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TITLE: Large Area Digital X-Ray Imaging System

PRINCIPAL INVESTIGATOR: D. H. Pommerrenig

CONTRACTING ORGANIZATION: E-O Products, Corporation
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APPENDIX B
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U.S. DEPARTMENT OF DEFENSE

SMALL BUSINESS INNOVATION RESEARCH PROGRAM
PHASE 1 — FY 1987
PROJECT SUMMARY

Topic No. A88 191

Military Department/Agency Army.

Name and Address of Proposing Small Business Firm

E-O Products, Corporation
23101 Moulton Pkwy., Suite 210
Laguna Hills, CA 92653

Name and Title of Principal Investigator

Dieter H. Pommerrenig, Senior Scientist

Proposal Title

Large Area Digital X-Ray Imaging System

Technical Abstract (Limit your abstract to 200 words with no classified or proprietary information/data.)

Design trade-off, and performance analysis performed during Phase 1 show conclusively, that large area, solid state digital x-ray imaging panels can be produced cost competively. Their performance level is projected to exceed teh film/screen combination presently used. Also, it was concluded that the radiation dose applicable will not have detrimental effects on the gate array architectures of the electronic read-out device.

Anticipated Benefits/Potential Commercial Applications of the Research or Development

Large area digital x-ray imaging panel will find utility in both medical diagnostic as well as industrial inspection applications. Their use will potentially replace the film currently used in these applications.

P1

List a maximum of 8 Key Words that describe the Project.

X-Ray Imaging, Digital Radiography, Industrial Inspection.

2

TABLE OF CONTENT

TABLE OF FIGURES

I. Summary

Key technologies related to the development of large area, digital x-ray imaging panels were identified during the course of this Phase I study program.

The critical technologies can be summarized as follows:

Panel Architecture

Component Configurations

Radiation Damage Assessment

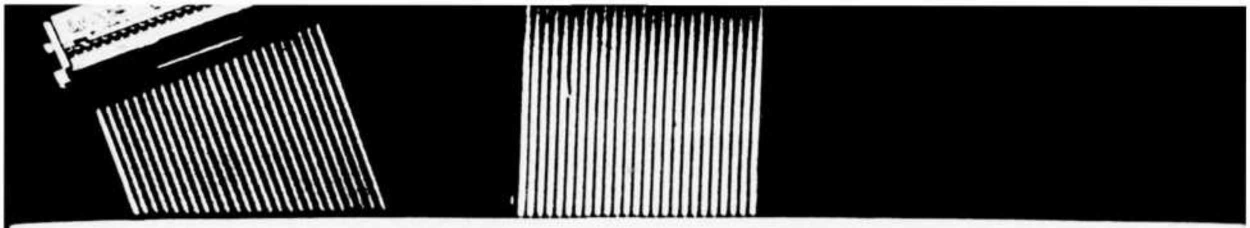
Pixel Read-Out Rates

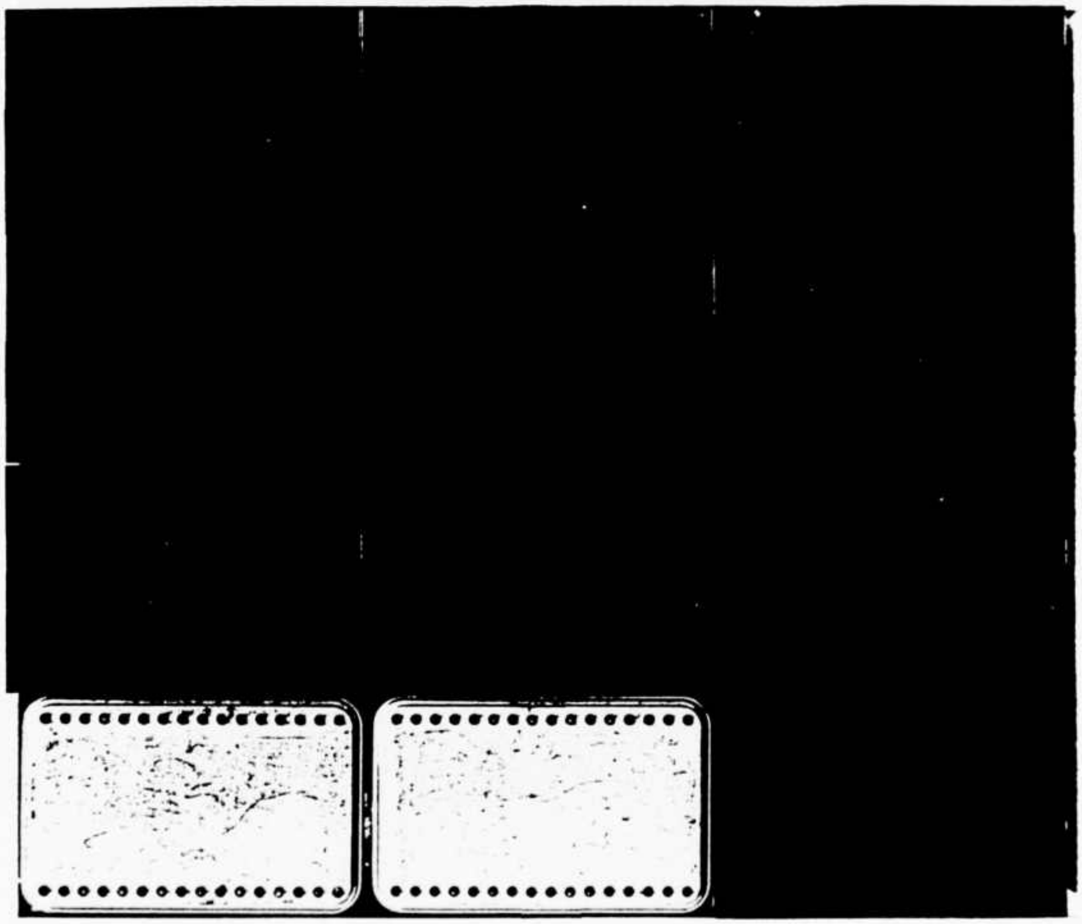
Performance Projections and

Cost Analysis

It was concluded that large area, solid state x-ray imaging panels can be produced using present technologies. Charge Coupled Devices (CCD) are the most suitable electronic read-out devices because of their low noise floor. In addition, they are available at increased dimensions. CCDs as large as 1 inch square can be produced at least by three US semiconductor manufacturers. Utilizing these devices, panels of the size of 4x4 inches require only 16 parts. To assemble panels of the above size, standard industrial equipment and practices can be effectively applied. Also, it was found, that the scintillator/CCD combination, used as the detection building block, yields a better performance than film/screen combination. Electronic adress schemes, using a parallel serial pixel read-out, will allow effectively high data rates. Potential radiation damage effects in MOS devices were found not to be applicable because of the low dose levels and use of a radiation-hard fabrication process. It was found that the flat, backside illuminated architecture shows the highest promise. Repairability and assembly yields can be kept at an optimum level.

In summary, the development of large area, digital x-ray imaging panels is quite feasible using presently available technologies.





II. TECHNICAL DISCUSSION

During the Phase I of this program, the objectives were expanded to cover the majority of the pertinent technologies related to the development of large area panels. Not only design options and architectures were evaluated but also questions related to radiation damage and adress electronics were evaluated.

A. Panel Design Options:

In order to fabricate the large area x-ray imaging panel there are multiple design options. The areas that contain options are:

1) configuration and orientation of the 128 x 128 CCD imagers.

2) assembly configuration and techniques to reduce the dead space and form the integrated large area assembly.

3) the techniques and structure needed to hold and encapsulate the integrated imager to provide a durable unit which is repairable in a cost effective manner.

There are two possible configurations for the individual 128 x 128 imagers. These are:

1) front side illuminated (i.e., the side with the CCD structure on it).

2. back side illuminated.

