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APPENDIX A
INDUCTIVE ADDER FOR RADIOGRAPHIC APPLICATIONS

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* See Appendix A for paper given by Bruce Miller at1989 Flash Radiography Topical, August 14-18, 1989. Portland Oregon

INDUCTIVE ADDER FOR RADIOGRAPHIC APPLICATIONS

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For some problems of interest, it is desirable to produce high energy x-rays (≥ 800 kV), but to do so using a remote tube head. TITAN has met this need by developing an inductive adder. To use this device, a suitable HP pulser, such as the model 43734A, is operated in a dual remote tube head mode. However, both high voltage output cables are inserted into TITAN's inductive adder which effectively sums the two voltage pulses. This higher voltage is then delivered to an appropriate x-ray tube such as the 1 MV 5081-9551 tube.

ADDER DESCRIPTION

Consider the HP Model 43734A 450 kV pulser operated in the dual remote tube head configuration, as illustrated in Figure 1. In this mode both tubes are fired simultaneously by the same pulser, thereby providing the capability for obtaining orthogonal radiographs of rapidly moving objects, at the expense of reduced radiation dose (and penetrating power) from each tube. If it were possible to construct a device that could add the voltage pulses provided to the two separate tube heads as illustrated in Figure 2, then substantially higher penetrating power and x-ray doses could be provided in a remote tube head configuration. The development of such a technique would represent a significant new capability and could provide an important product improvement option for existing HP units already in field use. TITAN Technologies/Spectron Division has successfully developed and tested this inductive adder concept.

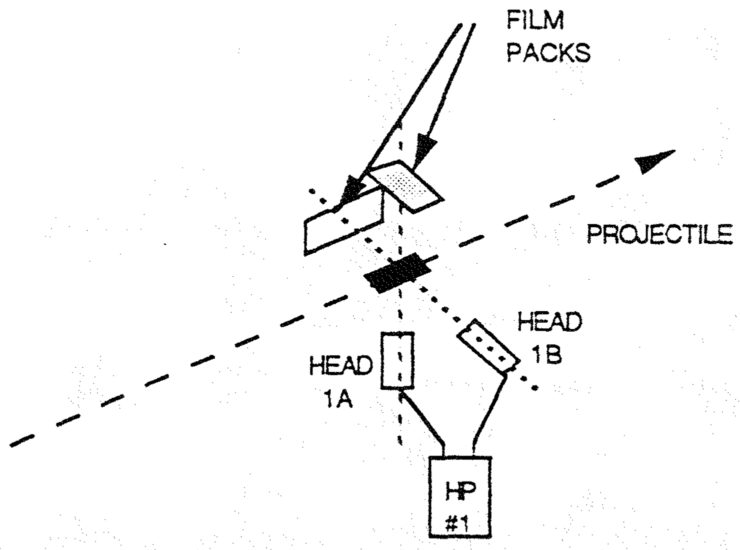

Figure 1. Standard dual remote tube head radiography configuration.

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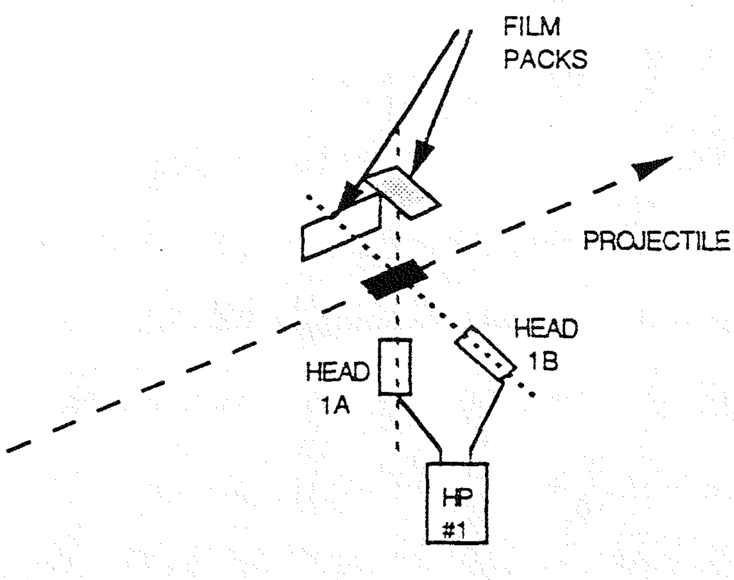

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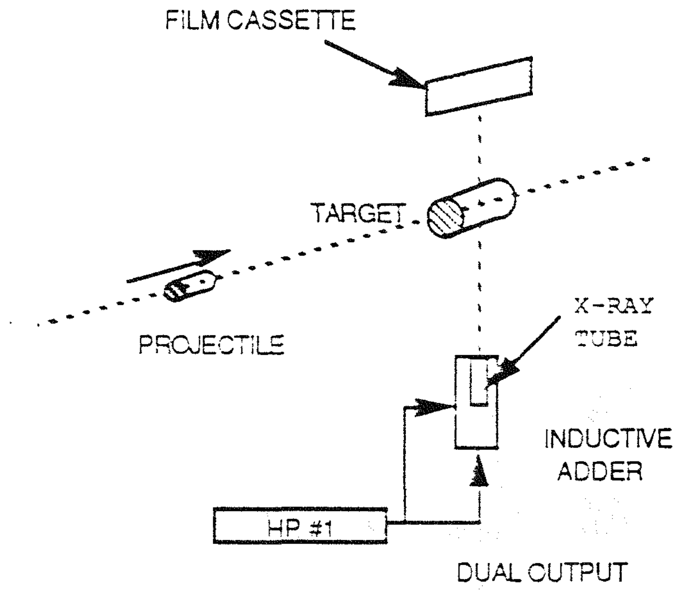

Figure 2. Desired inductive adder radiography configuration.

