific heat of 0.511 cal/gm-°C gives an eight hour rise of 27°C (48°F). This suggests that cooling will be needed if the machine is to operate for protracted periods.

In practice, testing of the machine and manufacture of short lengths of 138 and 230 kV cable should not require long running times, so that oil temperature may never approach the critical point during operations which are presently scheduled. For this reason it seems appropriate to dispense with cooling, at least until temperatures recorded during operation indicate that it is required.

1.11 Facility Site and Cable Handling

Discussions regarding possible locations for the machine concluded that the optimum arrangement would be to leave it at the site of manufacture (IPC) and ship cable to it for crosslinking. A number of factors contributed to this decision, but two of the major ones were availability of a suitable location which could be used with minimal improvements, and existence of a trained radiological health staff. Final disposition of the unit after contract completion was not specified in the contract.

Preliminary design of the machine led to the following set of requirements for a site:

- overhead hoist of 6 ton minimum capacity.
- minimum 12 ft clearance from top of Marx tank to lift hook.
total required height 25 ft approximately.
- area easily accessible to the outside of building (preferably near present drives, large doors, etc.)
- near oil storage area
- floor area in sq. ft. required is a minimum of 24X54 (without rollaway design).
- area must be easily adaptable for the confinement of oil spill.
- area must be readily equipped with radiation shielding, and located away from heavily traveled aisles, etc.
- sufficient clearance available to permit cable handling operations.

Several possible locations were identified and surveyed; of these, one appeared to be clearly preferable for reasons including availability, existence of adequate power mains, and ease of shielding. This site - Bay 26 at IPC - was originally built to house a 20 MV tandem gas insulated Van de Graaf accelerator (XTU) whose dimensions were similar to those of the cable irradiator. The Van de Graaf was dismantled during summer of 1975, leaving the area

clear for alternative uses. Some features of Bay 26 are the following:

- Lifting hooks are 20 ft above floor level but the XTU trench is 10' deep and 42'-6" long. This would provide 8 ft clearance from bottom of lowest capacitor to top of tank during extraction of capacitors. The trench length is marginal, but an additional 4' on either end is easily obtained by removing one step.
- The remaining trench would also act as a safety reservoir in case of oil spill. This area will hold at least 24,000 gallons of oil. Several additional trenches and smaller pits can be utilized in other ways. Example:
 - (a) Running plumbing and wiring to and from pulser.
 - (b) Provide an area to locate power supply, oil pumps, vacuum pumps and necessary hardware.
- Pit provides an excellent start for shielding. Less external shielding would have to be added.
- Pit also will eliminate most of staging or walkways around top of tank.
- Existing pumps, plumbing, power supplies, etc., might be utilized.

Agreement was reached to hold this area open for the cable irradiator, and it is presently being used as a point of storage for components as they are received.

Subsequent to selecting a machine location, efforts were made to place and orient equipment and to define cable handling items which will be needed. A layout drawing of a proposed handling scheme was made and reviewed with the production department of the cable manufacturer.

The layout shows a reverse bend in the cable as it angles down to make a 90 degree turn into the diode. A number of alternatives to this were considered, such as

- tilt capstan downhill toward the diode

- lift tank so cable entrance into diode is at floor level.
Bring in cherry picker to remove peaking capacitor if raising the tank causes problems with head room
- try for a straight shot through the diode
 - (a) break a hole in the outside wall, excavate to diode level (requires removal of about 15 feet of earth), install a 180⁰ quadrant roller and re-enter through another hold. Push earth back on top and leave the roller buried for all time.
 - (b) excavate outside wall for a small shed which would house a takeup reel there for however long it takes to make the required length of cable.

Upshot was that no solution could be found which represented an improvement and it was agreed to consider the initial layout as the baseline approach.

A quadrant roller arrangement required to turn the cable into and out of the diode is shown in fig. 75. The sketch shows a typical quadrant, with floor mounting points in phantom. It is planned to fabricate these to size at the time of installation.

It appears desirable to include a cable support system inside the irradiation zone to minimize unsupported span (hence reducing cable tension and protecting the window against accidental scrapes). A preference was shown for guide rollers rather than stationary parts; roller sizes are somewhat arbitrary, but will probably be specified to match the quadrants, if space permits.

In discussions relating to layout of working areas, it was indicated that it will be necessary to have people working near the takeup, at least during initial stages. This implies a need for shielding and interlocking the takeup area.

CABLE GUIDE

Figure 75

1 . 12 Shielding

1 . 12. 1 Radiation Protection Standards

Operators of equipment which produces ionizing radiation are bound by the Code of Federal regulations (pertinent paragraphs have been incorporated into the OSHA) to reduce radiation exposure below certain limiting levels, and to verify, through a program of continuous monitoring, that these levels are not exceeded.

The law recognizes the general public and radiation workers as two distinct classes of individuals and specifies that considerably more stringent protection must be provided for the former. Dose rates in areas to which the general public has access (so called unrestricted areas) must be limited to 0.25 mrem or less. Restricted areas of several types can be established, and in these areas radiation workers equipped with suitable monitoring devices can be subjected to higher dose rates.

The Code of Federal Regulations, 10-CFR-20, establishes the allowable dose for a radiation worker as 1.25 rem per quarter to the whole body, or 5 rem per year; under emergency circumstances, a whole body dose as high as 3 rem may be received in any one quarter, but the cumulative dose of 5 rem per year may not be exceeded. Averaged over the course of a year, 5 rem corresponds to about 2.5 mrem per hour for a 40 hour week, hence shielding is often designed to reduce dose rates to this level in controlled "Radiation Areas" in proximity to the source.

(49)

Ion Physics Corp. is governed by Corporate safety policies as well as by federal law, and these policies tend to be the more restrictive. They state in part that:

- "No employee or visitor under 18 years of age is to be exposed to ionizing radiation in excess of 0.25 mrem in any one hour.
(paragraph 9)

- Radiation work areas should be preplanned and adjusted so that radiation emitted from the shielding does not exceed an exposure of 0.25 milliroentgen in one hour at a point 5 cm outside the external surface. The preferred objective is less than 0.1 mr/hr. (paragraph 33)
- Any area, accessible to personnel, in which there exists radiation in excess of 2.5 mr/hr, but less than 100 mr/hr, must be designated a radiation area and be conspicuously posted. . . . " (paragraph 36)

It should be noted that 10-CFR-20 defines a somewhat more lenient radiation area;

"Radiation Area means any area, accessible to personnel, in which there exists radiation at such levels that a major portion of the body could receive in any one hour a dose in excess of 5 mrem, or in any 5 consecutive days a dose in excess of 100 mrem".

Regulations of the federal government and policies of HVEC indicate that dose rate at the nearest point of unrestricted approach should be reduced to 0.25 mrem/hr or less, and that operating personnel should be protected against dose rates in excess of 2.5 mrem/hr. These criteria form the basis for our shielding design.

Dose Rate Effect On Acceptable Levels

Because they have been established by deliberative bodies thinking in terms of continuous sources or sources in which dose rate varies slowly with time (such as a reactor coming up to power), it is necessary to ask how these criteria should be applied to a generator which emits short bursts of radiation on a continuous basis. It is such a machine that is being designed; peak dose rate will be about six orders of magnitude greater than the average value, therefore it is a question of some importance to determine whether it can be shielded on the basis of time averaged dose rate or whether dose rate must at all times be kept below the limits given in 10-CFR-20. If biological effects

depend only upon the total number of ionizing events and not upon the rate at which they occur, then it would be sufficient to shield to the average dose rate. Obviously this would be the preferred situation from an economic point of view.