The front side illuminated case is the most risk free from the aspect that the elemental CCD is exactly the same as that used in the dental x-ray device. However, using the device in this form requires a "shingling" approach when forming the 64 element large area imager. This is necessary to reduce the dead space that would occur between elemental imagers due to the read-out pads on the one edge of the CCD's. This technique requires that the elemental imagers be staggered in the z direction and that the edge of one imager overhang the next in one direction x or y. Figure 3 shows the cross-section of the imaging panel with a 100% full-factor.

The back side illuminated case requires some minor modifications to the existing device. The device must be thinned to efficiently collect the photo generated carriers in the CCD. To avoid shingling, the dead space may, in this case, be reduced by changing the layout of the output pads.

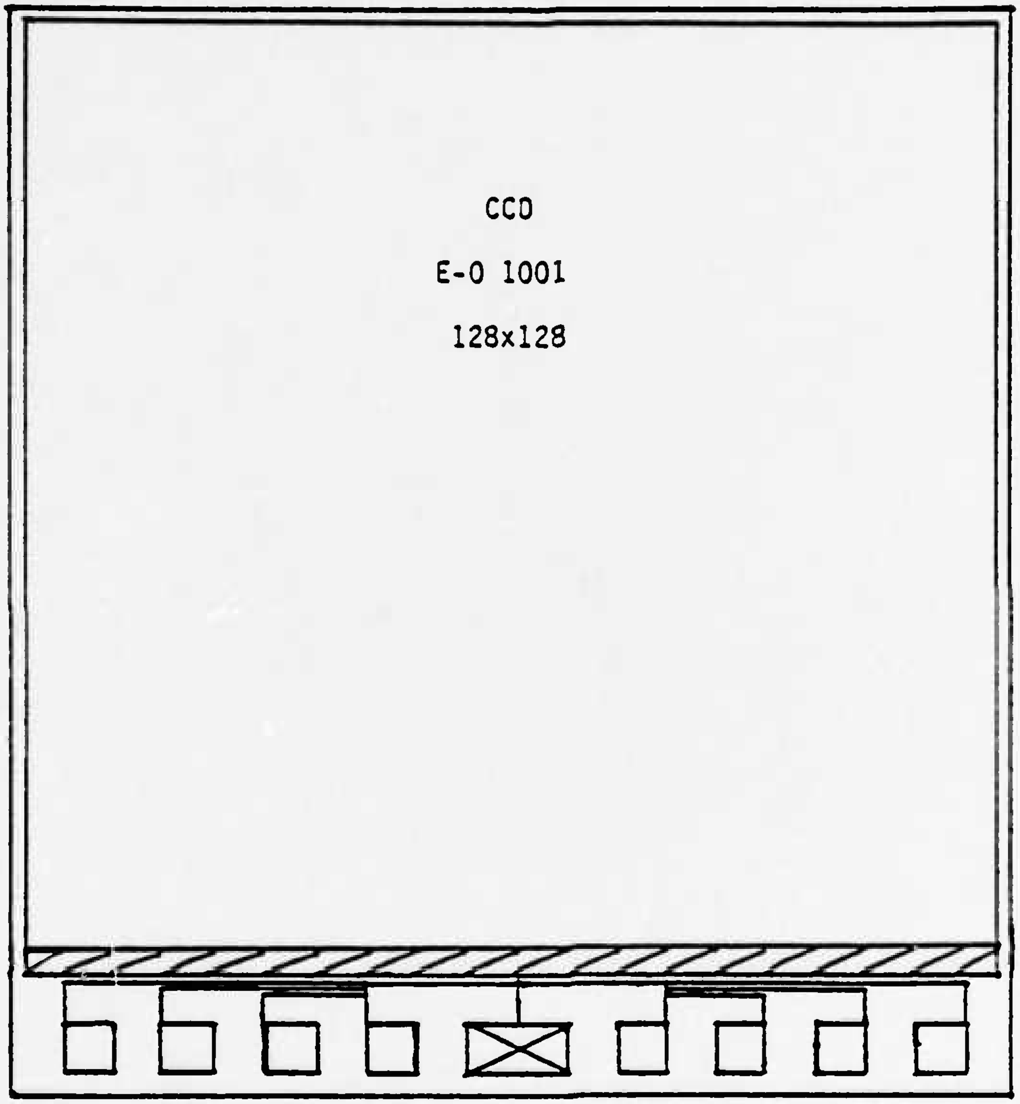


Fig.2 Top-view of CCD imager E-0 1001 (Front side ulluminated). bonding pads are located on one side near the output mux.

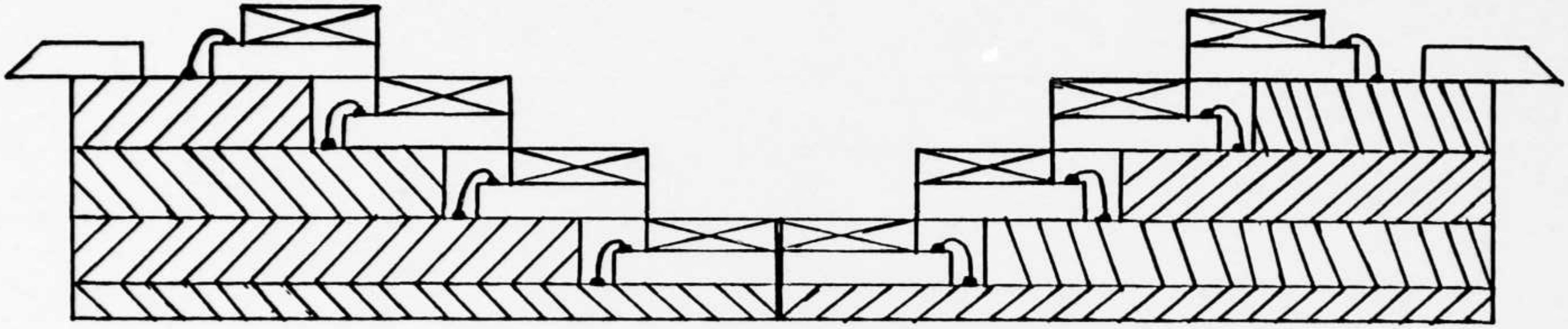


Fig.3 Cross-Section of X-Ray Imaging Panel (4 x 5 inches)

The output pads can be re-designed to fold back under the active area of the device. The pads will be isolated from the device by the oxide and the same dead space reduction as in the shingled case can be achieved. It is possible to use this technique in the back side case and not the front side case, because doing the same modification in the front side case would make the output pads block some of the active area. In the back illuminated case the pads are under the CCD and therefore not between the device active area and the x-ray source. Figure 4 shows the "folded-pad" design.

Packaging the assembly of 64 individual CCD imager into one large area unit is critical to the long term usefulness of the unit and the repairability of the unit when elements fail. The large area x-ray detector must be repairable in a most effective fashion. In order to accomplish these ends, two design concepts seem viable. The first is a concept where a subzone mother board is employed to hold the individual imagers in a shingled configuration. The imagers will be wire bonded to the mother board. In the second concept, the case of back illumination, the imagers will be bump bonded to the mother board. In both cases the mother board is then soldered to the interconnection cables. A repair in these cases at the individual CCD imager level must be done at the factory since shingling and flipchip bonding require special assembly and alignment equipment. Repair at the zone and subzone level, however, can be easily accomplished.

An alternate technique for a zone is the assembly of the individual CCDs onto individual substrates. These substrates could be bolted together to form a zone assembly consisting of 8 individual CCDs on their own substrates.