The adder unit is nominally designed to combine the two high voltage cable outputs of the 43734A pulser to deliver approximately 800 kV to a high impedance version of the 1 MV HP 5081-9551 x-ray tube. The induction cell assembly and the x-ray tube are contained within the adder chamber, which is about 31 inches long, 13 inches in diameter, and weighs approximately 200 pounds. Transformer oil is used as the high voltage insulating medium in the adder volume. A reset circuit box conveniently fits inside the HP control cabinet. Figures 3 and 4 show pictures of the Adder in its operating configuration, and with the x-ray tube removed.

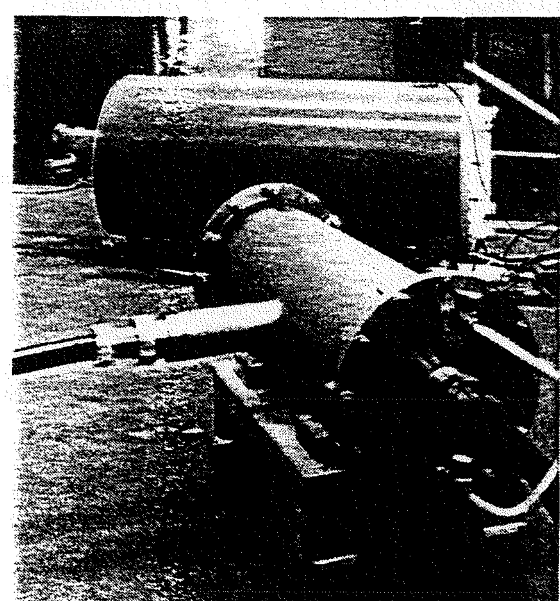

Figure 3. Picture of the Inductive Adder.

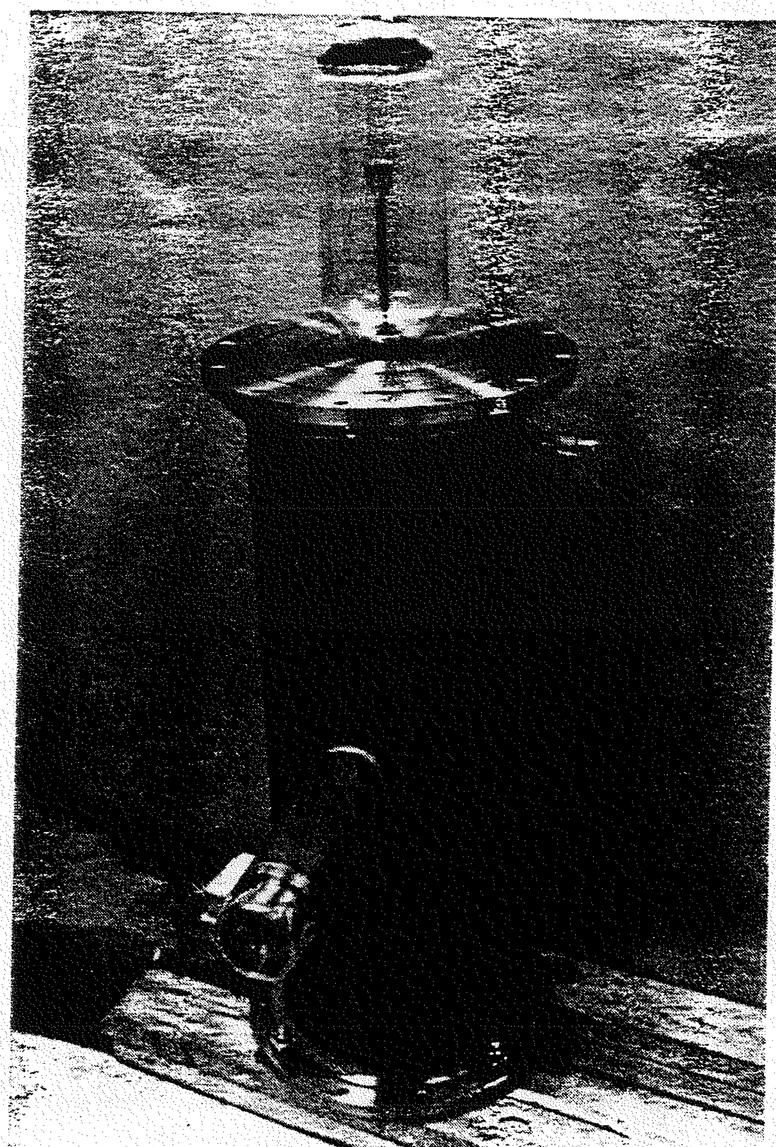

Figure 4. Picture of Adder with the x-ray tube removed.

