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A STUDY OF POWER AND ENERGY IN THE AURORA MODIFICATION PROJECT. (U)
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report summarizes the results of a series of computer runs at NRL which were designed to determine if the measured loss of power and energy in the Aurora Modification Project tests in the Fall of 1978 was due to increasing capacitance in the water switches during the transit times of the streamers or was due to resistive losses in the water switches. From the results of these analyses, it is concluded that the losses were mainly due to resistance in the intermediate store and pulse forming liner output switches and that the changing switch (Continues)		

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20. Abstract (Continued)

capacitance mainly rounded the pulse shapes near the peak values without contributing to a major loss of energy.

It is suggested that oil switches be considered as a replacement for the water switches since they have less loss, although there are risks and problems involved in their use.



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A STUDY OF POWER AND ENERGY
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THE AURORA MODIFICATION PROJECT

This report is a sequel to the "Report on the NRL Transient Analysis of the Physics International Design for the AURORA Modification" by John D. Shipman, Jr. in 1977 which predicted that the most probable output of the proposed AURORA Modification Project (AMP) would be limited by water switch losses to 8.25 TW and 0.75 MJ.

When the machine was built and tests completed in the Fall of 1978 the output was well below the above prediction but at that time the loss was attributed by Physics International (PI) to the large increasing capacitances of the water switches during the transit times of the water switch streamers, rather than due to losses in the series water switch resistances.

The aforementioned NRL report did not consider the effect of these changing switch capacitances so the NRL Transmission Line Analysis computer program was modified so that changing capacitance in the water switches could be modeled as follows: The capacitance of a switch region remains constant up to the time that streamers are assumed to start. From that time, until the time of closure, the parallel plates of the capacitor representing the surfaces containing

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the tips of the streamers in the switch region are programmed to move together at constant velocity until they touch, shorting out the switch. In modifying the program to provide this feature it was important to insure that the act of moving the plates together did not pump anomalous energy into the system, and this requirement was met.

The transmission line circuit for the AMP system used in the computer analyses of this report is shown in Figure 1. This circuit differs slightly from the one in the first report to reflect some changes in the Physics International design between May 12, 1977 and the final design configuration in the April through June 1978 Quarterly Progress Report. The line elements were also adjusted slightly to make the ends of transmission line elements coincide with the locations of the physical voltmeters on the system so that the calculated voltage waveforms from the computer program could be compared directly with the experimental data.

Several computer runs were made in which the initial water switch capacitance values, streamer transit times, and series resistances of the water switches were varied until the computed voltage pulses agreed closely with the experimentally measured pulses of AMP Shot No. 149 on 18 September 1978. This was one of the most powerful shots with a charge voltage of 115 kV per stage of the Marx Generator, an intermediate store (IS) switch spacing of 89 cm, a pulse forming line (PFL) output switch spacing of 42 cm and a water prepulse switch spacing of 8.5 cm. The conditions for the closest fit between