After the zones are assembled, eitht zones then could be bolted together to form the 64 element large area x-ray imager. This assembly could be easily field replaceable down to at least the zone level, and probably the subzone assembly level by unbolting the assembly, removing the bad zone or subzone, inserting a new one, and bolting it back together. No special alignment or handling would be required. Repair at the zone level seems especially natural and easy, since the first level of multiplexing, in this concept, occurs at the zone level by multiplexing the individual elements of a zone into a data stream. This means that the system is completely modular, and any malfunction, optical or electrical, can be repaired in the field by replacing a zone. A zone, in this concept, consists of the 8 individual CCDs on two mother boards bolted together and soldered to an interconnect cable, which is in turn soldered to an 8 to 1 multiplexer on the output and to the drives and biases on the input. A malfunction

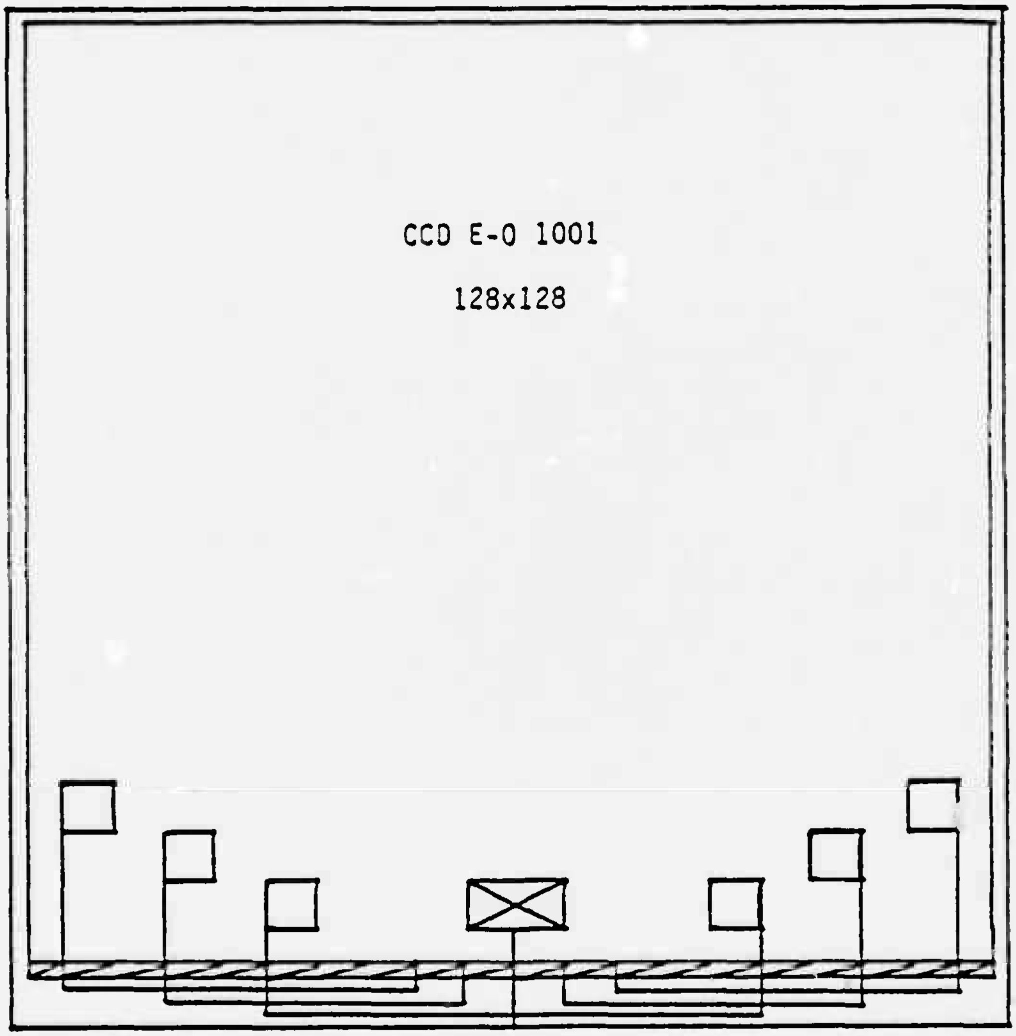


Fig.4 Top view of redesigned CCD imager E-0 1001 (backside illuminated). All bonding pads are folded over and located on top of imaging section.

10

could exist in the down stream elecronics, but this also could be field replaceable since the remaining electronics are also modular in their functions. These remaining functions are an additional 8 to 1 multiplexation to put the 8 zones into one data stream and a frame grabber. Figure 5 shows the panel configuration.

The modular approach allows for future growth in size. The size of the imaging array is effectively unlimited. Structurally all that is needed is longer bolts in one dimension and more individual CCD imagers per subzone in the other dimension. Electrically it is expandable also. A larger array simply means more multiplexation, which is within todays technology. The limiting factor, as to size of the array, is the number of pixels that must be processed within a given period of time. If a larger number of pixels must be processed within the same frame time, the CCD imagers must run faster. There will be some upper limit to this speed depending upon the maturity technology. Present technology would allow the expansion of imaging array active area by at least an order of magnitude. Future technological improvements could increase the possible array size even more.

In addition to increases in size, this approach in particular, using the back illuminated concept, allows improvements in detection by the implementation of other detection schemes than scintillators. The use of a P-I-N structure for detection could possibly lead to greater detection with radiation dosage and be particularly useful in the x-raying of soft tissues.

B. COMPONENTS:

The critical components of an x-ray imaging panel are both the CCD design and the multilayer board, which provides the interconnect bus system for the chip integration. Figure 7 and 8 show both the horizontal as well as the vertical leads, which are interconnected at the cross-over points. It is apparent that larger CCD devices will result in fewer bus lines, which in turn leads to less shorts. During the course of the program the market for large CCD devices, developed from a research level to custom production quantities, grew. Larger chips require better production environment as well as a higher level of process integration. The process, presently used to fabricate the 128 x 128 imager, is listed in the following process - follows:

CCD Array Processing - Processing of wafers will follow established process steps as follows:

	Process Step	Mask Used
1)	Four inch dia silicon wafers .020 thick, P-doped (30-50 ohm cm).	
2)	Oxide - 500 angstrom	
3)	Nitride - 400 angstrom	
4)	Etch oxide & nitride	1) Active area mask
5)	Field oxidation - 1 micron	
6)	Phosphorus implant buried channels at $1.2\text{x}10^{12}$ Atoms/cm ^{2}	2) Buried channel mask
7)	Poly Silicon - 6000 angstrom	
8)	Phosphorous Dope Poly Si	
9)	Etch Poly Si	3) Poly #1 mask
10)	Oxidize Poly Si - 3000 angstrom	
11)	Deposit Poly Si - 6000 angstrom	
12)	Phosphorous Dope Poly Si	
13)	to 16) - Repeat (9) thru (12)	4) Poly #2 mask
17)	Etch Poly Si	5) Poly #3 mask

	Process Step	Mask Used
18)	Oxidize Poly Si - 3000 angstrom	
19)	Etch Nitride	
20)	Arsenic Implant Source/Drain Area at $5x10^{15}$ Atoms/cm ^{2}	
21)	Oxidize - 700 angstrom	
22)	Etch Oxide	6) Contact area mask
23)	Deposit aluminum - 1 micron	
24)	Etch aluminum	7) Metalization mask
25)	Deposit glass - 1 micron	
26)	Etch glass	8) Pad mask
27)	Clean wafer backside	
28)	Metalize backside	
29)	Anneal wafer	

Figure 9 shows a 4 inch silcon wafer containing four one inch square CCD imager chips. It should be noted, however that it will require a dedicated process line to produce sufficient quantities at acceptable yield levels. The capital investment for such a production facility will be in the range of $10M, with the help of partially used equipment.

The design and manufacturing of the pc-boards, enclosures, and cables utilize standard technologies and can therefore be competitively procurred.