PERFORMANCE TESTS

The equivalent circuit network for the pulser, adder, and x-ray tube is shown in Figure 5. As a result, the voltage V_L applied across the x-ray tube is determined according to

$$V_L = V_m [R_c/(R_m + R_c/2)] [R_L/(R_c + R_L/2)] \quad (1)$$

where R_L is the load impedance of the x-ray tube. The characteristic impedance R_c of the high voltage cables is 63 ohms. Using resistive loads of varying impedance we separately determined that the internal impedance R_m of the HP Marx pulser was about 85 ohms. The open circuit Marx voltage, V_m, is given by $V_m = 30\ V_{ch}$, where V_{ch} is the charging voltage of the HP control console. Substituting these values into Eq. (1) yields

$$V_L = 16.2\ V_{ch} [R_L/(63 + R_L/2)] \quad (2)$$

which explicitly shows how the performance of the adder is determined by the impedance of the x-ray tube load.

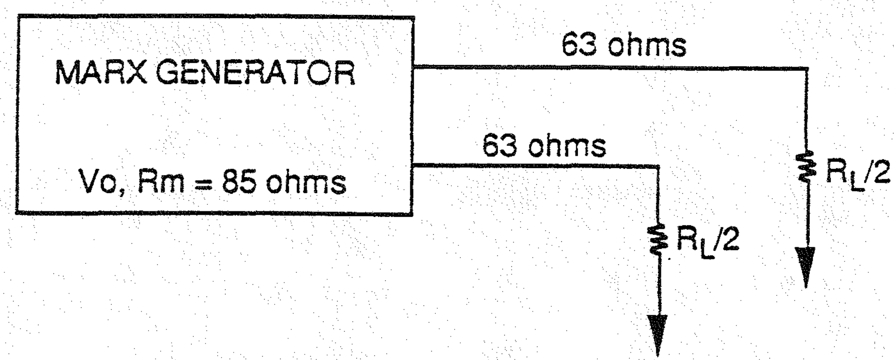

Figure 5. Equivalent circuit of the Inductive Adder.

This predicted adder performance was subsequently checked by varying the impedance of a resistive load, which was inserted into the adder in place of the x-ray tube. The current through the resistive load was measured using calibrated B-dot and Rogowski coils. The peak output voltage data for several different charge voltages are displayed in Figure 6 as a function of the impedance of the resistive load. These data are in substantial agreement with the performance predicted on the basis of Eq. (2), which is shown as the solid line. From these simple analyses it is apparent that substantially higher load voltages could be achieved if the impedance mismatch between the pulser and the two output cables were reduced.

Following the resistive load checks a standard 1 MV HP tube (Model Number 5081-9551) was inserted into the adder. The current through the tube was monitored using a B-dot probe and a Rogowski coil, while the x-ray pulse waveform was monitored using an uncalibrated PIN diode. The total x-ray dose was monitored using a quartz fiber dosimeter.

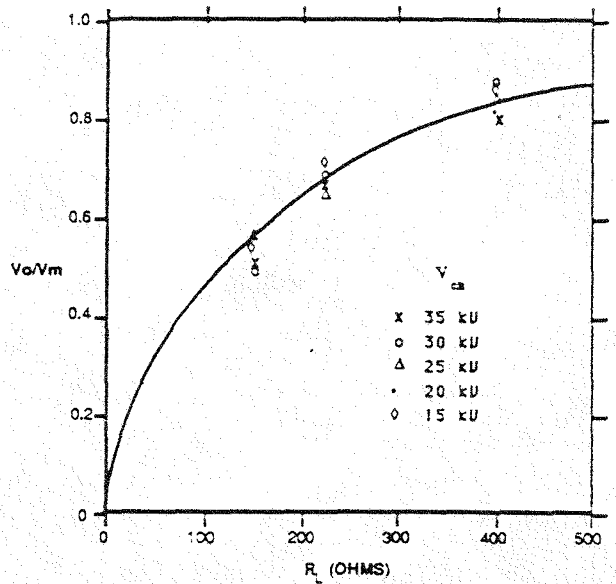

Figure 6. Dependance of load voltage on load impedance.

As an example of these data, Figure 7 shows the current through the standard 1 MV tube for a charging voltage of 35 kV, while Figure 8 exhibits the output waveform of the x-ray pulse as measured by the PIN diode. The current waveform exhibits two distinct peaks, with the second being almost twice as large as the first. The total duration of this pulse is almost 90 ns. Although the PIN diode trace also indicates two peaks in the x-ray pulse, the second peak is approximately equal to the first peak in amplitude, and the FWHM of the x-ray pulse is about 50 ns.