Some work has been done on the survival rates of mammalian cells subjected to high dose rates. Berry et al⁽⁵⁰⁾ employed a pair of pulsed cold cathode machines at the Atomic Weapons Research Establishment, Aldermaston, England, to irradiate cells from a human carcinoma and from the lung of a new-born hamster at dose rates from 10^{10} to 10^{12} rads/sec. Radiation consisted of bremsstrahlung photons peaked at about 700 keV and 1.1 MeV; machines produced pulse widths of 7 ns and 50 ns respectively. Comparative data were also taken with a Cobalt-60 source; Co-60 decays by emission of 1.1 and 1.3 MeV photons, so that experiments were conducted with radiation of similar energy from both pulsed and isotopic sources. Results were as follows:

- At 7 ns pulsewidth and doses below 750 rads, the number of surviving cells of both types was the same for Co-60 and flash X-ray. At higher doses, fewer cells survived Co-60 irradiation.
- At 50 ns pulsewidth survival of both cell types was independent of dose rate.

The conclusion appears to be that high rate irradiation produces the same effect as, or possibly is less effective than, low dose rates in causing biological disruption. From this (admittedly skimpy) evidence, it would seem reasonable to shield pulsed machines for average external dose rates as called out in 10-CFR-20. Accordingly, calculations have used time averaged dose rates of 0.25 mr/hr for unrestricted areas and 2.5 mr/hr for controlled access zones.

1.12.2 Methods of Dose Reduction

The methods of protecting against radiation are (1) interposing mass between the source and point to be shielded and (2) interposing distance between them. Because radiation flux falls off, at least approximately in most installations, as the reciprocal of distance squared, significant benefit accrues from the use of distance; in general, however, a combination of distance and mass is required to give a practical shield.

Attenuation cross sections for high energy photons are only weakly dependent upon the choice of shielding material, so that concrete is approximately as effective as lead in equal mass. Because lead is more than 5 times as dense as concrete, $1/5$ of the thickness provides equal attenuation. Where space is at a premium, therefore, lead may be preferred, but in general concrete is a more economical shielding medium. Concrete is relatively strong when loaded in compression and can be used to build load bearing walls, an advantage in some construction schemes.

1.12.3 Radiation Sources

In addition to direct photons, scattered radiation can be an important source to consider. In particular, upward going photons scattered toward ground by interactions with air represent a distributed source which can contribute significantly to dose and which has the ability to illuminate areas outside shielding walls. This "skyshine" can be reduced by placing shielding over the source and/or by raising the height of walls to cut down the solid angle of sky viewed by the source.

Substantial amounts of energy can be reflected from surfaces, so that care must be taken to prevent "streaming" through shield penetrations or around corners. Effect of streaming can be minimized by designing for multiple scattering paths.

It is considered good practice to design shielding for "worst case" radiation conditions, thus providing for safe operation under all foreseeable circumstances. These should include use of the machine in modes

other than that for which it is being designed; such modes could include generation of short bursts of protons or ions and neutron generation through any one of several charged particle reactions. A fair amount of knowledgeable effort would be required to convert the machine to effectively produce ion beams, hence it seems reasonable to assume that the question of adequately shielding against reaction products of such use would be brought up at the time conversion took place. Accordingly, only radiations which could be produced, inadvertently or otherwise, with high energy electrons have been considered. These radiations are

- electrons
- Bremsstrahlung photons
- neutrons

Electrons: it is conceivable that the machine could be operated in such a way as to bring an electron beam outside the confines of the Marx tank and into the accelerator room; to do this would require redesigning the diode, hence it could not be done casually. Maximum range of 7 MeV electrons in air is in the vicinity of 100 feet. Shielding against these electrons would be relatively straightforward, however, for the equivalent of 3.6 gm/cm^2 of aluminum is sufficient to stop them. This corresponds to

1.3 cm	aluminum
0.3 cm	lead
1.6 cm	concrete

Some gamma radiation would be generated by electron deceleration in the shield, hence additional attenuating material would be needed to stop this.

Neutrons: can be produced by reaction of energetic photons with the nuclei of certain atoms; generally, the threshold energy for neutron production through these (γ, n) reactions is quite high. The most energetic photons which can be generated with our machine will be 7 MeV. Neutron producing reactions which can take place at lower energies are listed below, together with natural abundances of the isotopes involved.

Isotope	Photoneutron Threshold Energy, MeV	Isotopic Abundance Percent
Be ⁹	1.67	100.
H ²	2.22	0.0156
O ¹⁷	4.1	0.04
C ¹³	4.9	1.11
W	6.25-7.15	*
Mo	6.75-13.28	*
Zn	7-11.7	*

In general the cross section for photoneutron production is very small near the threshold and it is necessary to approach the region of "giant resonance" before significant yields can be obtained. This lies well above the threshold.

For the present situation, where neutron generation would be undesirable, it is a fortunate circumstance that the few isotopes with low threshold all have low atomic number so that photon generation by electron deposition is minimal.

Under normal cable making operations, the two isotopes from which neutrons might be generated are C¹³ and deuterium, both present in small amounts in polyethylene. Yields would be negligibly small. Only if beryllium were introduced in quantity into the irradiation cavity would measurable neutron fluences be generated. From the standpoint of shielding, they would not aggravate the problem because attenuation lengths in concrete are roughly equal for energetic photons and neutrons below 10 MeV. Shielding against foreseeable bremsstrahlung yields would provide a design safe against worst case neutron fluences as well.

* Isotope not specified

Bremsstrahlung Photons: Shielding dimensions will be controlled by the need to attenuate bremsstrahlung radiation to acceptably low levels.

Shielding mass required escalates linearly with atomic number (Z) of the nuclei struck by electrons. Under normal operation (as a pure electron beam machine) the highest Z material likely to be encountered either in the vacuum diode or as a part of the cable is copper ($Z = 29$). It is conceivable that a lead jacketed cable could be strung through the diode in a production misunderstanding, and this would approximately triple radiation output.

For our in-house installation, where control can be exercised over the unit and over material processed by it, it seems reasonable to take copper as the highest Z target likely to be encountered. Because it is anticipated that approximately 70 percent of the beam will be stopped in polyethylene with the balance thermalizing in aluminum, this choice should create a built in safety factor of about two.

1.12.4 Preliminary Shielding Design

A preliminary shielding design has been completed, taking into account attenuation in the Marx tank oil. This design anticipates the use of standard interlocking high density concrete blocks which are available at HVEC. Calculations call for 4 courses of block around the head of the machine, tapering to 1 course at the foot. Computations have included an extra absorption half-thickness to account for buildup in the shield due to scatter. To control skyshine it is planned to place 2 courses of block above the forward third of the machine, and 1 course over the middle third. With this arrangement it is estimated that dose rate on the roof of the main building (located about 30 feet above the source) will be 15 mr/hr. Rather than add additional mass (and supporting structure) our preliminary plan, subject to review by the HVEC Radiation Protection Officer, is to control access to the roof while the machine is in operation. This procedure is already in use for other HVEC installations and the necessary gates are in place. An administrative policy will be drawn up to assure that departments likely to require roof access (maintenance) are aware

of our schedule.

Rough estimates indicate that two courses of vertical shielding should adequately control skyshine, but further refinements in our calculations are in order here.

1. 13 Cable Crosslinking With a Bremsstrahlung Machine

Because it could be converted from electron beam to gamma ray production by replacing the window with an appropriate converter, the cable irradiator has a great deal of flexibility. Gamma rays are deeply penetrating and with them it should be possible to crosslink cables of arbitrarily high rating; six or eight inch diameters would present no problem. One can conceive of the machine being used in the electron mode for cables to 230 kV, then switching to gamma rays (absorbing the loss in efficiency which accompanies conversion) to crosslink cables having higher voltage rating.

1. 13.1 Bremsstrahlung Experiments on FX-35

A quick calculation was made to determine whether useful quantities of X-radiation could be obtained from FX-35. The machine could be easily outfitted with a cylindrical converter and used as a testbed for photon crosslinking experiments.