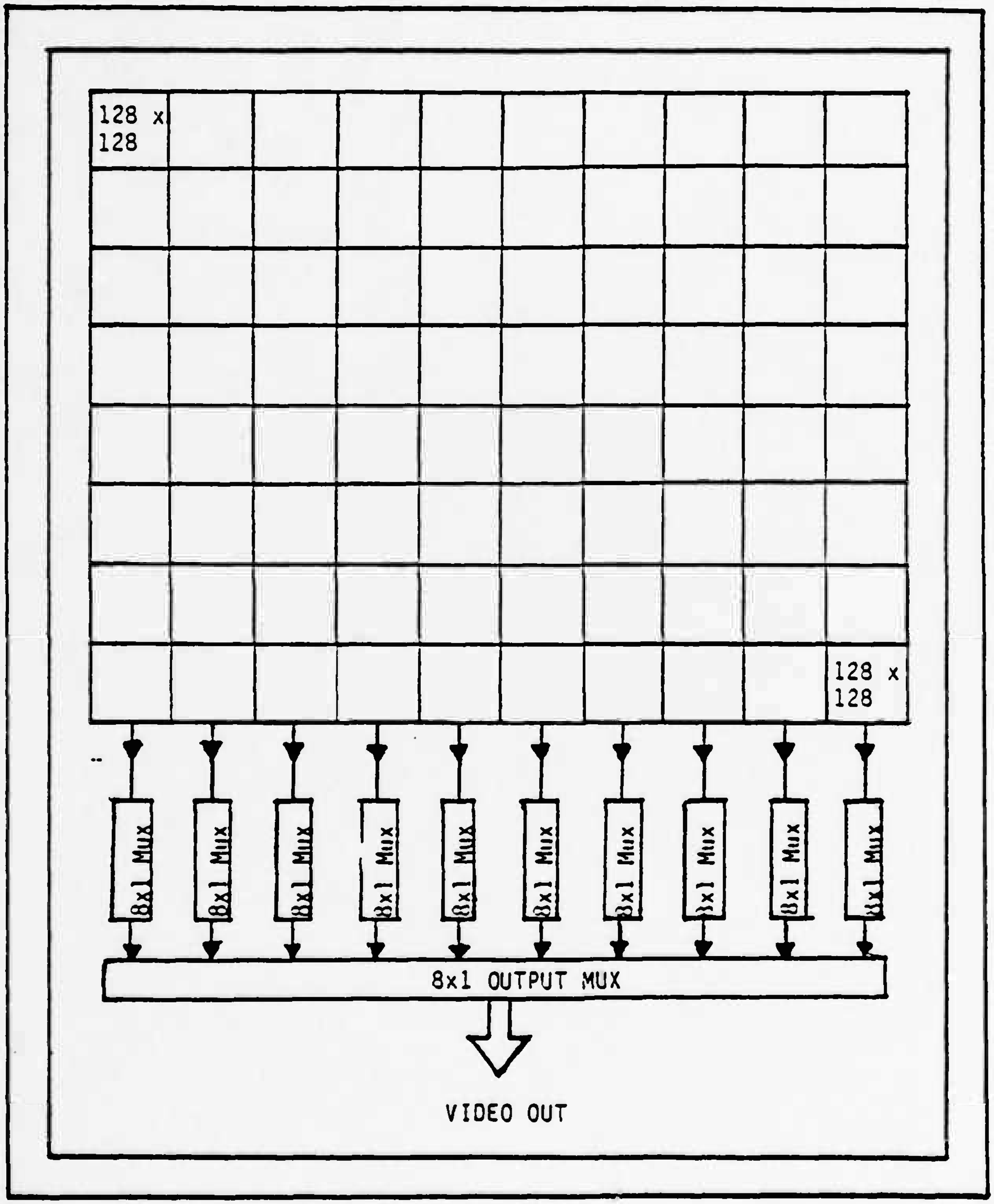


Fig.5 5x4 Inch x-ray Imaging Panel (1280x1024 Pixel Format)

C. ELECTRONICS:

The electronics we have developed for the dental panel (2x3 CCDs) can be modified to run a block of 10 CCDs in the same way without much change in the total read time. The 4'x5' (8x10 CCDs) panel can be divided up into eight rows of ten CCDs each. Each block can then be operated independently from the other seven (parallel processed). The image produced by each block can then be stored in a designated area in the memory. The data in memory can then be displayed or processed further etc.

$$T10 = T6 + Te$$

where.

T10: Time to read block of 10 CCDs (in micro seconds).
T6: Time to read block of 6 CCDs (in micro seconds).
Te: Extra time needed to read the 10 CCD block.

As can be seen from the above, the total read time for a block of 10 CCDs depends on the resolution of the CCDs used.

Te = 65600 micro seconds for 5 lp/mm.
Te = 263000 micro seconds for 10 lp/mm.

Figure 6 shows the schematic of 0 the parallel processor.