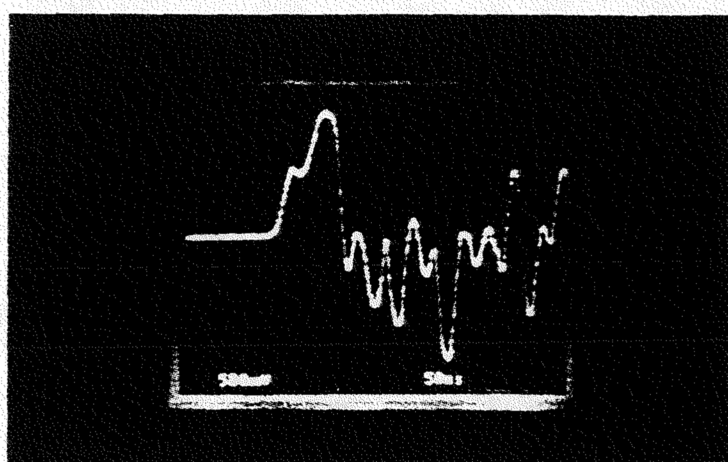

Figure 7. Current through the Inductive Adder. The maximum current in the first peak is 3.15 kA, the time scale is 50 ns per division. (Standard HP 1 MV, 6 kA x-ray tube.)

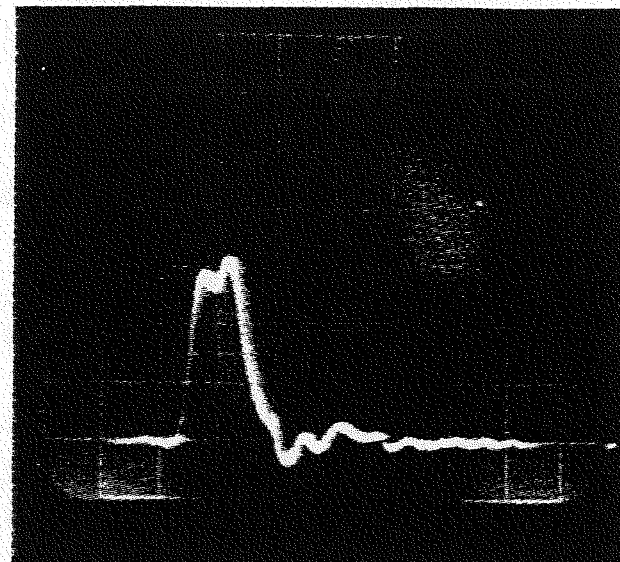

Figure 8. Characteristic waveform of the x-ray pulse.

These data suggest that the x-ray tube impedance collapses as the result of plasma closure in the anode-cathode gap of the tube at late times in the pulse. Assuming the correctness of our circuit model, the amplitude of the first current peak (3.15 kA) implies a nominal tube impedance of 234 ohms, and the corresponding output voltage across the tube is 737 kV. In comparison, the amplitude of the second current peak (6.3 kA) implies that the tube impedance has decreased to 54 ohms, and the tube voltage has dropped to 340 kV. The load impedances and tube voltages corresponding to the first current peak are graphed as a function of the Marx charging voltage in Figures 9 and 10.

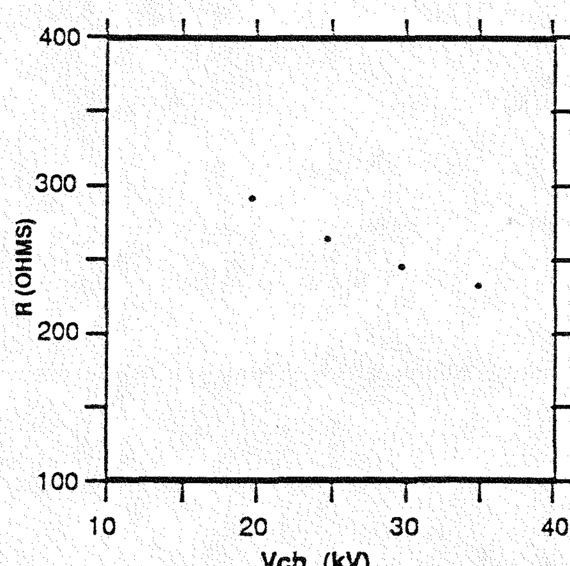

Figure 9. Load impedance of the standard 1 MV x-ray tube as a function of Marx charge voltage.

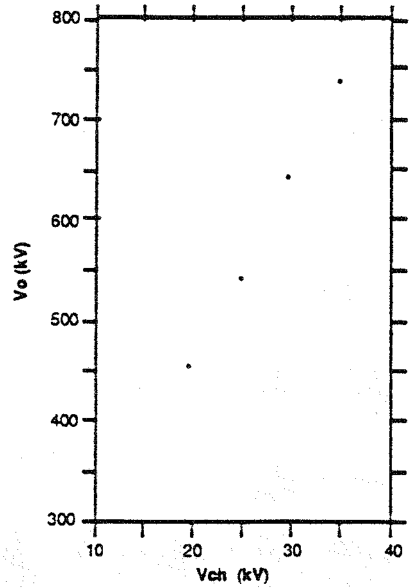

Figure 10. Adder output voltage for the standard 1 MV x-ray tube as a function of Marx charge voltage.