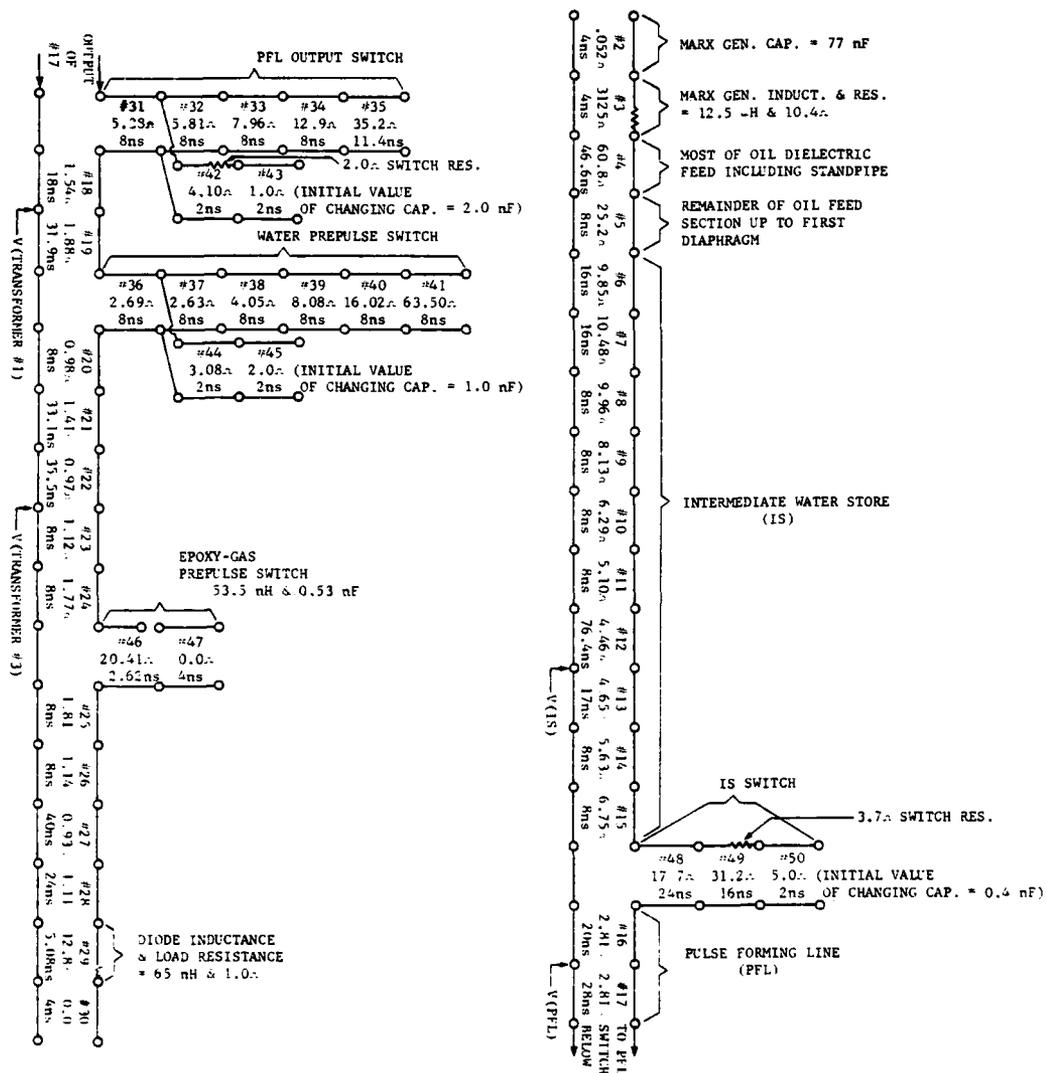


Fig. 1 - Circuit of the pulse power generator in terms of transmission line elements

computed and experimental data are shown in Figure 2. A value of 10.4 ohms of series resistance in the Marx generator was required to make the computed and measured intermediate store peak voltages agree. This resistance remained constant in all of the computer runs of this report. The IS switch required 3.7 ohms with this switch capacitance varying from 0.4 nF to ∞ nF in 448 ns transit time. The PFL switch required 2 Ω with this switch capacitance varying from 2 nF to ∞ nF in 144 ns transit time. No resistance was required in the water pre-pulse switch with this switch capacitance varying from 1 nF to ∞ nF in 110 ns transit time.

The above transit times, required to get a "best fit", are longer than was expected. In the Atomic Weapons Research Establishment (AWRE) Report SSWA/JCM/704/49 entitled "Nanosecond Pulse Techniques" by J. C. Martin, he states that, for voltages in the 1 MV to 5 MV range, streamers from both the positive and negative switch electrodes in oil and water obey a velocity formula,

$$\bar{U}_{\pm} = \frac{KV^{1.6}}{d^{\frac{1}{2}}}$$

where \bar{U}_{\pm} is the mean velocity for positive or negative streamers in cm/ μ sec,

V is the max voltage across the switch in MV,

d is the switch electrode spacing in cm, and

K is a constant equal to 80 for oil and a lower value for water, but data is lacking for water.