LARGE PANEL PARALLEL PROCESSING

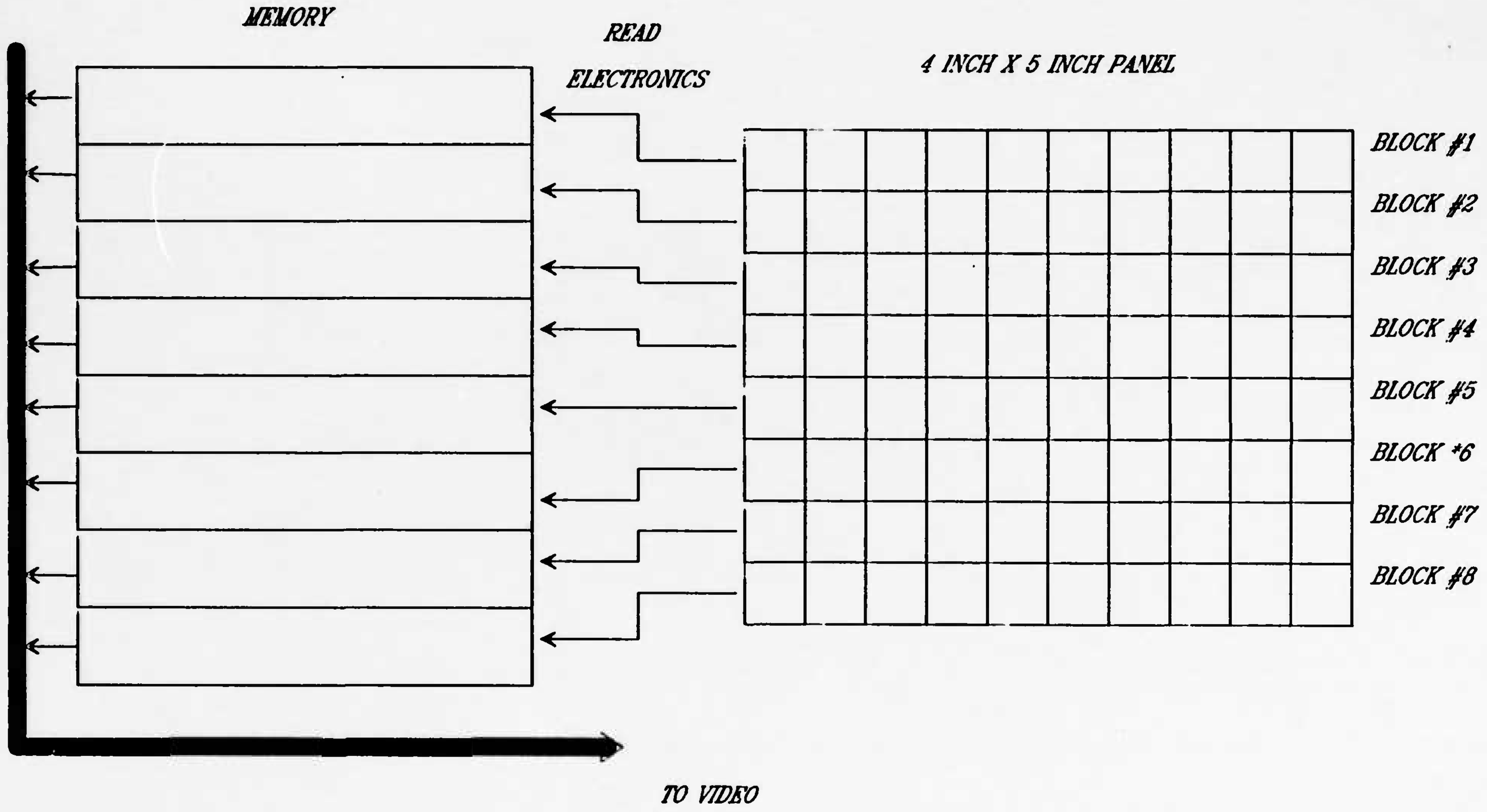


Fig.6

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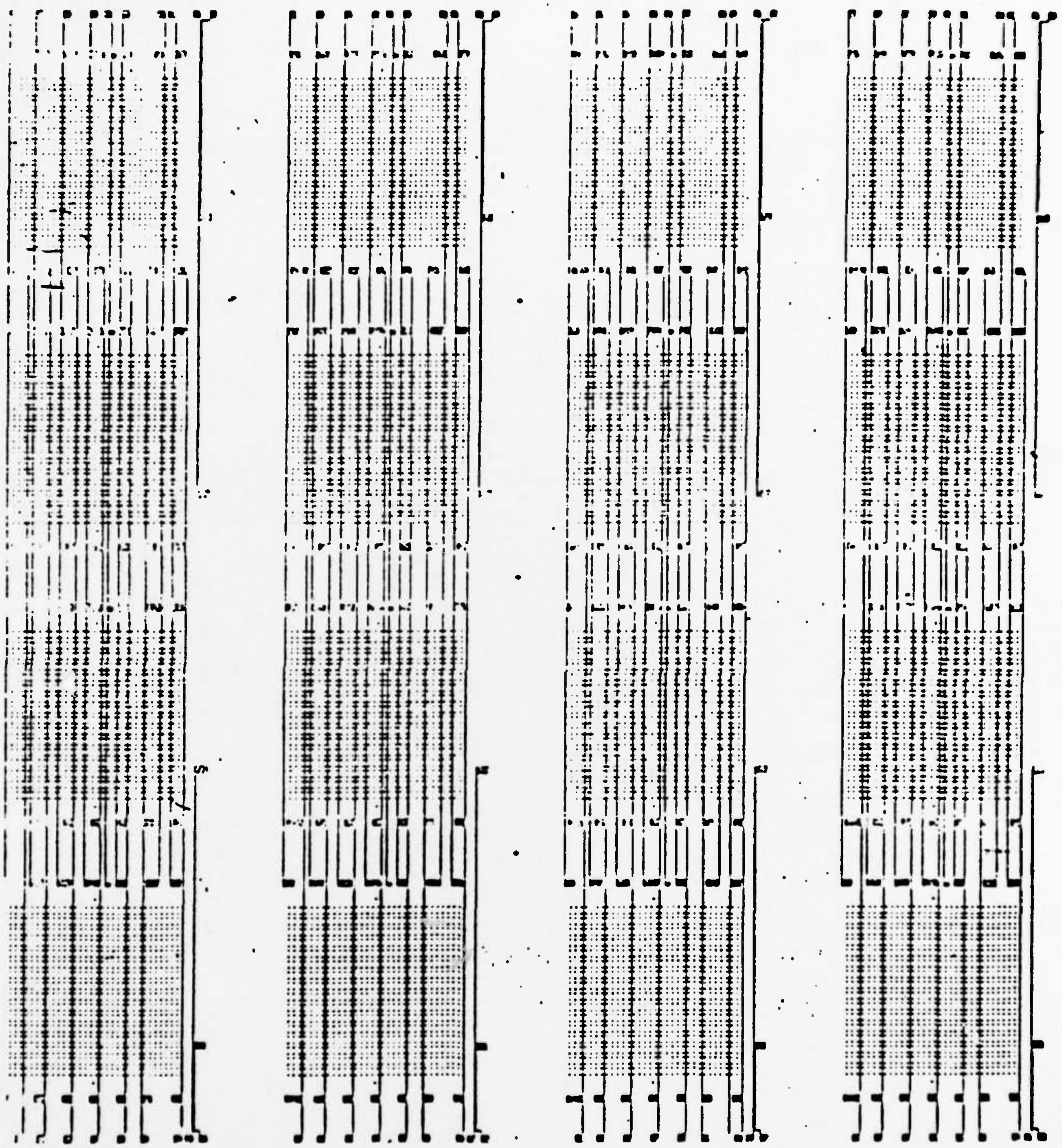