The total x-ray dose as measured by the quartz fiber dosimeter located one meter from the tube is also displayed in Figure 11 as a function of Marx charging voltage. A maximum dose of 30 ± 5 mR is obtained at the highest charging voltage (35 kV), although the peak voltage on the x-ray tube apparently never exceeds about 740 kV.

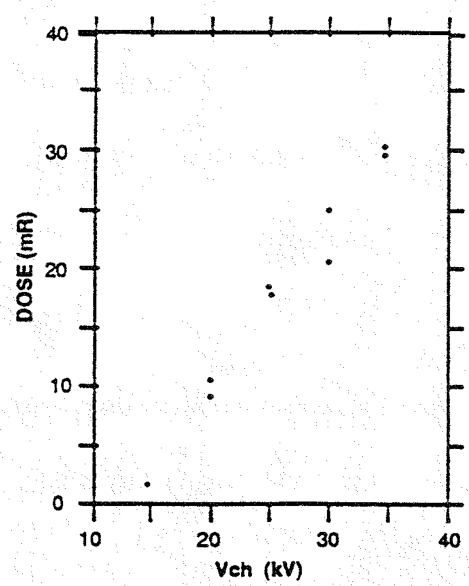

Figure 11. X-ray dose at one meter vs Marx charge voltage (standard 1 MV tube).

The standard HP 1 MV tube has six cathode splines. In an effort to increase the tube impedance (thus allowing a higher voltage across the tube), a three-spline tube was specially ordered. The resulting adder current trace for a charging voltage of 35 kV is shown in Figure 12. The first peak of the current pulse is now 2.6 kA, and the average dose at one meter has increased to 35 ± 5 mR. The corresponding tube impedance is 310 ohms, and the peak calculated voltage is 806 kV.

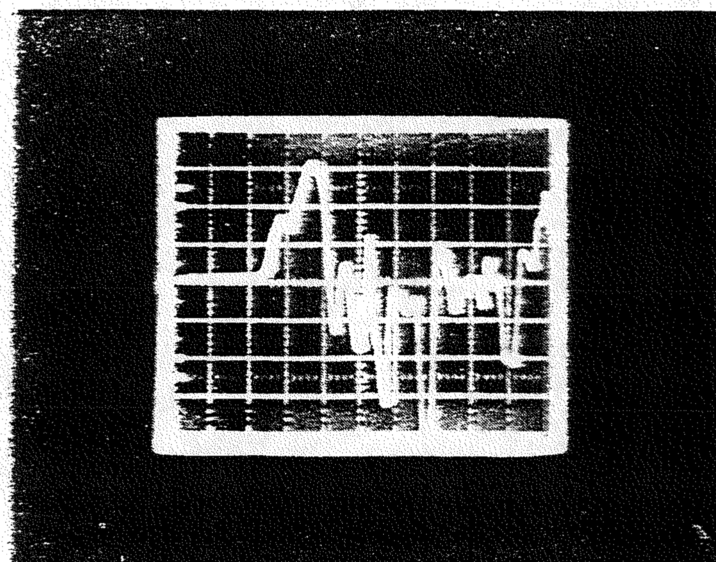

Figure 12. Current through the Inductive Adder. The maximum current in the first peak is 2.52 kA. (Modified high impedance HP x-ray tube.)

In order to demonstrate the enhanced penetrating power provided by the inductive adder, we performed several radiography experiments using stationary targets. The high impedance 1 MV tube was employed. Prior to these measurements we first determined the decrease in x-ray dose delivered to a quartz fiber dosimeter placed one-half meter from the tube as a function of Marx charging voltage. These data are graphed in Figure 13. Very roughly, the thickness of steel required to reduce the dose by a factor of 2 was about 0.25 inches.

The configuration for the radiography tests is shown in Figure 14. The target set could be placed between various thicknesses of steel plate, and the tube-target and target-film plane distances could be varied independently. The target set consisted of six steel ball bearings with diameters of 0.1250 in, 0.1555 in, 0.1875 in, 0.2505 in, 0.3155 in, and 0.3765 in, respectively. A small lead shot pellet of 0.0806 in (3.17 mm) diameter was an additional object.

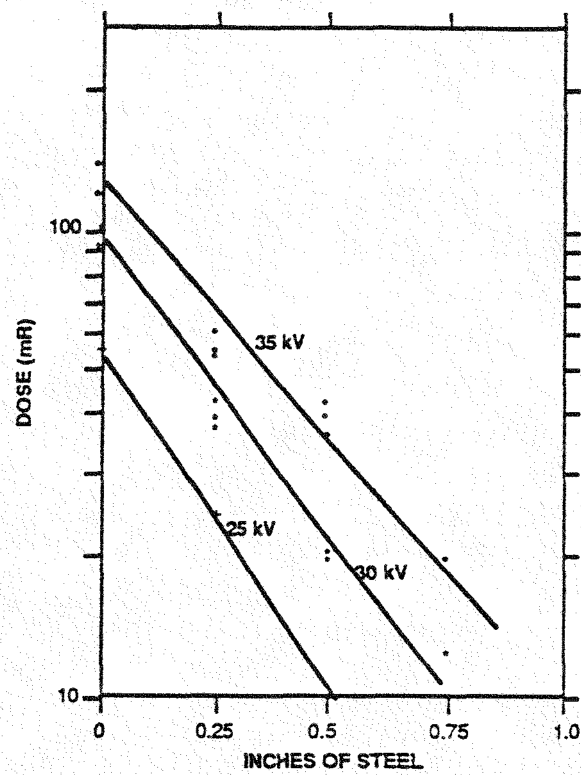

Figure 13. Variation of x-ray dose at 50 cm from the tube as a function of steel penetration thickness for several Marx charge voltages.