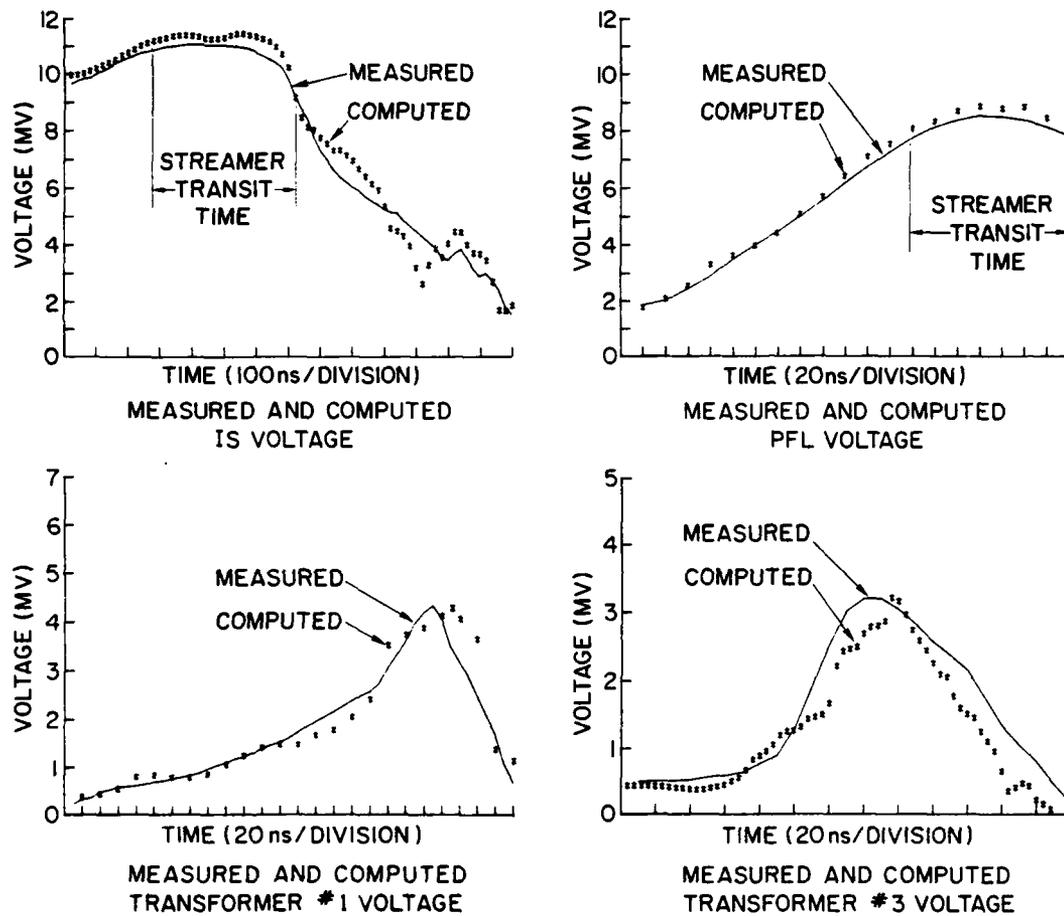


Fig. 2 - The above voltage pulse shapes show the "Best Fit" comparison between computed and measured data on shot #149. The switch conditions for the above data were as follows:

- IS switch: 0.4 nF to ∞ nF in 448 ns, 3.7 Ω
- PFL switch: 2.0 nF to ∞ nF in 144 ns, 2.0 Ω
- Water prepulse switch: 1.0 nF to ∞ nF in 110 ns, 0.0 Ω

using the "best fit" transit times for the IS and PFL water switches in AMP, one can calculate K values of ~ 9 and ~ 18 but this is an inaccurate method of determining K. Although the AMP voltages are higher than 5 MV, this formula was applied with $K = 80$ to the AMP switches (in order to calculate the shortest transit time) resulting in transit times of 80 ns in the IS switch, 66 ns in the PFL switch and 26 ns in the water prepulse switch.

A computer run was made using these transit times to determine the sensitivity of the voltage pulse shapes to the transit times used. The results are shown in Figure 3. The effect on the pulse shapes on the IS and PFL are noticeable but not dramatic, whereas the changes on the transformer #1 and #3 pulses are hardly detectable.

To show the dominant effect of series switch resistance in the IS and PFL output switches on the voltage pulses, a computer run was made with everything the same as the optimum run except that the series resistance in the IS switch was reduced from 3.7 to 0 ohms, and that in the PFL output switch from 2.0 to 0 ohms. The results are shown in Figure 4. The plot of the IS computed voltage drops well below the experimental shape after switch closure. The computed PFL voltage peak is 28% higher than the measured value. The peak of the transformer #1 computed voltage is 49% higher than the measured value and the same is true of the transformer #3 voltage.