Fig.7 VERTICAL BUS INTERCONNECT SYSTEM

16

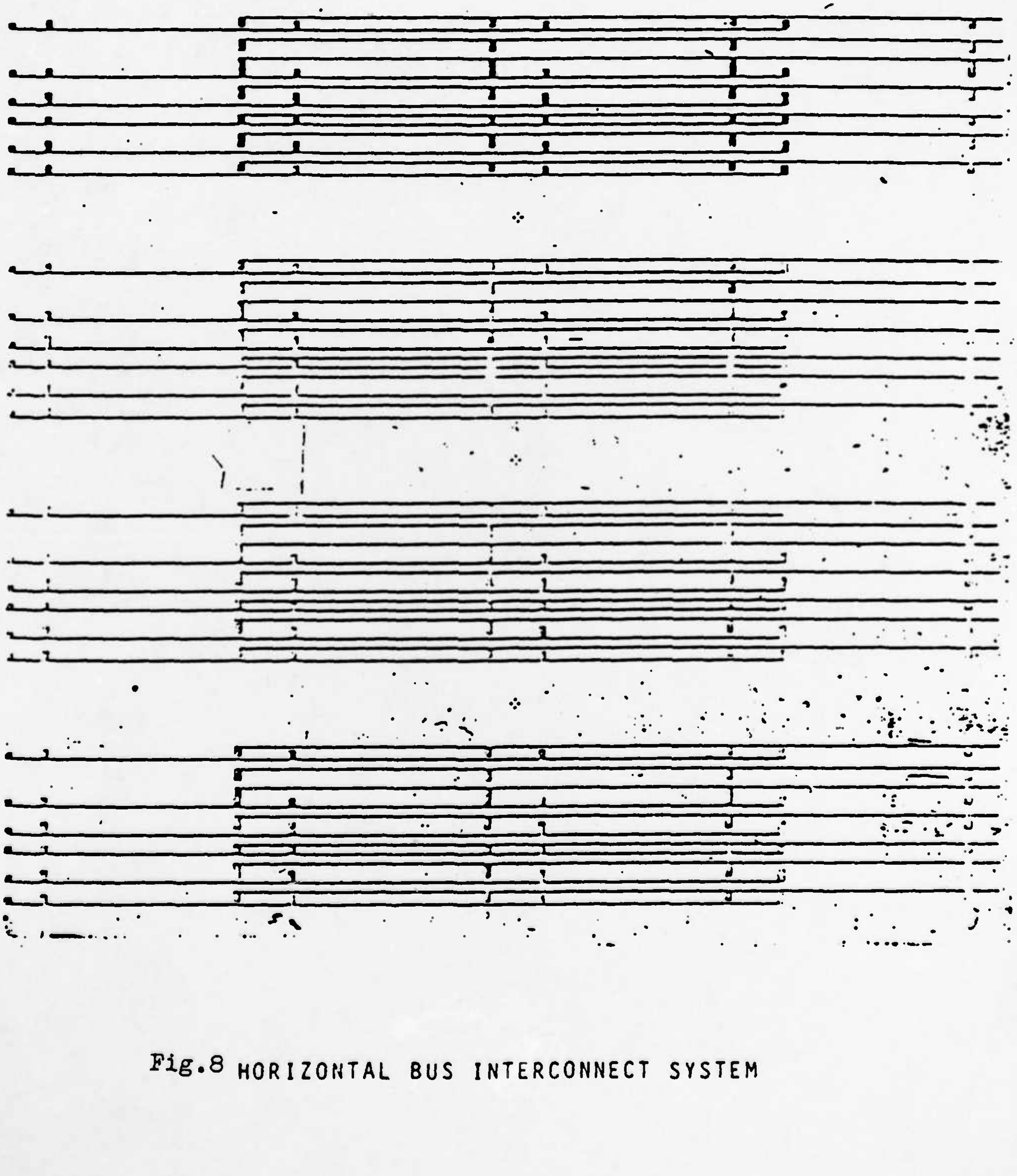


Fig.8 HORIZONTAL BUS INTERCONNECT SYSTEM

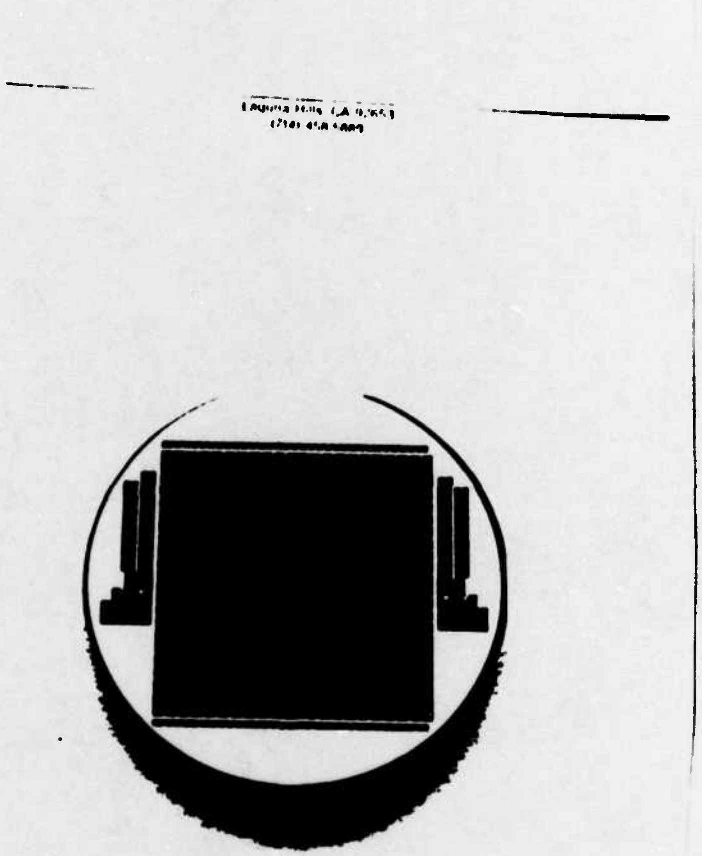


Fig.9 Wafer with four one inch diameter CCDs

D. RADIATION DAMAGE:

The Charge Coupled Devices (CCDs) used in this application are subjected to x-ray radiation, ranging from 25 to 100 mrad. The dominant effects resulting in either permanent or operational (temporal) damage can be described in the following way. Doses, exceeding 1000 rad, will induce permanent charging sites in the gate oxides, and create deep level traps in the bulk silicon, which is the substrate material for the CCDs. The effective results of these damages are increased levels of dark current and shifts in threshold voltages. The latter effect will reduce the performance, in particular the charge transfer efficiency, which will produce poor imaging qualities.

Figure 11 shows a typical x-ray noise spectrum of a CCD device, fabricated by a standard MOS process. The spectrum can be described as the number of equivalent noise electons, measured by integrating the noise spectrum over the Nygnist bandwidth by evaluating the following integral:

$$N^2 = \frac{1}{R^2} \int_0^{fc/2} V^2(f) \frac{1}{G^2(f)} \, df$$

where N = equivalent noise electrons
R = responsivity of the CCD in V/electron
V(f) = normalized noise voltage from spectrum
G(F) = Sin (IIftc) IIftc
tc = 1/fc
fc = CCD clock frequency

The equation is the equivalent standard deviation on the number of electrons per charge packet.

X-rays, not absorbed by the scintillator, will generate electron/hole pairs in the CCD depletion regions. However, the number of carriers generated can be neglected when compared with the thermal noise, as well as the signal elctrons, induced by the scintillator photons at 550mm.

The low radiation doses used in this application (10-20 mrem) will have no significant effects on the operation of an x-ray imaging panel. From experimental evidence, obtained during the development of an intra-oral x-ray panel, one can conclude that the critical dose will be in the order 10 exp 5 rad, provided, that the imagers are fabricated to use a radiation hard process. The CCDs used in the intra-oral panel are fabricated by an DNA CCD radiation hard oxide.

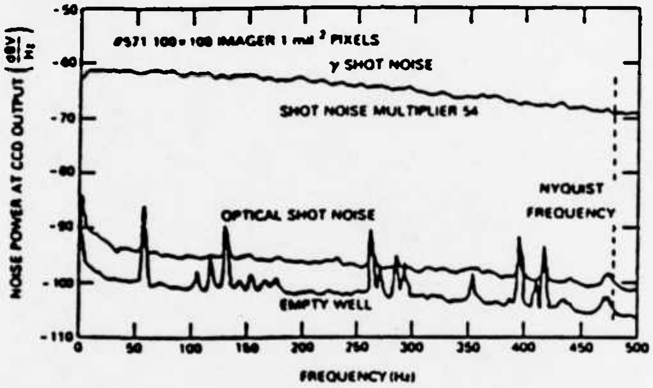


Fig. 10 Shot Noise Spectrum of Buried Channel CCD

E. COST ANALYSIS:

SYSTEM LEVEL

A preliminary system level cost analysis was performed to assess the viability and competiveness of large area digital x-ray imaging panels. It was assured that the panels are to be constructed in a modular fashion, with a basic module dimension of about 2x2 inches. Also, it was assumed that the military units will meet MS 38510 specification for compactness, ruggedness, and quality. The figures represent approximation, but can be scaled up- and/or downwards, depending on quantities assumed. One can conclude that the unit costs projection will meet these requirements.

The following graphs represent digital x-ray imaging systems, consisting of a configuration of a 4 x 4 size. The panel size covers an area of 1250 square mm. A mathematical model should be developed to establish the cost scale factors for larger panels and advanced electronics.

COST EMTIMATES FOR ARMY PRODUCTION UNITS

CALENDAR YEAR 1990	OPTION A	OPTION B	OPTION C	OPTION D
ARMY QUANTITY	10	100	500	1000
COMMERICAL QUANTITY	350	350	350	350
TOTAL	360	450	850	1350
ARMY UNIT PRICE	$27,000	$23,000	$16,500	$13,500

CALENDER YEAR 1991	OPTION A	OPTION B	OPTION C	OPTION D
ARMY QUANTITY	500	1000	2000	3000
COMMERICAL QUANTITY	880	880	880	880
TOTAL	1380	1880	2880	3880
ARMY UNIT PRICE	$14,500	$13,000	$11,500	$10,750