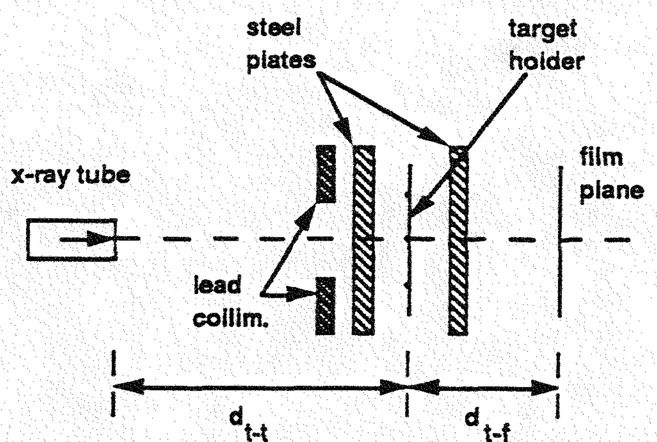

Figure 14. Configuration of radiography tests.

The x-ray film used in these measurements was Kodak XAR-7 x-ray film. In addition, we used three different image intensifier screens, a CRONEX NDT-2, NDT-9, and a CRONEX QUANTA FAST DETAIL screen.

A representative list of our x-ray tests is included in Table 1. Within the limits of our film reproducing capabilities, a few examples are exhibited in Figures 15-17. As a general summary, we could easily record all seven target objects through an inch of steel plate. In fact, we were able to record very good target images through up to 1.75 inches of steel. We obtained best results with the QUANTA image intensifier screen. In addition, use of a 0.25 in thick lead aperture also improved our target images. Best results were generally obtained at the highest charging voltages, especially for the thickest layers of absorber. However, by varying the time for film developing and using thicker image intensifier screens we were able to obtain very good images at lower voltages for smaller thicknesses of absorber. As expected, the smallest target object, the lead pellet, was easier to observe than the steel ball bearing which was almost twice as thick.

Based on these observations, use of the inductive adder in conjunction with the HP 43734A pulser should permit the observation of few-millimeter-thick tungsten (or other suitable high-Z/high-density material) shards through an inch of steel armoring, provided that the tube-film plane distance is less than about one meter. Some experimentation with different recording films, developer times, image intensifiers, etc. is recommended to obtain best results.

SUMMARY

TITAN has successfully developed an inductive adder for use with a Hewlett-Packard Model 43734A Marx pulser. The unit provides an 800 kV peak output pulse to a modified HP 5081-9551 1 MV x-ray tube. The tube fits into the adder unit, and can thus be remotely operated. The total on-axis x-ray dose at one meter from the tube is 35 ± 5 mR, as measured by a quartz fiber dosimeter. The FWHM duration of the radiation pulse is ≤ 50 ns. Based on the the results of radiography measurements using stationary targets, this unit permits the user to observe few-millimeter-thick tungsten (or other suitable high-Z/high-density material) shards through an inch of steel armoring, provided that the tube-film plane distance is less than about one meter.

Table 1. Summary of Stationary Radiographic Shots

Shot No.	V_{ch} (kV)	Front Attenuation (in of steel)	Back Attenuation (in of steel)	Tube-Target Distance (in)	Target-Film Distance (in)	Intensifier Screen	Developer Time (min)	Remarks
1	25	0	0	20	7.5	--	7	
2	30	0	0	20	7.5	--	7	
3	35	0	0	20	7.5	--	7	
4	35	0	0	20	7.5	NDT-2	7	
6	35	0.25	0.25	20	7.5	NDT-2	7	
7	35	0.5	0.5	20	7.5	NDT-2	7	
9	30	0.5	0.5	20	7.5	NDT-2	7	
10	30	0.5	0.25	20	7.5	NDT-2	7	
11	30	0.25	0.5	20	7.5	NDT-2	7	
12	35	0.25	0.5	20	7.5	NDT-2	7	
13	25	0.25	0.5	20	7.5	NDT-2	7	
14	35	0.25	0.5	33	8.0	NDT-2	7	
19	35	0.5	0.5	33	8.0	QUANTA	3	
20	35	0.5	0.5	33	8.0	QUANTA	2	
21	35	0.5	0.5	33	8.0	QUANTA	1.5	
22	35	0.5	0.5	33	8.0	QUANTA	1.0	
24	35	0.5	0.5	33	8.0	NDT-9	1.5	
25	30	0.5	0.5	33	8.0	QUANTA	1.5	Pb Collimator
26	35	0.5	0.5	33	8.0	QUANTA	1.5	Pb Collimator
27	25	0.5	0.5	33	8.0	QUANTA	2	Pb Collimator
28	30	0.5	0.75	33	8.0	QUANTA	3	Pb Collimator
29	35	0.75	0.75	33	8.0	QUANTA	3	Pb Collimator
30	35	0.75	0.75	12	3.5	QUANTA	3	Pb Collimator
31	30	0.75	0.75	12	3.5	QUANTA	3	Pb Collimator
32	25	0.75	0.75	12	3.5	QUANTA	3	Pb Collimator
33	35	0.75	0.75	12	3.5	QUANTA	2	Pb Collimator
34	35	0.75	1.0	12	3.5	QUANTA	3	Pb Collimator
35	35	0.75	1.0	12	3.5	QUANTA	3	No Collimation