Assuming a tantalum converter and peak voltage of 2.5 MV (effective voltage of about 2 MV for radiation production), then conversion efficiency would be 9.5 percent. Half angle of the intensity distribution, using the rule

$$V\theta = 150 \text{ MV-degrees},$$

should be in the vicinity of 75 degrees. Since we would be irradiating a 1 inch cable in a 2 inch converter, the geometric half angle is 30 degrees, and only about a third of the photons could be expected to pass through the workpiece. Mean free path in polyethylene would be 30 cm or more; assume 30 cm. The useful energy fraction would then be

$$f = (.092)(.33)\left(\frac{2.5}{30}\right)$$

$$f = 0.0025$$

Charged to 5 MV the FX-35 (280 pf) should store 3.5 kJ, so that with 100 percent transfer to the converter, as many as 8.7 joules could be deposited in the cable. Estimating 50 percent transfer, 4 joules would be intercepted. If it were spread uniformly over a length of 10-inches, then the average dose in a 1 inch diameter cable would be 3.3 kr per pulse.

It seemed impractical to think in terms of accumulating 20 megarads at this rate; something like 6000 shots would be needed. It would take 3 shifts if a shot could be made every 15 seconds.

Because nature is perverse, dose in the cable grows slowly but dose at the operator's station grows rapidly, at least relative to the 100 mr allowable for a 40 hour week. The 330 joules of X-rays which would be generated from 100 percent transfer of 3.5 kJ at 9.5 percent efficiency will radiate into 4π . In the usual bremsstrahlung setup on FX-35, flux is forward directed and must backscatter off vault walls to reach the control console. With X-rays emitted isotropically, however, there can be some direct radiation at the foot of the vault and skyshine may be increased.

From the diode to the console is a distance of 35 feet; nominal dose per pulse is, therefore, (neglecting attenuation in air),

$$D = \frac{\mu U}{4\pi r^2} = \frac{(0.03)(330)}{(4\pi)(1000)^2} \cong 0.75 \times 10^{-6} \text{ j/gm}$$

$$\mu = 0.03 \text{ cm}^2/\text{gm for tissue at 500 keV}$$

$$U = 330 \text{ joules}$$

$$r = 35 \text{ ft} \cong 1000 \text{ cm}$$

Because a megarad is 10 j/gm , D is equivalent to $0.75 \times 10^{-7} \text{ Mr}$ or 75 millirads per pulse. By ducking behind the concrete shadow shield at the console this can be cut to 0.3 mr (the shield is 2 ft thick or about 8 half layers for 2 MV X-rays; $75/2^8 = 0.3$). This amounts to an acceptably low level, even if skyshine should increase it by a factor of 3. We would be limited, however, to making no more than about 300 shots per week unless additional shielding were added.

In view of this it seemed the most that could be extracted from cylindrical converter experiments were measurements of the magnitude and distribution of dose. These data could be obtained from a few shots, and would provide a means of evaluating the calculations made in the preceeding section.

To this end a quick dosimetry experiment was conducted. The e-beam window was removed and replaced with a 2-inch diameter 80 mil wall aluminum pipe having 15 mil tantalum sheet rolled around it. This combination has an areal density of 1.2 gm/cm^2 , which should be range thick for electrons up to 2.4 MeV. In some of our depth dose measurments with cellophane and Mylar, range up to 1.3 gm/cm^2 was estimated by extrapolating the tail of the dose curve. For the last of three measurements made, an additional 0.062 inches (0.438 gm/cm^2) of aluminum was added to assure that the converter was range thick.

Dose was measured with lithium fluoride thermoluminescent dosimeters (TLD's) read with a ConRad reader using a calibration determined against a cobalt-60 standard. Under irradiation, LiF molecules are excited to a metastable state from which they can decay to ground when heat is applied. Decay is accompanied by light emission which can be detected with a photomultier circuit and integrated in an electrometer to obtain a quantity related to dose in a known way.

Before use, TLD powder was sifted and annealed to reduce background readings to a minimum. Background for three measurements made on unirradiated powder cassetts were:

<u>Dosimeter</u>	<u>Background Dose, R</u>
1	8.0
2	9.2
3	13.1
Mean	10.1

Twenty dosimeters were placed at various locations on the diode axis and about the exterior of the vacuum vessel, locations being those shown in Figure 7b. Of greatest interest were the units located in the diode, numbered 1 through 5 from left to right looking down on the diode from the machine. Dosimeters 1 and 5 were each 8-inches from the cathode centerline, 2 and 4 were 3-1/2 inches away (one left and one right), and number 3 was on axis and on centerline. Readings from these five dosimeters are summarized in Table XXI.

Dosimeters at the head and foot of the tank read essentially background, while those around the perimeter near the diode recorded about 6R. Distribution of dose on the axis was sharply peaked near the ends of the converter, and dose in these peaks far exceeded that estimated for the experiment. To test for the possibility that electrons might be penetrating to the LiF powder, dosimeters were housed inside an additional 0.0625 inches of aluminum on shot 3. This did not remove the peaks, but served to reduce dose everywhere along the axis by (roughly) a factor of 6. A shielding effect of this magnitude was unexpected, and implies that mean photon energy must have been relatively low. An estimate of average X-ray energy can be made by taking 0.062-inches as the 1/6th length and solving for the corresponding absorption coefficient in aluminum. The process is:

$$1/6 = e^{-\mu x}$$

$$\mu = \frac{1}{x} \ln 6$$

$$x = \text{wall thickness, equal to } 0.44 \text{ gm/cm}^2$$

$$\text{then } \mu = \frac{1.79}{.44} = 4.07 \frac{\text{cm}^2}{\text{gm}}$$

Figure 76 . Location of Dosimeters For FX-35
Bremsstrahlung Experiment

TABLE XXI.
SUMMARY OF TLD READINGS

TLD LOCATION	Dose, R		
	Shot 1	Shot 2	Shot * 3
1	70	-	12
2	22,900	68,000	14,200
3	1,570	2,780	420
4	122,000	116,000	20,400
5	250	1,660	25

* TLDS housed in 1/16" wall aluminum tubing.

Note: Background of 10R has been subtracted from readings to obtain tabulated values.

From energy absorbtion coefficients published by Hubbell⁽⁵¹⁾, this implies an X-ray energy of just under 20 keV. If this were the case, mean free path would reduce to about 1/15th of that used in arriving at the 3.3 kilorad mean dose estimated earlier, and this would have the effect of increasing dose by a factor of 15. An average dose of about 50 kilorads would then be expected.

Very roughly, an average dose over the converter length can be computed by spatially weighting readings from the 3 centermost dosimeters, or taking

$$D = \frac{1}{L} \sum d_i \ell_i$$

ℓ = length of converter each dosimeter is assumed to represent

d = dose

L = converter length, equal to 10-in.

Computing this average gives 48 krad for shot 1 and 61 krad for shot 2. These seem to be consistent with a low photon energy.

For photon experiments with FX-35 in planar geometry, it has been calculated that the photon spectrum from a converter with dimensions similar to those used here should peak near 150 keV and be essentially cut off by self absorbtion at the tantalum K edge (67 keV). For this reason it is surprising to find evidence for very low energy photons, although their presence would dramatically increase efficiency of bremsstrahlung crosslinking.