In order to determine if changing water switch capacitance could possibly explain the measured loss of power and energy if the

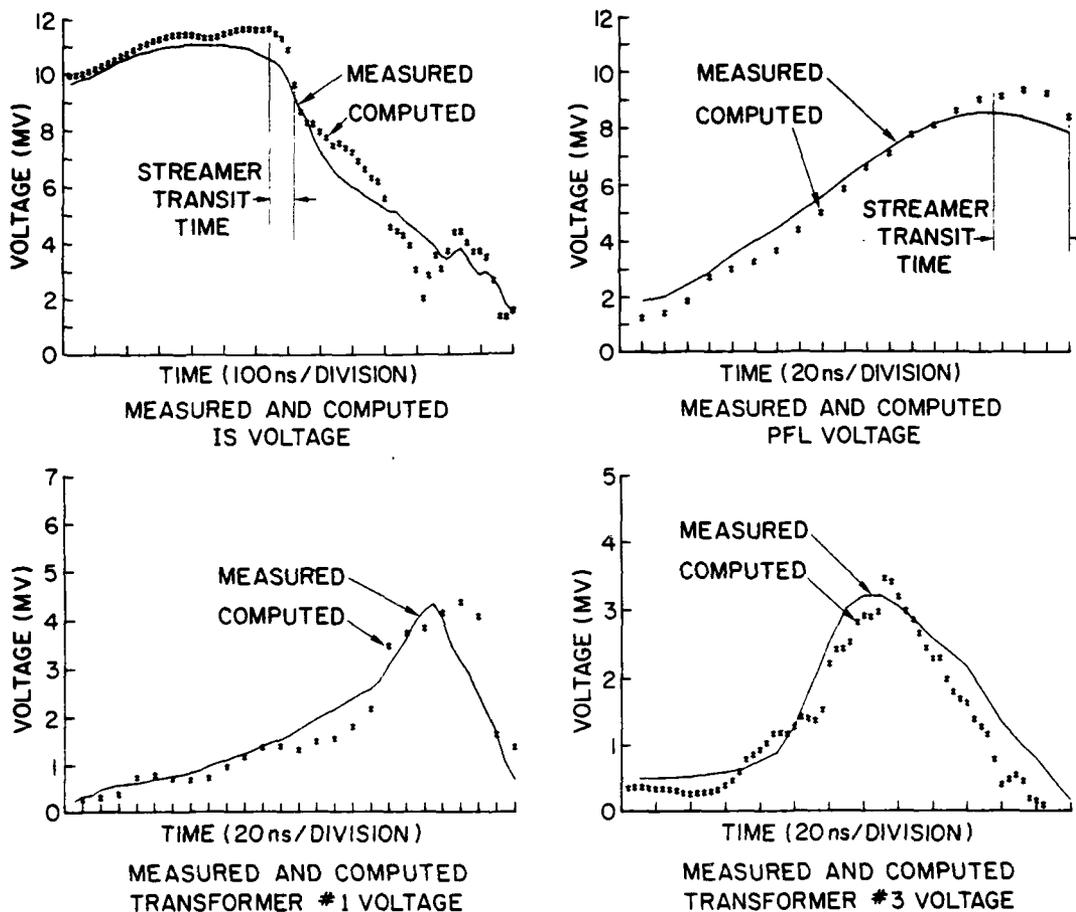


Fig. 3 - The above voltage pulse shapes show the comparison between computed and measured data on shot #149 with the switch streamer transit times greatly reduced from the "Best Fit" case of Figure 2, other factors remaining the same. The switch conditions for the above computed data were as follows:

- IS switch: 0.4 nF to ∞ nF in 80 ns, 3.7 Ω
- PFL switch: 2.0 nF to ∞ nF in 66 ns, 2.0 Ω
- Water prepulse switch: 1.0 nF to ∞ nF in 26 ns, 0.0 Ω