NOTES

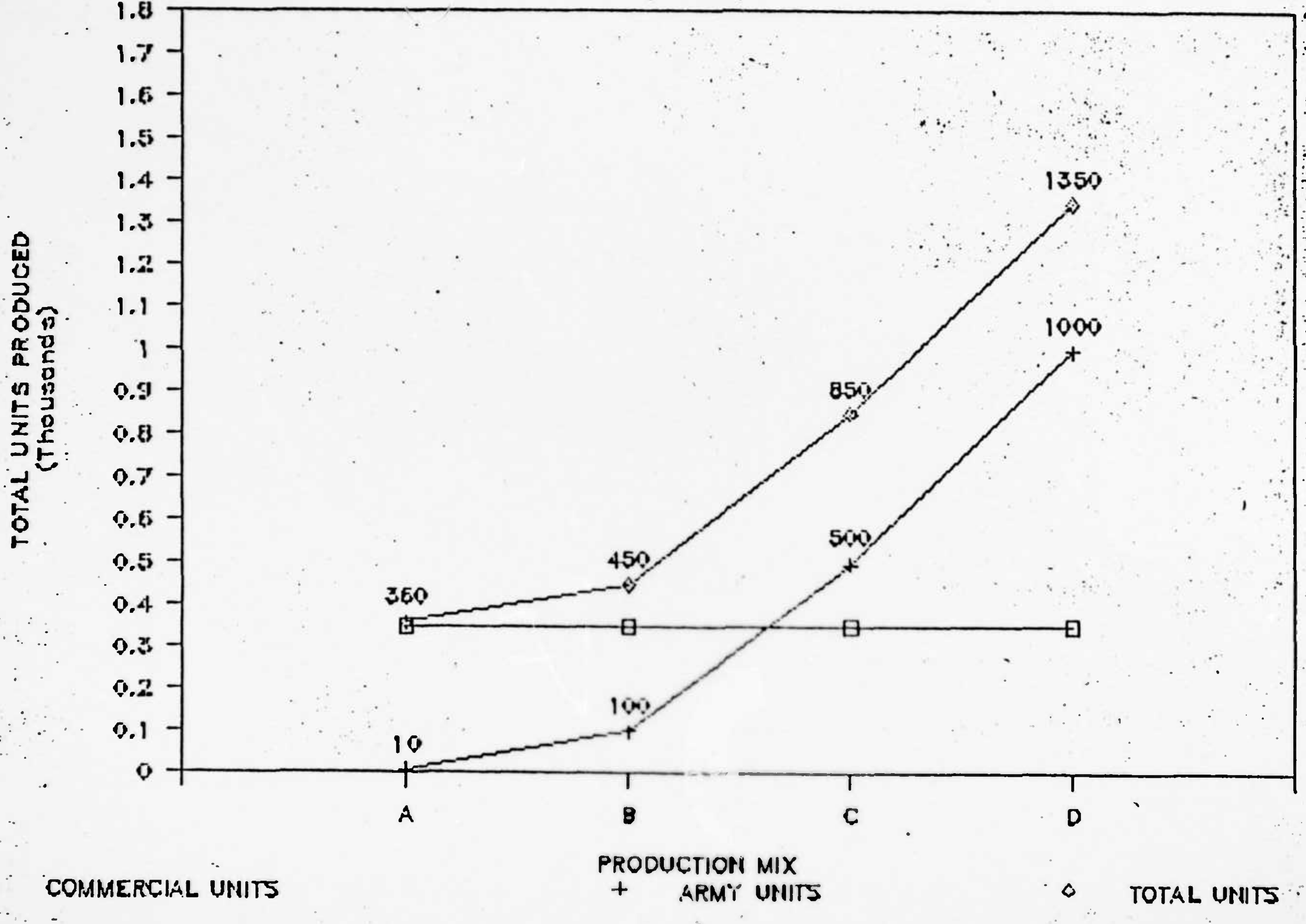
(1) ARMY DIGITAL DENTAL XRAY IMAGER UNIT - HIGH PERFORMANCE UNIT. MEETS MILITARY QUAL AND REL SPECIFICATIONS (e.g. MS 38510).

COMPACT AND RUGGEDIZED.

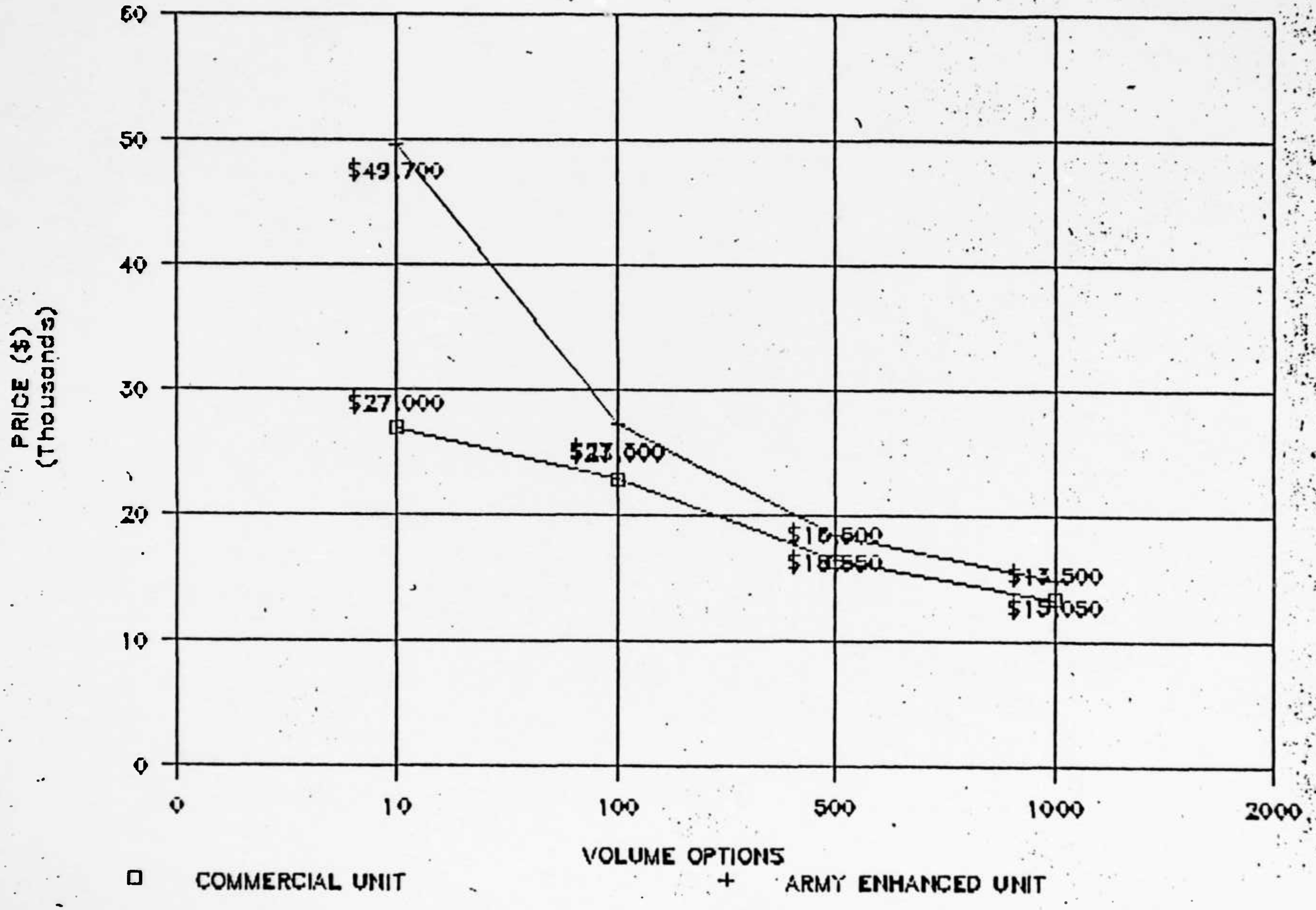
(1) PRICING ASSUMES COMMERICAL BASELINE PRODUCTION AT RATES LISTED.