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APPENDIX A

A1.0 BLUE CELLOPHANE CALIBRATION DATA

A2.0 CALIMETRIC VERIFICATION OF BLUE
CELLOPHANE MSC 300 CALIBRATION CURVE

All dose measurements reported in this document were made colormetrically using DuPont MSC-300 blue cellophane. Use of color changes in dyes or aqueous solutions (colorimetry) as a means of determining radiation dose is a method of long standing. A number of systems have been employed for this purpose, including barium platinocyanide, mixtures of iodoform and chloroform, oxidation of ferric to ferrous compounds, reduction of ceric to cerous ions, liberation of free iodine from iodine compounds, and decolorization of methylene blue dye. These systems were described in detail as early as 1956 by Hine and Brownell⁽⁵²⁾, it is the last which is the active element in blue cellophane. Use and calibration of DuPont MSC-300 cellophane was first discussed by Henley and Richman⁽⁵³⁾ in 1956; MSC-300 was intensively studied as a diagnostic for high energy electrons by Ion Physics and others in the middle and late nineteen sixties. Graybill and Nablo⁽⁵⁴⁾ reviewed the status of blue cellophane as a diagnostic for pulsed electron beams in 1966; the following material has been excerpted from their report:

"A very useful method for the mapping of high intensity beams has been developed using dose sensitive DuPont MSC-300 blue cellophane film. The principle of operation was first discussed by Henley and Richman and consists of measuring the increase of transmission of light at the transmission minimum ($6550 \text{ \AA}^0$) due to the fading of the blue dye under irradiation. The method allows a complete map of the beam in a single pulse due to the negligible energy loss of a relativistic electron in traversing the 3.5 mg/cm^2 film, e.g., $\sim 6 \text{ keV}$ at 2 MeV .

One of the limitations of the technique results from inadequate data concerning rate and pressure effects on dye response. Two calibration curves recorded in air for the film are shown in Figure 77 and

Figure 77 Blue Cellophane Calibration Data

demonstrate an apparent rate sensitivity of the film, a problem which had not appeared to exist at levels up to at least 10^6 r/second. The upper calibration curve was recorded with the use of the AFCRL Co⁶⁰ facility at a fixed dose rate of 120 rads/second. The lower curve was recorded on the pulsed electron accelerator with single pulse irradiation ($T = 20 \times 10^{-9}$ secs) so that the rates varied from 10^{13} to 10^{15} rads per second. The delivered dose was calculated from the recorded temperature rise in a thin foil immediately behind the dosimeter. Readout of the film was normally accomplished with a Beckman Model DU Spectrophotometer. One comparative curve is shown in Figure 81, for the electron calibration of similar film at ~ 2 MeV reported by Henley and Richman taken at dose rates of $> 2 \times 10^5$ rads/second. No electron data appear to have been reported at rates much above 10^6 rads/sec.; hence, comparative data for the lower curve are not available. Charlesby and Woods⁽⁵⁵⁾ have demonstrated a linear density-dose relationship for similar film up to 30 megarads with a fall-off in response above this level due to depletion and eventual destruction of the dye."

Subsequent to this analysis, efforts were made at Ion Physics to obtain additional calibration data; using FX-35, staff members produced curves for irradiation in vacuum and in air which verified the lower curve of Figure 77 (Childers and Breen, 10^{-3} torr, 12/67; Braybill and Ames, atmospheric, 1/66). Oswald⁽⁵⁶⁾ duplicated these measurements and obtained similar results. A series of measurements were also made with a steady beam producing 10^4 rads/sec and a pulsed beam at 10^{14} rads/sec, 300 μ pressure. These appeared to show that there is no rate dependence up to 10^{14} rads/sec. In discussions held with Dr. Ari Brynjolfsson at the Army's Natick Laboratories during the summer of 1974

the extensive calibration work done there with MSC 300 and red perspex was described, and Brynjolfsson indicated that this work had showed no rate dependence.

In December of 1974, a calibration check was made on the cellophane dosimeter system then in use at IPC; this is the same system we are using to derive doses for the present work. It consists of reading the fractional changes in light transmission at 655 nm with an ICT-106 film reader manufactured by High Voltage Europa, an HVEC subsidiary. The calibration curve supplied with the instrument is used to convert from optical change to dose. It was shown that this approach produced absorbed energy measurements which are consistent with calorimetry.

A 2.0 Calimetric Verification of Blue Cellophane MSC 300 Calibration

The methods of determining the absorbed dose for plaques, tapes, and cables are discussed in Sections 2.3 and 3.3 of Part I. The MSC 300 cellophane is known to fade within proportional limits, depending upon the radiation it absorbs. The resultant increase of light transmission through the cellophane has been calibrated by optical densometer and related to dose in megarads. This method of dosimetry has been independently verified by comparison with calorimeter responses.

Temperature of a calorimeter which is simultaneously heated and cooled, can be found from the equation

$$\frac{d(mCT)}{dt} = S - kT \quad (1)$$

S = rate of heating, cal/sec

T = temperature

k = a bulk heat transfer coefficient describing the combined effects of radiation, convection, and conduction

m = calorimeter mass

c = heat capacity

The solution of (1) is:

$$T = \frac{S}{k} \left(1 - e^{-\frac{kt}{mc}} \right) \quad t < t_c \quad (2)$$

$$T = T(t_c) e^{-\frac{k(t - t_c)}{mc}} \quad t > t_c \quad (3)$$

where t_c is the cutoff time at which the source, S , is turned off. These equations say that calorimeter response should look like the sketch below, slope of the temperature rise near $t = 0$ being proportional to S/mc and cooling after the time t_c being controlled by k .

The loss coefficient k can be readily found from the cooling portion of the temperature-time curves.

The source S can be determined from calorimeter behavior during the period when t is less than t_c ; it is given by

$$S = mc\dot{T} \exp(kt/mc) \quad (4)$$

where

$\dot{T}$ = is the measured rate of temperature increase at t

If the term k/mc is small, then no correction is necessary. It turns out that this is the case with our calorimeter, so that

$$S = mc\dot{T} \frac{\text{cal}}{\text{sec}} \quad (5)$$

Because the calorimeter is monitoring a finite spot size and because cellophane gives total energy in areal units, it is useful to normalize this to energy per unit area.

Loss coefficient k was determined to be $k = 2.8 \times 10^{-3}$ cal/sec °C; linearity of the rising portion of the curves indicates this to be negligible.

Using a conversion of 25 °C/mV for chromel-alumel thermocouples, heating rates of 0.2 and 0.19 °C/sec were measured. Taking $\dot{T}$ as 0.2 °C/sec, then S is

$$S = mc\dot{T} = (2.4) (.203) (.2) = 0.1 \frac{\text{cal}}{\text{sec}}$$

Calorimeter area was 2.8 cm^2 , therefore the areal heating rate was $0.035 \text{ cal/cm}^2\text{-sec}$ or $0.15 \text{ joules/cm}^2\text{-sec}$. The cutoff time was recorded as 27 seconds and 100 pulses were counted; this corresponds to 3.7 pulses/sec.

Energy per pulse was therefore about $0.04 \frac{\text{joules}}{\text{cm}^2}$ | pulse.

Measurements were made with the following conditions:

1 mil Ti window
Hibachi #2
1-3/8-in. air
Variac at 220 VAC
No magnetic field
100 pulses

To use this data to check cellophane calibration, the depth-dose profile determined from thin film dosimetry can be integrated to give

$$J = \int_0^R D(x) dx \quad \frac{\text{joules}}{\text{cm}^2}$$

Here $D(x)$ is the dose profile, x is the mass depth, and R is range. At the time the calorimeter data were taken a comparison measurement was made with blue cellophane; conditions were:

1 mil Ti window
Hibachi #2
1-1/2-inches air
Variac at 220 VAC
No magnetic field
100 pulses
Cellophane read with ICT-106

Using the calibration curve published by HVE for the ICT-106, peak dose was about 13 megarads. Approximating the profile as linear and terminating it at a range equal to 18 layers (0.063 gm/cm^2) gave absorbed energy equal to

$$J = \left(\frac{1}{2} \right) \left(130 \frac{\text{joules}}{\text{gm}} \right) \left(0.063 \frac{\text{gm}}{\text{cm}^2} \right) = 4.1 \frac{\text{joules}}{\text{cm}^2} ,$$

This was the result of 100 pulses, so that energy per pulse was 0.041 joules/cm²; this figure is in good agreement with the calorimetric value.