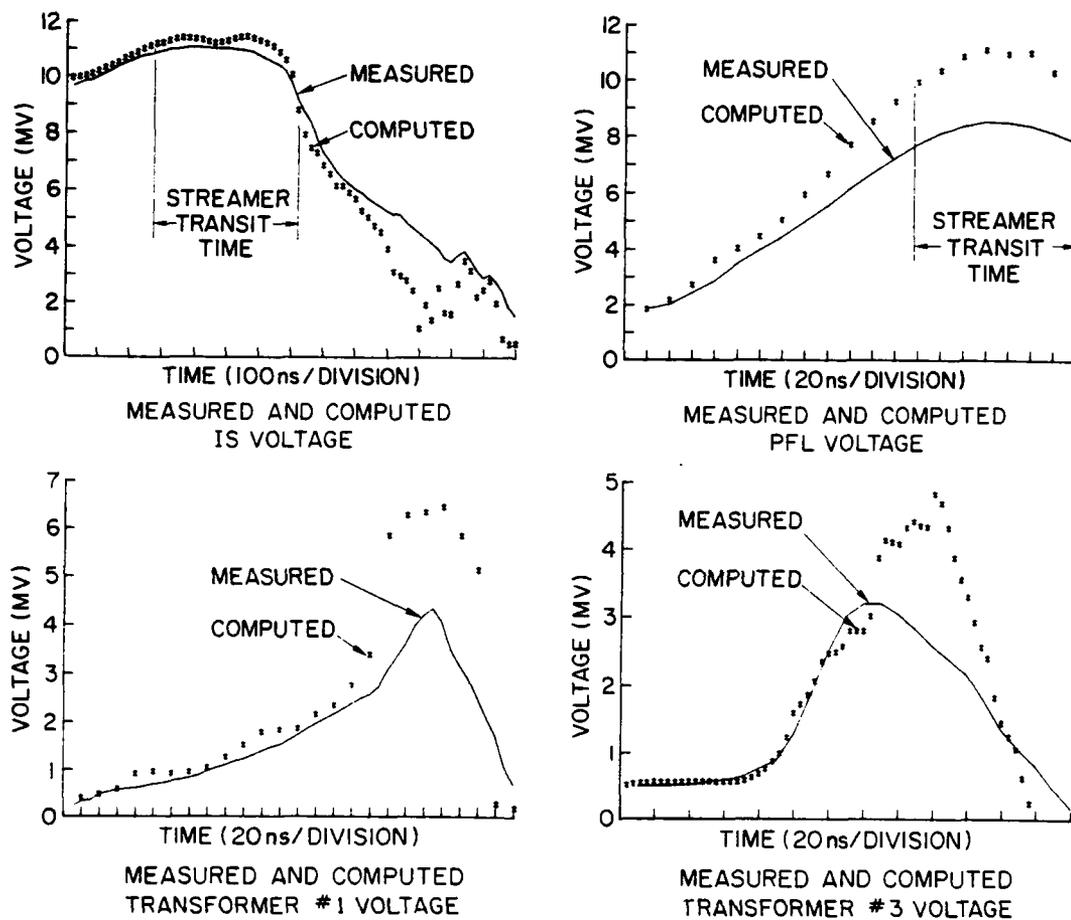


Fig. 4 - The above voltage pulse shapes show the comparison between computed and measured data on shot #149 with the switch resistances reduced to zero from the "Best Fit" case of Figure 2, other factors remaining the same. The switch conditions for the above computed data were as follows:

IS switch: 0.4 nF to ∞ nF in 448 ns, 0.0 Ω
PFL switch: 2.0 nF to ∞ nF in 144 ns, 0.0 Ω
Water prepulse switch: 1.0 nF to ∞ nF in 110 ns, 0.0 Ω

initial capacitance values were made large enough, a computer run was made with 0 resistance in all water switches but with unreasonably large values of initial switch capacitance. The initial value of the varying portion of the IS switch capacitance was raised to 2 nF with a transit time of 448 ns. This value of capacitance with an initial spacing of 89 cm would require an effective electrode diameter for the moving switch capacitor plates of 179 cm, which is unreasonable. The initial value of the varying portion of the PFL output switch capacitance was raised to 8 nF with a transit time of 144 ns. This value of capacitance with an initial spacing of 42 cm would require an effective circular moving electrode diameter of 246 cm which is also unreasonable. The initial value of the varying portion of the prepulse water switch capacitance was raised to 4 nF with a transit time of 110 ns. (All of these transit times are the same values as in the optimum run of Figure 2). This value of capacitance would require an effective width to a 90 inch mean diameter annular ring type capacitor plate with an initial 8.5 cm spacing of 7 cm which is also unreasonable. Even using these unreasonably large initial switch capacitance values, the results of the computer run as shown in Figure 5 did not result in the power and energy loss required to match the experimental results. The match near the peak of the IS pulse was excellent but there was noticeable divergence after switch closure.