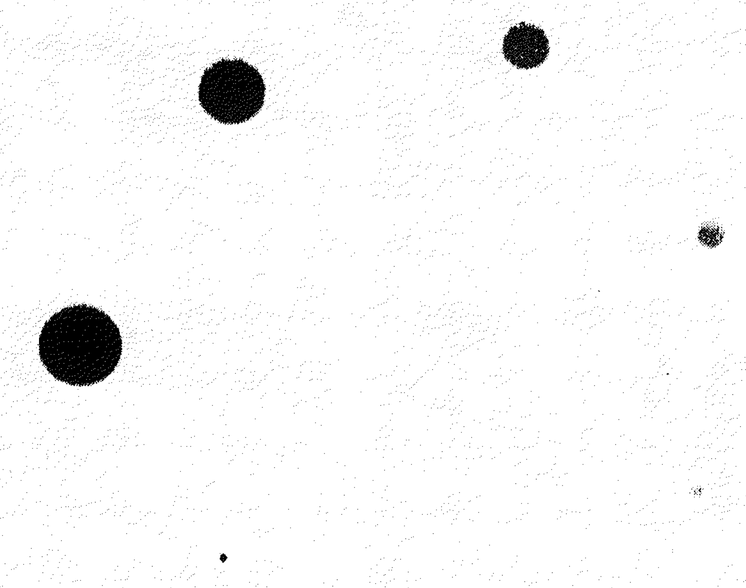

Figure 15. Radiograph for shot #4. NDT-2 intensifier screen. No steel attenuation (35 kV).