Conclusion:

The HVE ICT-106 reader and accompanying calibration curve represent a self-consistent dosimetry system.

APPENDIX A

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APPENDIX B

- B1 CALCULATION OF CHARGING CIRCUIT EFFICIENCIES
 - B1.1 SIMPLE RESISTIVE CHARGING
 - B1.2 CHARGING VOLTAGE IN EQUAL STEPS
 - B1.3 CHARGING VOLTAGE IN EQUAL ENERGY PER STEP
 - B1.4 CHARGING VOLTAGE IS A LINEAR RAMP
- B2 ALTERNATE CHARGING CIRCUITS
 - B2.1 CIRCUIT CONFIGURATION
- B3 POWER SUPPLY SPECIFICATIONS

B.1 Calculation of Charging Circuit Efficiencies

B 1.1 Simple Resistive Charging

$$E_c \text{ at } t = 0 = E_0$$

$$i \text{ at } t = 0 = 0$$

$$i = \frac{E_b - E_0}{R} e^{-\frac{t}{RC}}$$

Let:

W_R = energy dissipated in R in a time period $0 \leq t \leq t_1$

W_A = energy added to C in a time period $0 \leq t \leq t_1$

W_S = energy removed from supply, E_b , in a time period $0 \leq t \leq t_1$

$$W_R = \int_0^{t_1} i^2 R dt = \frac{C}{2} (E_b - E_0)^2 \left(1 - e^{-\frac{2t}{RC}} \right)$$

$$W_A = \frac{C}{2} (E_c^2(t_1) - E_0^2)$$

$$E_c(t_1) = E_o + \frac{1}{C} \int_0^{t_1} i \, dt = E_o + \frac{1}{C} \int_0^{t_1} \frac{E_b - E_o}{R} e^{-\frac{t}{RC}} \, dt$$

$$= E_o + (E_b - E_o) \left(1 - e^{-\frac{t_1}{RC}} \right)$$

$$W_A = \frac{C}{2} \left[2 E_o (E_b - E_o) \left(1 - e^{-\frac{t_1}{RC}} \right) + (E_b - E_o)^2 \left(1 - e^{-\frac{t_1}{RC}} \right)^2 \right]$$

$$W_S = \int_0^{t_1} E_b i \, dt = E_b \int_0^{t_1} \frac{E_b - E_o}{R} e^{-\frac{t}{RC}} \, dt$$

$$= C E_b (E_b - E_o) \left(1 - e^{-\frac{t_1}{RC}} \right)$$

$$W_A + W_R = C E_b (E_b - E_o) \left(1 - e^{-\frac{t_1}{RC}} \right) = W_S \text{ as it should}$$

$$\text{efficiency of charge} = \eta = \frac{W_A}{W_S}$$

$$\eta = \frac{\frac{C}{2} (E_b - E_o) \left[2 E_o \left(1 - e^{-\frac{t_1}{RC}} \right) + (E_b - E_o) \left(1 - e^{-\frac{t_1}{RC}} \right)^2 \right]}{C E_b (E_b - E_o) \left(1 - e^{-\frac{t_1}{RC}} \right)}$$

$$\eta = \frac{E_o + E_b}{2 E_b} \left(1 - e^{-\frac{t_1}{RC}} \right)$$

for $t_1 \gg RC$

$$\eta = \frac{E_o + E_b}{2 E_b}$$

This is within 2% for $t_1 \geq 4 RC$ and within .3% for $t_1 \geq 6 RC$

if η is to be	60%	70%	80%	90%
then $\frac{E_b}{E_o}$ must be	5	2.5	1.67	1.25

assuming $t_1 \gg RC$

And in the common case of resistive charging over many time constants with zero starting voltage on the capacitor:

$$t_1 \gg RC$$

$$E_o = 0$$

So

$$\eta = \frac{E_b}{2 E_b} = 50\%$$

B 1.2 Charging Voltage

E_b applied in N
Equal steps

- N equal steps
- $E_b(t) = 0, E_1, E_2, E_3 \dots E$
- each step is $\frac{E_b}{N}$ volts
- assume the time each step voltage is applied is equal and that time $\gg RC$

if $N = 1$, the simple case,

$$W_R = \frac{C E_b^2}{2}$$

if $N = 2$,

$$W_R = \frac{C}{2} \left(\frac{E_b}{2} \right)^2 + \frac{C}{2} \left(E_b - \frac{E_b}{2} \right)^2 = C \frac{E_b^2}{4}$$

if $N = 3$,

$$W_R = \frac{C}{2} \left[\left(\frac{E_b}{3} \right)^2 + \left(\frac{2 E_b}{3} - \frac{E_b}{3} \right)^2 + \left(E_b - \frac{2 E_b}{3} \right)^2 \right] = \frac{C E_b^2}{6}$$

if $N = N$,

$$W_R = \frac{C}{2} \left[\left(\frac{E_b}{N} \right)^2 + \left(\frac{2 E_b - E_b}{N} \right)^2 + \left(\frac{3 E_b - 2 E_b}{N} \right)^2 + \dots + \left(\frac{N E_b - (N-1) E_b}{N} \right)^2 \right]$$

or

$$W_R = \frac{C E_b^2}{2 N}$$

and

$$\frac{W_R (N = N)}{W_R (N = 1)} = \frac{1}{N}$$

and

$$W_R (N = 1) = W_C$$

so

$$W_R (N = N) = \frac{1}{N} W_C$$

for N equal steps where each step time is $\gg RC$

$$\eta = \frac{W_C}{W_C + W_R (N = N)} = \frac{W_C}{W_C + \frac{W_C}{N}} = \frac{1}{1 + \frac{1}{N}} = \frac{N}{N + 1}$$

if the number of voltage step is	1	2	3	7	15
then the charging efficiency is	50%	67%	75%	87%	94%

So with supply voltage steps it is possible to increase the efficiency of resistive charging.

B 1.3 Charging Voltage

E_b applied in N steps
Equal energy per step

- charging is resistive with voltage applied in steps
- each step is of equal duration
- the voltage increment of each step is such that energy added to the capacitor is equal in each step.

The voltage increment of the i^{th} step is $\sqrt{\frac{i}{N}} E_b$

$$W_R = \frac{C E_b^2}{2} \left[\left(\sqrt{\frac{1}{N}} \right)^2 + \left(\sqrt{\frac{2}{N}} - \sqrt{\frac{1}{N}} \right)^2 \right. \\ \left. + \left(\sqrt{\frac{3}{N}} - \sqrt{\frac{2}{N}} \right)^2 + \dots + \left(\sqrt{\frac{N}{N}} - \sqrt{\frac{N-1}{N}} \right)^2 \right]$$

$$= \frac{C E_b^2}{2} \sum_{i=1}^N \left(\sqrt{\frac{i}{N}} - \sqrt{\frac{i-1}{N}} \right)^2$$

$$\left(\sqrt{\frac{i}{N}} - \sqrt{\frac{i-1}{N}} \right)^2 = \frac{i}{N} - 2 \sqrt{\frac{i(i-1)}{N^2}} + \frac{i-1}{N}$$

$$= \frac{2i-1}{N} - 2 \frac{\sqrt{i(i-1)}}{N} \quad \text{and} \quad \sum_{i=1}^N \frac{2i-1}{N} = N$$

$$W_R = \frac{C E_b^2}{2} \left[N - \frac{2}{N} \sum_{i=1}^N \sqrt{i^2 - i} \right]$$

$$W_R (N=1) = \frac{C E_b^2}{2}$$

$$\frac{W_R (N=N)}{W_R (N=1)} = N - \frac{2}{N} \sum_{i=1}^N \sqrt{i^2 - i}$$

$$W_R (N = 1) = W_C$$

$$\eta = \frac{W_C}{W_C + W_R (N = N)} = \frac{1}{1 + \frac{W_R (N = N)}{W_R (N = 1)}}$$

$$\eta = \frac{1}{1 + N - \frac{2}{N} \sum_{i=1}^N \sqrt{i^2 - i}}$$

if N is	1	2	3	4	5	6	7	10	15
then η is	50%	63%	70%	75%	78%	81%	83%	86%	90%

This is the efficiency of resistive charging where the voltage is applied in N steps, the duration of all steps is equal and is much greater than RC , and the voltage of each step is such that the energy added to the capacitor in all steps is equal.