PRODUCTION OPTIONS

(1990)

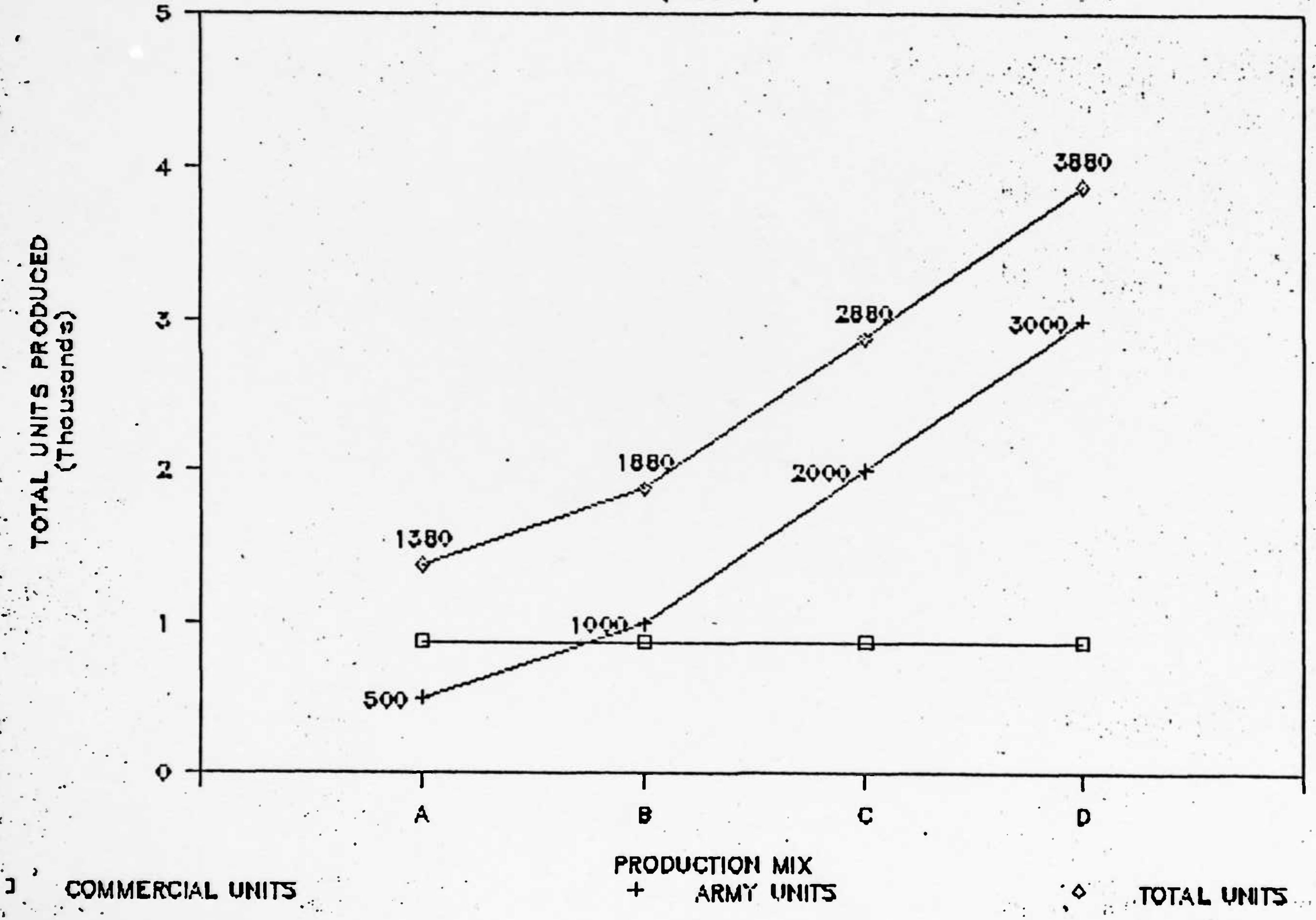


PRICE vs VOLUME - 1990

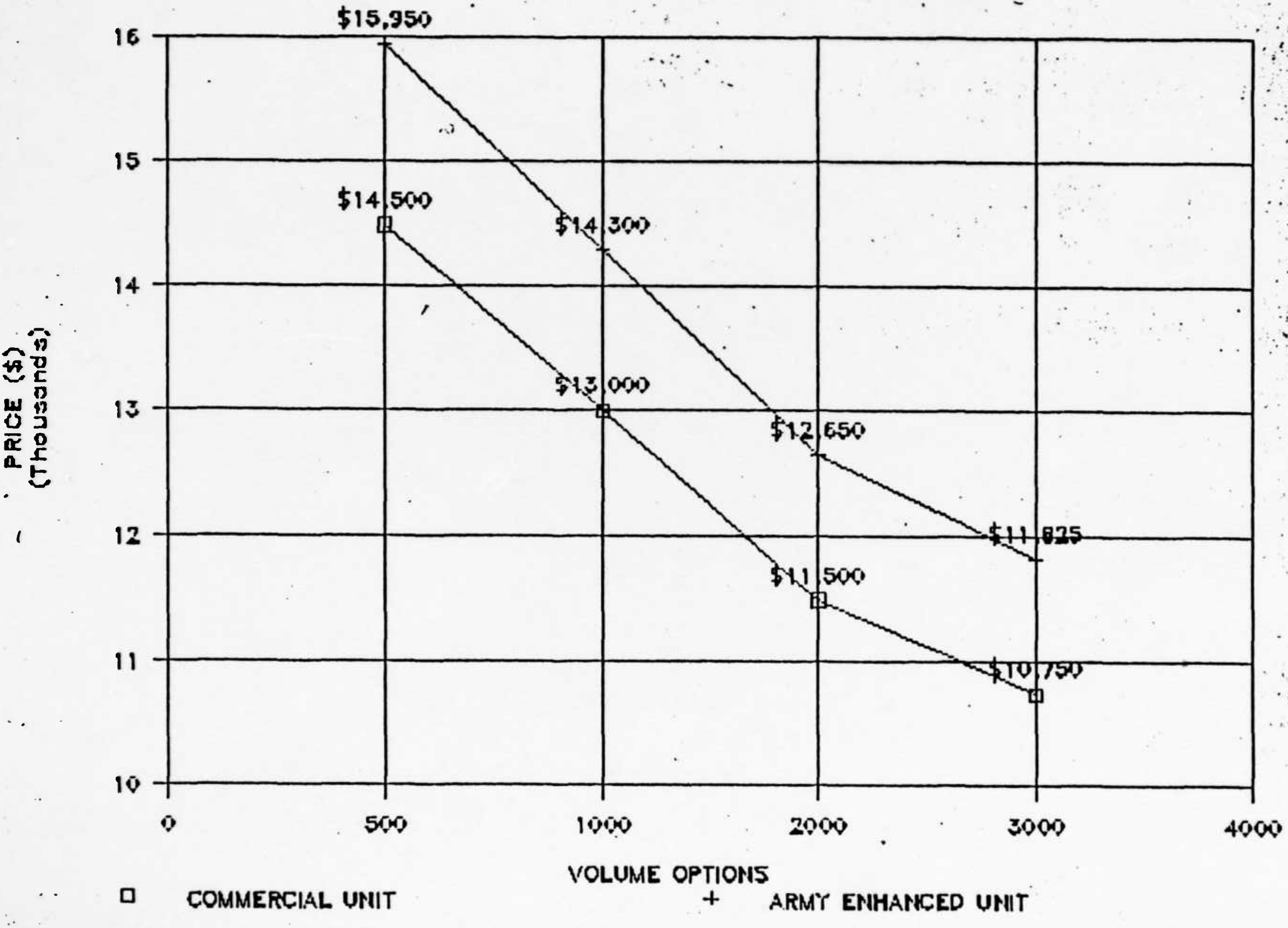


PRODUCTION OPTIONS

(1991)



PRICE vs VOLUME - 1991



III. CONCLUSIONS AND RECOMMENDATIONS

Design trade-offs, performance assessments, and a cost analysis were established for large area digital x-ray panels. It was concluded that larger than 4x4 inch panels are technically feasible at reasonable costs.

A large panel model was constructed to evaluate pertinent construction issues, such as assembly and bus line routing.

It is recommended that a 4x4 inch panel should be constructed during Phase II of this program. CCD components for this project are already developed and can be readily manufactured. The project would include fabrication of the multilayer board, and expanding the existing electronics to adopt the multichannel outputs. Testing and characterization will be part of the proposed project.