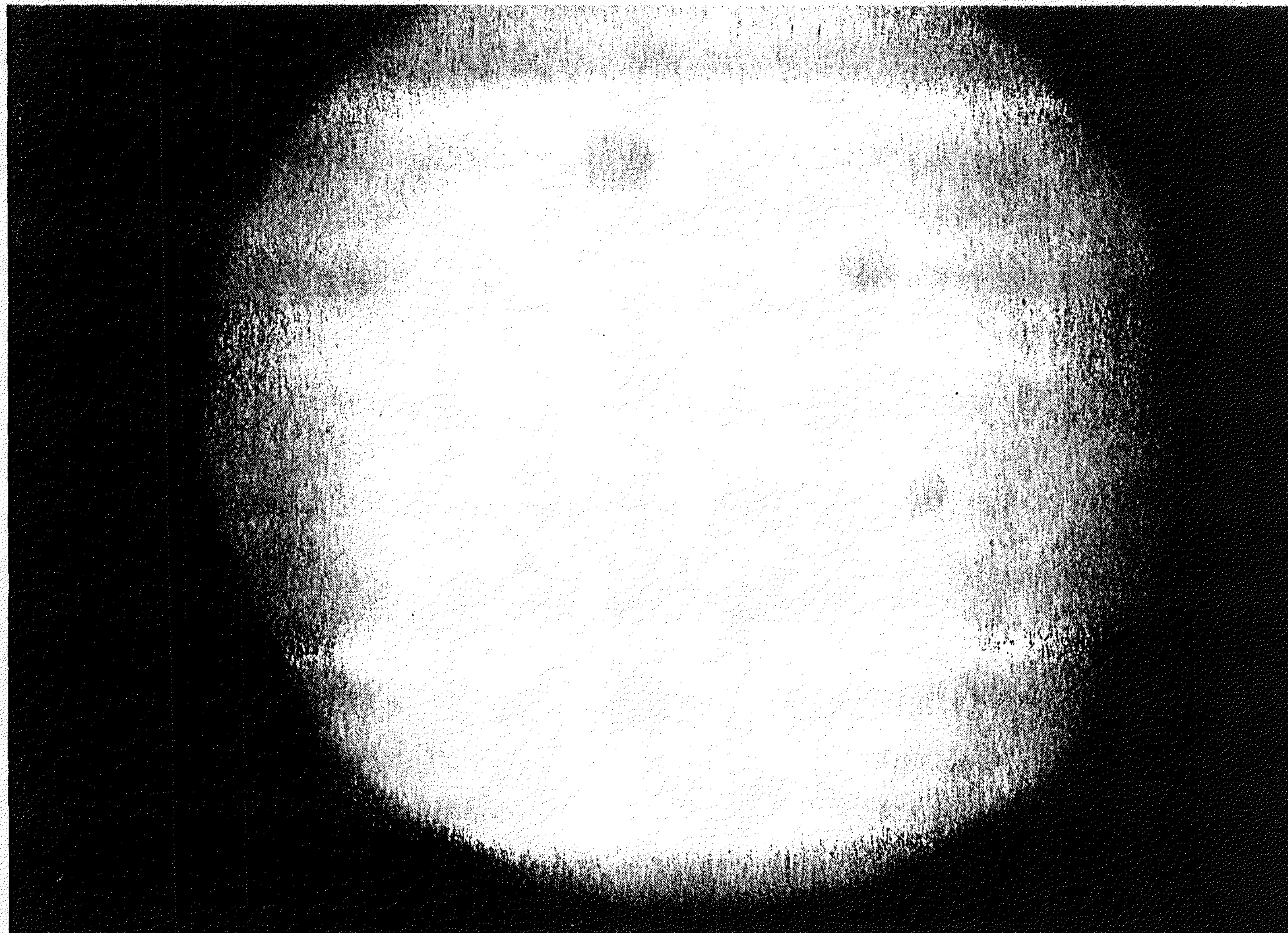

Figure 16. Radiograph for shot #33. QUANTA intensifier screen. 1.5 inches of steel attenuation (35 kV).

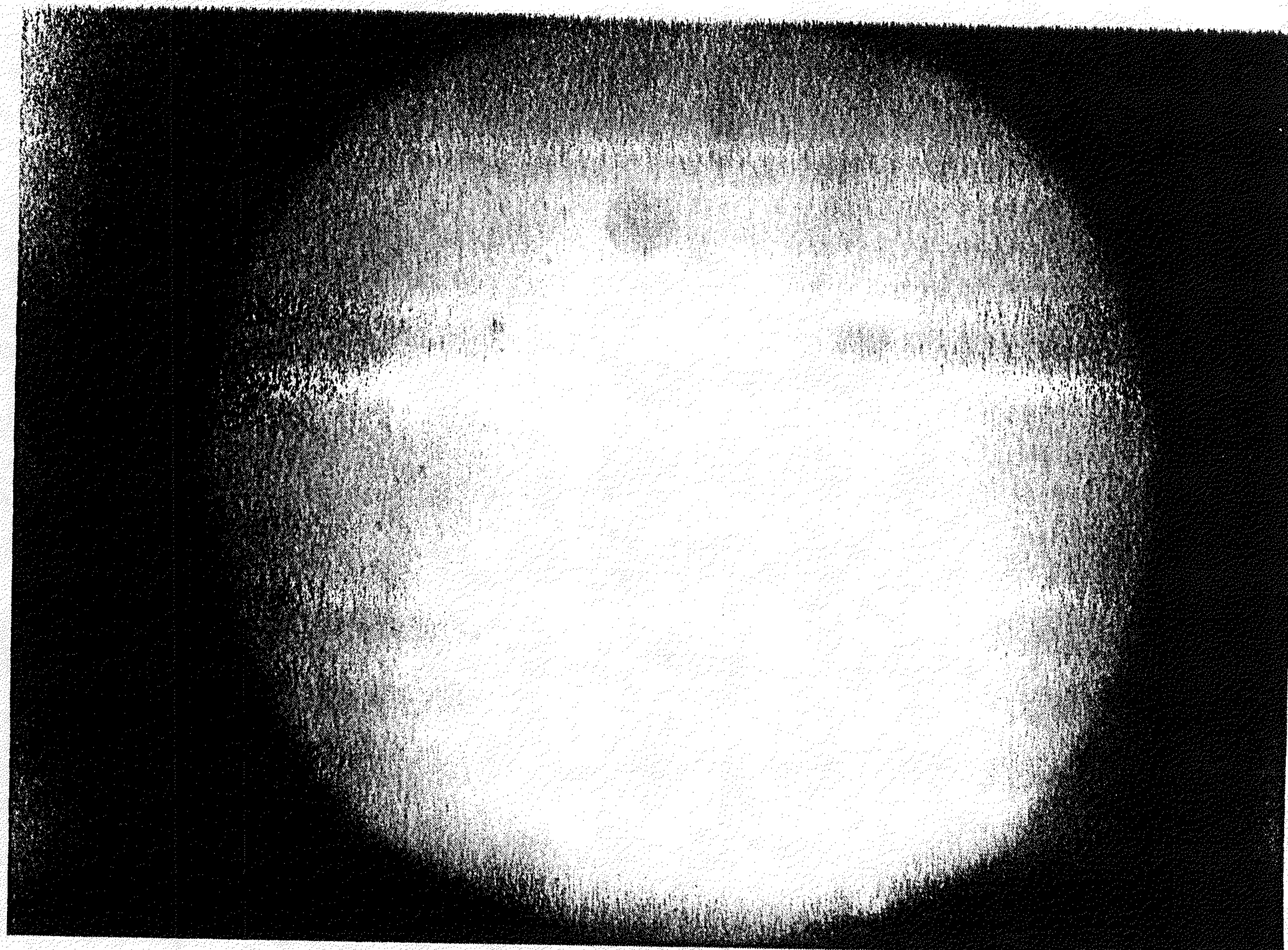

Figure 17. Radiograph for shot #34. QUANTA intensifier screen. 1.75 inches of steel attenuation (35 kV).