B 1.4 Charging Voltage is a Linear Ramp

- $v_b(t) = E_b \frac{t}{a} \quad 0 \leq t \leq a$
- $v_b(t)$ is a linear ramp of duration 'a' seconds

$$i = \frac{1}{R} (v_b(t) - E_c(t)) \quad E_c(t) = \frac{1}{C} \int_0^t i \, dt$$

$$\frac{di}{dt} + \frac{1}{CR} i = \frac{E_b}{aR}$$

this is a linear differential equation of the first order and has the solution:

$$i(t) = \frac{E_b C}{a} \left(1 - e^{-\frac{t}{RC}} \right)$$

$$W_R = \int_0^a i^2 R \, dt = \frac{R E_b^2 C^2}{a^2} \int_0^a \left(1 - 2e^{-\frac{t}{RC}} \right.$$

$$\left. + e^{-\frac{2t}{RC}} \right) dt$$

$$W_R = \frac{R E_b^2 C^2}{a^2} \left[a - 2RC \left(1 - e^{-\frac{a}{RC}} \right) \right.$$

$$\left. + \frac{RC}{2} \left(1 - e^{-\frac{2a}{RC}} \right) \right]$$

$$W_S = \int_0^a E_b(t) i(t) \, dt = \frac{E_b^2 C}{a^2} \int_0^a t \left(1 - e^{-\frac{t}{RC}} \right) dt$$

$$W_S = \frac{E_b^2 C}{a^2} \left[\frac{a^2}{2} + e^{-\frac{a}{RC}} (R^2 C^2 + RCa) - R^2 C^2 \right]$$

$$E_c(a) = \frac{1}{C} \int_0^a i \, dt = E_b \left[1 - \frac{RC}{a} \left(1 - e^{-\frac{a}{RC}} \right) \right]$$

$$W_A = \frac{C}{2} E_c^2(a) = \frac{E_b^2 C}{2} \left[1 - \frac{2RC}{a} \left(1 - e^{-\frac{a}{RC}} \right) + \frac{R^2 C^2}{a^2} \left(1 - 2e^{-\frac{a}{RC}} + e^{-\frac{2a}{RC}} \right) \right]$$

$$\eta = \frac{W_a}{W_S} = \frac{\frac{1}{2} - \frac{RC}{a} \left(1 - e^{-\frac{a}{RC}} \right) + \frac{R^2 C^2}{2a^2} \left(1 - 2e^{-\frac{a}{RC}} + e^{-\frac{2a}{RC}} \right)}{\frac{1}{2} - \frac{R^2 C^2}{a^2} \left(1 - e^{-\frac{a}{RC}} \right) + \frac{RC}{a} \left(e^{-\frac{a}{RC}} \right)}$$

$$\eta = 1 - \frac{1 + 2 \left(1 - e^{-\frac{a}{RC}} \right)^{-1} + \frac{2a}{RC} \left(1 - e^{-\frac{a}{RC}} \right)^{-2}}{1 + \frac{2a}{RC} \left(1 - e^{-\frac{a}{RC}} \right)^{-1} + \frac{a^2}{R^2 C^2} \left(1 - e^{-\frac{a}{RC}} \right)^{-2}}$$

$$\eta \approx 1 - \frac{RC}{a} \quad \text{for } a \gg RC$$

power from supply

$$v_b(t) i(t) = \frac{E_b^2 C}{a^2} t \left(1 - e^{-\frac{t}{RC}} \right)$$

for

$$t \gg RC = \frac{E_b^2 C}{a^2} t$$

power is essentially a linear ramp in time.

B 2 ALTERNATE CHARGING CIRCUITS

B 2.1 Circuit Configurations

Perhaps the simplest charging system would use a constant voltage DC supply and resistive current limiting. The circuit is shown in Figure 78 it suffers from poor efficiency and uneven power line draw. The efficiency is 50 percent as much power is dissipated as heat in the resistor as is delivered to the capacitor. This circuit is widely used in single shot machines and low power equipment where simplicity is important and efficiency is not. An interesting application in certain types of high power equipment occurs when some part of the associated manufacturing process must be heated, and energy dissipated in the charging resistor is used for process heat.

Resistive charging can be improved upon by varying voltage of the DC supply during the charge cycle. If supply voltage is low at the start of the cycle, when capacitor voltage is low, and if it is then increased either continuously or in steps as the capacitor charges, efficiency can be improved significantly. With three discrete steps in power supply voltage, efficiency is improved from 50 percent to 75 percent, and with seven steps, 87 percent. As the number of steps increases, voltage approaches a smooth ramp and efficiency can be made very high. If the steps or ramp are selected correctly (decreasing step amplitude or ramp rate of rise as the capacitor charges) power line draw can be made approximately constant.

Inductive charging is commonly used to charge capacitors in repetitively pulsed equipment such as radar, pulsed communications transmitters, and loran transmitters. A simplified diagram of an inductive charging circuit is shown in Figure 79. Charging current is limited by an inductor. Efficiency can be nearly 100 percent because the inductor does not dissipate energy; it stores it in the first part of the charge cycle and delivers it to the capacitor later in the cycle.

The size of the inductor to charge a 48 microfarad bank can be estimated in the following manner: the resonant frequency of L and C is selected to be half the pulsing rate, so that C reaches peak voltage just at the time when

Figure 78. Resistive Charging.

Figure 79 Inductive Charging.

it is desired to erect the Marx.

The requirement is

$$\frac{1}{2} f = \frac{1}{2\pi \sqrt{LC}}$$

where f is the pulsing frequency of the machine; then

$$L = \frac{1}{C\pi^2 f^2}$$

$$C = 120 \times .4 \times 10^{-6} \text{ farads}$$

$$f = 2 \text{ pulses per second}$$

$$L = 528 \text{ Henries}$$

At peak charging current the inductor stores 0.25 times as much energy as will be in the capacitor at full charge. This is equal to:

$$\begin{aligned} \text{peak energy in inductor} &= .25 \times 86.4 \text{ kilojoules} \\ &= 21.6 \text{ kilojoules} \end{aligned}$$

A rough estimate of the physical size of the inductor can be made using the empirical relationship between inductor stored energy and volt-amp equivalent.

$$\begin{aligned} \text{VA (equiv)} &= 94 \times \text{energy in joules} \\ &= 8.12 \times 10^6 \text{ volt-amps} \end{aligned}$$

A 60 Hertz transformer of 8 MVA capacity would weigh about 11 tons or 10,000 kilograms. It was concluded that inductive charging might be possible but, due to the large size of the inductor, it is not so attractive as other charging systems. It is the large stored energy of the Marx which makes the inductor so large; physical size is determined

only by the final energy stored in the capacitance and not by repetition rate.