The peak of the computed PFL voltage was only 13% high but the computed transformer #1 voltage was 43% high with more percentage

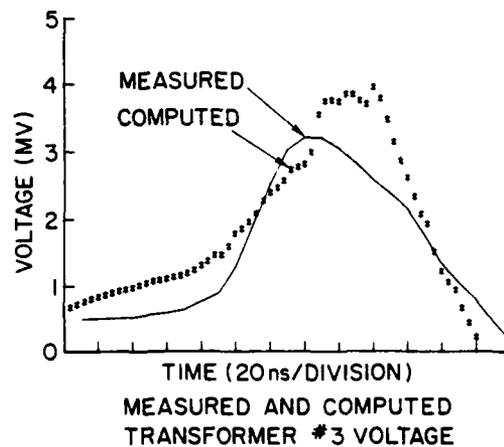
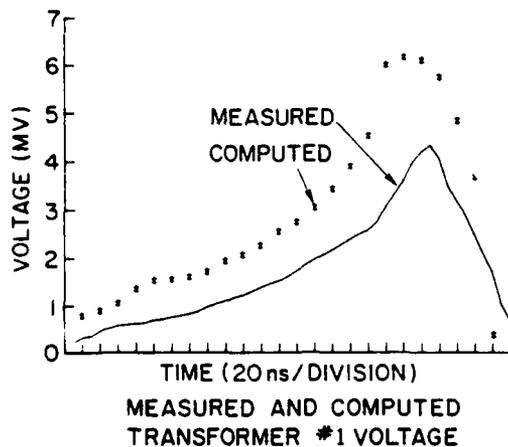
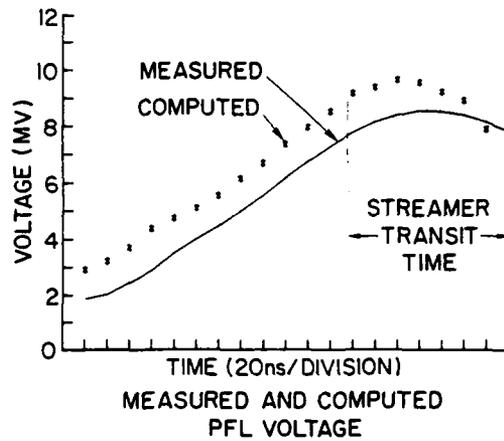
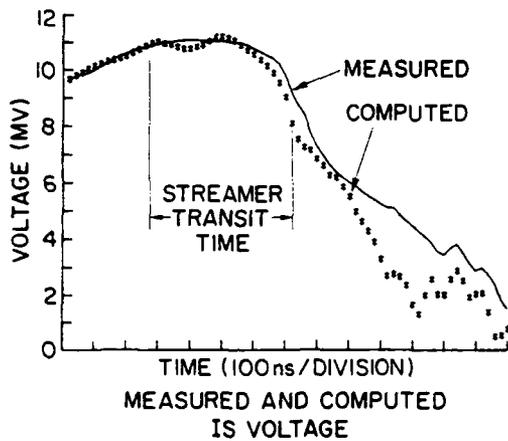


Fig. 5 - The above voltage pulse shapes show the comparison between computed and measured data on shot #149 with the switch resistances reduced to zero, but with the initial switch capacitances increased to unreasonable values, the transit times remaining the same as in the "Best Fit" case. The switch conditions for the above computed data were as follows:

- IS switch: 2.0 nF to ∞ nF in 448 ns, 0.0 Ω
- PFL switch: 8.0 nF to ∞ nF in 144 ns, 0.0 Ω
- Water prepulse switch: 4.0 nF to ∞ nF in 448 ns, 0.0 Ω

prepulse than measured. The computed peak voltage on transformer #3 was 23% higher than measured with more percentage prepulse.

Figure 6 is the result of a computer run in which the transmission line circuit including initial switch capacitance values and series switch resistance are the same as for the "best fit" run of Figure 2 but the transit times of the streamers were all arbitrarily made zero, which eliminates the changing capacitance effects entirely. The computed results show sharp drops near the peak voltages of the IS and the PFL with the computed peak PFL voltage about 16% higher than measured. The peak of the computed transformer #1 voltage was in good agreement with the measured value, and the peak of the computed transformer #3 voltage was only 15% higher than the measured value.