A third charging system, introduction of impedance in the power supply primary, should be considered. Here, impedance in the AC primary of the power supply transformer limits charging current to the capacitor bank. If the impedance is purely resistive, the system is essentially the same as simple resistive charging as shown in Figure 78 and efficiency is about 50 percent. An inductive impedance, however is not the same as the inductive charging shown in Figure 79. Placed in the primary, the inductance limits AC current into the rectifier transformer, thereby limiting current charging the Marx. A simple schematic is shown in Figure 80. The necessary inductance can be estimated in the following way. The capacitors are receiving 173 kilowatts; if 480 volt three phase power is assumed at 200 kVA, the average AC line current is:

$$\begin{aligned}\text{average line current} &= \frac{\text{kVA}}{\sqrt{3} \text{ V}} \\ &= \frac{200}{\sqrt{3} \times .48} \\ &= 240 \text{ amps average}\end{aligned}$$

Requiring the inductive reactance to limit peak current to 3 times average, the inductor is:

Figure 80 Inductive Current Limit in the Primary.

$$\begin{aligned}
 L &= \frac{V}{I \omega} \\
 &= \frac{480}{3 \times 240 \times 2 \pi \times 60} \\
 &= 1.77 \text{ millihenries}
 \end{aligned}$$

Peak energy in an inductor is:

$$\begin{aligned}
 E &= \frac{1}{2} L i^2 \\
 &= .5 \times 1.77 \times 10^{-3} \times (3 \times 240 \times \sqrt{2})^2 \\
 &= 918 \text{ joules}
 \end{aligned}$$

This is much less than the 21.6 kilojoules stored in the inductor used in the circuit of Figure 79. Disadvantages of this approach are that the inductor is quite large and three of them would be required, (one for each phase), the creation of a poor and time varying power factor, and uneven power draw from the power service.

Some general considerations of Marx charging have been discussed above. To summarize, simple resistive charging from a constant voltage supply results in poor efficiency and presents the problem of dissipating waste heat. Resonant charging requires an inductor which is impractically large. Constant voltage charging with resistors in the supply primary results in the same poor efficiency as the simple resistive approach, and charging with inductors in the primary results in large components, poor power factor, and uneven

power draw. Voltage ramps or sequences of steps can improve efficiency of the resistive charging scheme, and if the rate of rise of the ramp is correctly contoured over the charge time, a nearly constant power draw is possible. Voltage ramp is the most desirable of the several possible charging circuits from the standpoint of efficiency. It requires, however, a complex and probably expensive control circuit whose reliability becomes a factor in making the final tradeoff in selecting a charging supply.

Several of the most common methods of generating a voltage ramp or sequence could not be applied to the present machine.

Some accelerators and thermonuclear research facilities use vacuum triodes or tetrodes between the power supply and capacitor bank. With vacuum tubes it is possible to control charging rate at any point in the charge cycle, and even to stop it if desired. The tubes, however, are no more efficient than simple resistive charging, and require fairly complex controls. Other banks are charged with electromechanical motor-driven variable auto transformers or relay step switches in the power supply primary. Clearly, electromechanical control is not feasible for the short charging time and high power level required for this project.

Voltage control in the primary, either ramp or in steps, can be achieved with silicon controlled rectifiers. A phase angle firing circuit can be adjusted to provide a charge voltage ramp to approximate constant power charge. A schematic of the SCR phase control ramp

generator is shown in Figure 81. Phase control by SCR is used in industrial motor speed control and process temperature regulation at power levels much higher than needed here. The power factor varies significantly with the phase angle of firing, and the design must provide for conducted and radiated RFI reduction and for power line harmonic currents. A second SCR type of voltage control is transformer tap changing as shown in Figure 82. Only one set of SCR's is on at a time, and they can be switched at zero voltage points to minimize RFI and power line harmonic currents. The tap changing SCR configuration is electrically less noisy than phase angle control, but it requires many more pairs of SCR's and extra transformer capability.

Figure 81 Circuit Configuration, Phase Control
Ramp Generator.

Figure 82. Circuit Configuration, Tap Changing SCR Generator.

GENERAL

This is a statement of requirements for a power supply. The two balanced outputs are used to simultaneously charge two identical capacitor banks with a common grounded terminal. Because the supply is used to charge a capacitor which is discharged at regular intervals, the supply output current is constantly changing in a repetitive cycle.

ELECTRICALOUTPUT

Voltage: + and - 65 kV about ground

Voltage Variation: Some means for reducing output voltage is required.

Continuous variation is not required. Transformer taps which are manually changed is an adequate way to change the output voltage, because voltage change will not be frequent. The output voltages which are desirable are + and - 65 kV, 59 kV, 54 kV, 48 kV, 43 kV, and 32 kV. The exact voltage of each tap is not important so long as range from full to half voltage is covered.

Current: The output current varies in a cycle which repeats each half second. See Figure 83. The maximum value of output current is 8 amps, the average is 2.9 amps, and RMS over the half second cycle is 3.5 amps.

Regulation: Additional impedance will be added to the circuit to limit peak current, so power supply load regulation is not important.

Ripple: Since the power supply is being used to charge a large capacitance, output ripple level is not important.

INPUT

The input is 480 volts line to line, 3 phase. The auto-transformer used for

changing input voltage should be located in a NEMA 1 enclosure separate from the power supply oil tank.

METERING

Resistors are to be included for measuring **voltage**. The total variation in monitor resistance due to temperature, voltage, and 1000 hour aging should be less than 3%.

CURRENT LIMITING

Since the supply is used to charge a large capacitance on a repetitive cycle, it is subjected to a near short circuit at the beginning of each cycle when the capacitor voltage is nearly zero. Impedance will be placed both in the primary ac lines and in the power supply output to limit the maximum peak current to 8 amps. The limiting impedance is not a part of the power supply.

Figure 83. OUTPUT CURRENT

FIGURE 84. CIRCUIT USE

APPENDIX C

SELECTION OF ISOLATION COMPONENT VALUES

In the pages which follow, results of circuit calculations which led to the component values quoted in section 3.5.4 are discussed. These computations were made under certain assumptions concerning Marx erection time and allowable energy droop due to bleed down through isolation and charge impedances while charging. During erection, stages which fire first begin to discharge through their isolation resistance before the remainder of the Marx can be erected. Isolation components must be chosen to limit this energy loss, but an estimate of erection time is required to allow component specifications. By analogy with Aurora,* erection time has been assumed to be $1\mu\text{sec}$, although it is anticipated that it may be faster. Allowable energy droop due to charge circuit loading has been set at a design goal of 1 percent; this would result in a voltage drop of 0.5 percent in $1\mu\text{sec}$. A final assumption has been to neglect trigger resistances between stages. In practice, their effect will be to add a small additional loading.

*Aurora is an 11 mV, 5 megajoule flash x-ray machine operated by the Harry Diamond Laboratories at White Oak, Md. The Aurora energy store consists of four parallel Marx generators, each having 95 stages and physical dimensions roughly similar to the Marx which will be used in this program. For details on Aurora see: Bernstein and Smith, "Aurora, an Electron Accelerator", IEEE Trans. Nuclear Science, NS-20, June 1973, p. 294.

One stack of the erected Marx is shown in sketch below.

In the following calculations, end conditions have been neglected and central portions of the Marx have been considered. Because each resistor bridges four capacitors, the apparent load on one capacitor due to one resistor is $R/4$, but each capacitor is bridged by six resistors. Apparent load on any capacitor is therefore $R/24$. If each impedance is actually a resistance in series with an inductance, the apparent loading on each capacitor will be that shown below,

where L and R are actual values of components in the Marx stack.

To find values of L and R we next consider several conditions.

(1) Impedance is a Pure Resistance.

In this case L equals zero and a charged capacitor will decay in voltage according to

$$V = V_o e^{-\frac{t}{RC}},$$

For 0.5 percent droop in 1 μ sec, the time constant must equal 2×10^{-4} seconds. Using a capacity of .4 μ f gives an apparent R equal to 500 Ω . The required value is 24 times this, or 12 k Ω .

(2) Impedance is a Pure Inductance

While this would be a very undesirable design, it has been explored to obtain a feeling for inductor size. For a pure inductance, voltage will oscillate as

$$V = V_0 \cos wt$$

$$\text{with } w = \frac{1}{\sqrt{L C}} \text{ and } L = \frac{1}{w^2 C}$$

For a droop of 0.5 percent, $\cos wt = .995$; using the fact that wt is small, this can be written as

$$\frac{w^2 t}{2} = .005 ,$$

hence w^2 equals 10^4 and apparent inductance is 0.25 mH. Inductance, L, would have to be 24 times this, or 6 mH. A 6 mH inductor wound as a single layer of close spaced number 28 wire could be made about 0.75-inch diameter by 4-inches long.

(3) Ratio of r and ℓ Chosen Such That Damping is Much Greater Than Critical ($\frac{\ell}{r^2 C} = .01$)

In this case V/V_0 is given by

$$\frac{V}{V_1} = \left(\frac{\ell}{r^2 C} \right) \left(1 - \exp \left(-\frac{rt}{\ell} \right) \right) + \exp \left(-\frac{t}{rc} \right) .$$

Specifying 0.5 percent droop in 1 μ sec and solving for rc gives $rc = 0.8 \times 10^{-4}$ sec, hence r equals 200 Ω . Component resistors must then have values of 4.8 k Ω . Using $\ell = 0.01 r^2 C$ gives an ℓ of 1.6×10^{-4} , hence

inductors required would have to be 3.8 mH.

- (4) Ratio of r and l Chosen Such That Damping is About Ten Times Critical ($\frac{l}{r^2 C} = 0.1$)

In this case r and l are found to be 75Ω and .225 mH respectively, implying component values of $1.8 k\Omega$ and 5.4 mH.

Next consider power dissipated in the isolation components during charging and output. When charging, the Marx circuit can be represented by the sketch below.

There are two such units in each module and twenty in the machine overall. Because essentially no current flows through the grounding resistors, the circuit can be simplified to

Here R' is an external resistor which limits charging current. For operation at 2 hz, R' would be about $104 k\Omega$. Power dissipated in this and in the three isolation resistors is equal to $\frac{f}{2} CV^2$, where f is the pulsing rate. At 2 hz this amounts to 1.44 kw. Bulk of this is lost in R ; if R is set to $12 k\Omega$, then power lost in the R 's (reading from left to right in the sketch above) would be 173, 77, and 19 watts respectively. In the Marx as a whole, about

5.4 kw would be dissipated in the isolation resistors as charging losses.

To estimate losses during discharge, we assume that erection of the Marx will result in a square wave applied to R, having peak voltage of 240 kV and duration of 1μsec. Power dissipated in an isolation resistor will be

$$P = VItf = \frac{V^2 tf}{R}$$

where V is peak voltage, t pulse duration, and f pulse frequency. For a 12 kΩ resistor, this amounts to about 10 watts. Accordingly, overall losses (sum of charging and output) would be 183 watts per resistor at 12 kΩ in the worst case location. For smaller resistances, losses would be correspondingly less.

Table C-1 summarizes results of the above paragraphs, listing combinations of isolation components which would result in one percent energy loss in one μsec.

TABLE C-1

Combination of Isolation Components Giving One Percent Energy
Loss in One μsec

	R	L	Watts in "Top" R at 2 pps
	12 K	0	183
damping ~100x critical	4.8K	3.84 mH	70
damping ~10x critical	1.8K	5.4 mH	36
no damping	0	6 mH	

Attention is now turned to specifying isolation between modules.

When the Marx is erected it is in the configuration shown below

The task is to choose isolation inductors. If they are too small they will discharge the erected Marx quickly and if they are too large they will not fit in the tank.

For a normal pulse the Marx is erected for about 2 μsec and an isolation L of about 8 mH is adequate.

Should the output switch fail to close, however, a much larger inductance is required. Voltage will be present across the inductance until the energy is dissipated by the charging resistors in the stacks. To limit current in the isolation inductance and to keep most of the 1.8 megavolt stack to stack voltage off the top charge resistors, time constant of the inductor-charge resistor combination must be long relative to the self decay time of the Marx as it bleeds down. If the stacks are charged through a series combination of 4.8 k Ω resistors and 3.8 mH inductors, then the Marx will decay to about 90 percent of full voltage in 10 μsec and 30 percent in 100 μsec .

The stack-to-stack isolation circuit will look like the following sketch.

L_i = isolation inductance
stack to stack

There are actually 3 across $C/24$ in addition to the internal discharge circuit.

It is desired to choose L_i so that voltage over R never exceeds the 240 kV voltage for which the resistors are designed. If L_i is sized to provide critical damping, a value of 96 mH would be necessary. At critical damping, current will be given by

$$i = \frac{E_o t}{L_i} \exp \left(-\frac{Rt}{2 L_i} \right), \quad E_o = 1.8 \text{ MV}.$$

In fact, E_o is not constant, but decays with time as the Marx bleeds through the charging resistors and isolation inductors on the other two buses.

To hold voltage over the resistors below 240 kV, current should be limited to 100 amps; with constant E_o , current would rise in the following manner:

Time, μsec	Current, amps
1	16
10	146
100	227

If voltage decay were considered, these figures would have to be lowered, hence it is concluded that 96 mH isolation inductance is approximately the value required.

Isolation inductance could be reduced, if necessary, by electing to provide intrastack isolation with the series combination of $1.8\text{ k}\Omega$ and 5.4 mH . This would result in faster Marx decay should a misfire occur.

APPENDIX D

ENERGY DISSIPATED IN A FAULTED CAPACITOR

To show that energy dissipated in a faulted main bank capacitor will be equal to or less than

$$\left(1 + \frac{n r}{R} \right),$$

consider that the charging configuration to be used for each polarity is that shown in Figure 85a ; this can be approximated with the uniform ladder

Figure 85 Faulting Capacitor Energy Limiting.

Figure 86 Equivalent Circuit for Faulted Capacitor String

shown in Fig .85b. For a stack consisting of three capacitors with a fault developing in the central capacitor, the equivalent circuit will be that drawn in Figure 86. In this case the governing equations are

$$\frac{Q_1}{C} - 2R\dot{Q}_1 - r(\dot{Q}_1 + \dot{Q}_2) = 0$$

$$\frac{Q_2}{C} - 2R\dot{Q}_2 - r(\dot{Q}_1 + \dot{Q}_2) = 0$$

Symmetry of the problem requires that i_1 and i_2 ($\dot{Q}_1$ and $\dot{Q}_2$) be equal, so that

$$\frac{Q_1}{C} - 2(R+r)\dot{Q}_1 = 0$$

Subject to the initial condition that the fault develops when C_1 and C_2 are fully charged, the solution to this equation is

$$\dot{Q}_1 = i_1 = \frac{V}{2(R+r)} e^{-\frac{t}{2C(R+r)}}$$

Energy dissipated in the faulted unit is then

$$U = \int_0^{\infty} i^2 r dt = \int_0^{\infty} (2i)^2 r dt$$

Integrating gives

$$U = \frac{CV^2}{2} \left(\frac{2r}{R+r} \right)$$

showing that energy lost into the fault is equal to that stored in one capacitor multiplied by the factor $\frac{nr}{R+r}$. If the fault resistance is small compared to R , then

$$\frac{nr}{R+r} \approx \frac{nr}{R}.$$

It can be shown by analysis of larger networks that the multiplier will actually be less than nr/R , becoming smaller as n increases.

To this point we have calculated energy developed at the fault site when capacitors external to it discharge through the suddenly reduced resistance. In the worst case, the fault will occur in a fully charged unit and it must be assumed that this energy too will be internally dissipated. If this is the case, then energy deposited in the failed capacitor will be

$$U = \frac{CV^2}{2} \left(1 + \frac{nr}{R} \right).$$