As a result of these analyses, it is concluded that the major loss of energy in the AMP water system is dissipated in the effective series resistances of the IS and PFL output water switches. From the computer runs, it was found that 39% of the energy that would be passed in the first power pulse by a zero resistance IS switch is dissipated in the 3.7 Ω series resistance of the switch. 27% of the energy that would be passed in the first power pulse by a zero resistance PFL switch is dissipated in the 2 Ω resistance of the switch. The overall percentage loss of energy due to the resistances of these two switches is 56%. The effect of the changing capacitance of the switches is mainly to produce the rounding of the pulse shapes near and just after the peak voltage. The energy flowing past the

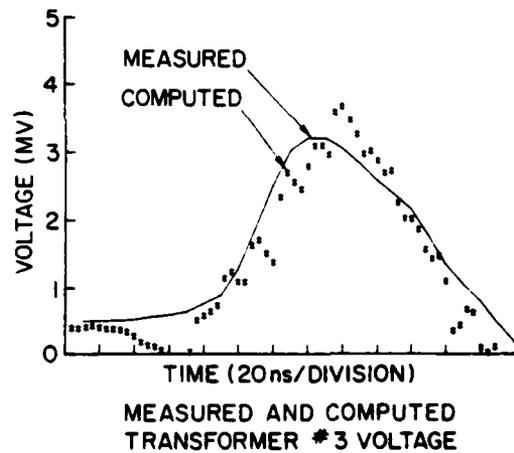
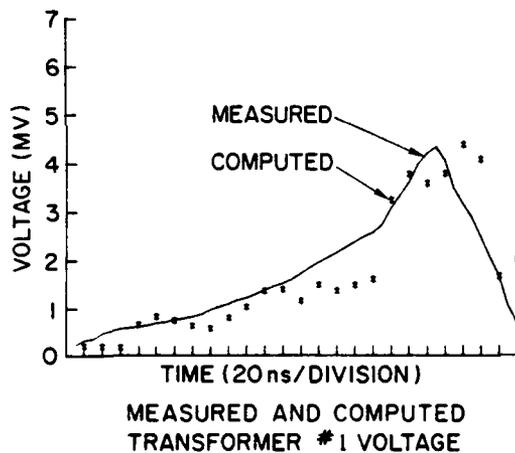
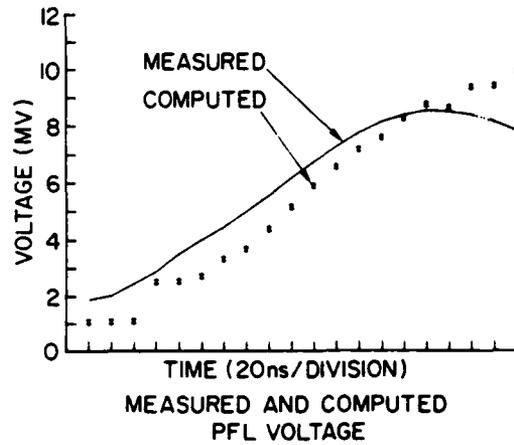
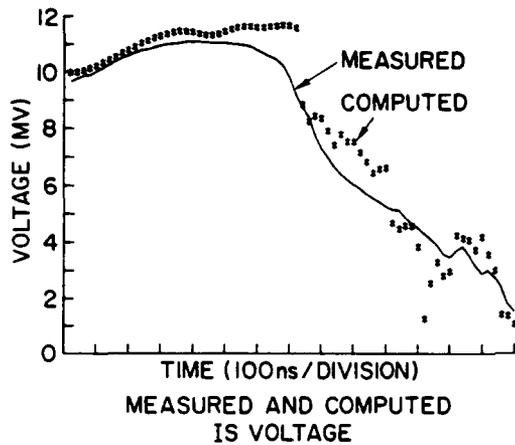


Fig. 6 - The above voltage pulse shapes show the comparison between computed and measured data on shot #149 with the switch resistances and initial capacitances the same as in the "Best Fit" case, but with the streamer transit times reduced to zero, thus eliminating the pulse rounding effect of changing capacitance more slowly. The switch conditions for the above computed data were as follows:

IS switch: 0.4 nF to ∞ nF in 0 ns, 3.7 Ω
 PFL switch: 2.0 nF to ∞ nF in 0 ns, 2.0 Ω
 Water prepulse switch: 1.0 nF to ∞ nF in 0 ns, 0.0 Ω

transformer #1 voltmeter position an AMP shot #149 in the first power pulse was only 482 kJ with a peak power of 4.1 TW according to the computer analysis of Figure 2 (which matches the measured voltages). The main reasons why the measured output is so much lower than predicted by the previous NRL report are the lower Marx output on the IS of 11.1 MV rather than 12 MV, and the greater overall losses of 56% rather than 34% in the water switches. These amount to an overall additional energy and power reduction factor of ~ 0.57 to be applied to the previous estimate.

Phil Spence, et al¹, at PI found that for single channel water switch configurations covering a voltage range from 3 to 3 MV, gaps from 7 to 35 cm, and mean switching fields from 150 to 350 kV/cm, an average resistance value of $35 \pm 14 \text{ m } \Omega/\text{cm}$ could be assigned to water switches. In an informal note by J. C. Martin on his analysis of some underwater spark data; he found, among other things, that the equivalent constant resistance per unit length of water switches was inversely proportional to the switch current. Therefore he deduced that splitting the current up into a number of channels does not help to reduce the overall resistance. (It does of course help to reduce the switch inductance.)

If one combines and applies the above ideas to the AMP water switches there is a measure of agreement. The resistance per cm of the AMP IS switch is $3.7/80 = 41.6 \text{ m } \Omega/\text{cm}$ which is well within the range of $35 \pm 14 \text{ m } \Omega/\text{cm}$. The resistance per cm of the AMP PFL switch

is $2/42 = 47.2 \text{ m } \Omega/\text{cm}$ which is also within this range. However, before the reader decides there is a degree of understanding about the resistance of water switches the following should be added.

The upgraded Gamble II generator at NRL was analyzed in the same manner as AMP was in this report. The resistance of the IS switch was found to be $2 \text{ } \Omega$ with a gap spacing of 31 cm at 5 MV. The resistance per unit length was $2/31 = 64.5 \text{ m } \Omega/\text{cm}$ which is only 32% higher than the upper limit of the PI range. In the belief that the resistance of the switch must indeed be proportional to the gap length, the gap was reduced to 16 cm at 5 MV by drastically reducing the surface field on the positive electrode. Amazingly, the change in energy loss in the switch was hardly detectable ($\sim 5\%$). The resistance per unit length was now $\sim 1.9/16 = 119 \text{ m } \Omega/\text{cm}$. This was a discouraging result, because it means that similar efforts to reduce the gaps in AMP may fail to significantly reduce the losses.

Of great interest in the upgraded Gamble II analysis was the fact that the resistive loss in the multichannel oil PFL output switch was too low to be measurable. This was true of both the positively enhanced multichannel overvolted switch with 16 cm gaps at 5 MV, and the unenhanced (9 cm gap at 5 MV) switch with a trigger disc driven by an overvolted axial gap. It is possible that the AMP generator might realize its high power and energy capabilities if oil switches were used in place of the present water switches. Such a conversion would involve great expense. More testing of the polyurethane diagrams used

to contain large oil switches should be undertaken before they are used on AMP. The Gamble II diaphragms have operated with surface fields in the 279 to 308 kV/cm range for 15 shots before tracking occurred. The time (t_{eff}) that the surface field was greater than 63% of the maximum was 0.06 μsec . Occasionally, however, tracking occurs with peak fields as low as ~ 250 kV/cm. In general, one can detect the occurrence of an initial diaphragm track by observing the voltage or current pulse measured at a point just past the oil switch. If detected when it first occurs, the carbonized track can be sanded out before it has a chance to absorb a much larger amount of energy in a subsequent firing and possibly rupture the diaphragm.

If oil switches with diaphragms were installed on AMP and the desired peak voltage of ~ 12 MV was attained on the PFL, for example, the diaphragm stresses would be in the 200 to 230 kV/cm range with $t_{\text{eff}} \sim 0.16$ μsec . The stressed area would also be about a factor of 13 larger than in Gamble II. Although the dependence of oil-urethane interface tracking on time and area is not known, some tracking would probably occur at the 12 MV level.

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