Conf-8310217--1

COMPUTED TOMOGRAPHY STATUS

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SUMMARY

Computed tomography (CT) is a relatively new radiographic technique which has become widely used in the medical field, where it is better known as computerized axial tomographic (CAT) scanning. This technique is also being adopted by the industrial radiographic community, although the greater range of densities, variation in sample sizes, plus possible requirement for finer resolution make it difficult to duplicate the excellent results that the medical scanners have achieved.

INTRODUCTION

CT displays a radiographic cross-section of a solid object, as if the object had been sliced, and viewed normal to the slice plane. There is no overlapping of images as there is in conventional projection radiography. It is also more sensitive to small changes in density than conventional radiography--typical medical systems claim 0.5% sensitivity, compared to 1% to 2% sensitivity for projection radiography. The best spatial resolution claimed by the medical scanners is in the 0.5 mm range.

CT data is taken by scanning a beam of X-ray photons through a well defined planar section of object, and detecting the transmitted beam with an electronic detector, as depicted in Fig. 1. There are various conventional scan geometries which have been "named". The simplest is the "first generation", where a single detector is used and the beam is translated through the object in the scan plane, taking 10 to 1000 data points depending on resolution required. Each data point represents a line integral of density through the part. These data points together constitute one "projection". The object is then rotated about an axis perpendicular to the scan plane and another projection is taken. Again depending on required resolution, tens to hundreds of projections are taken, covering at least 180 degrees of object rotation. A "second generation" scan uses an array of several detectors, taking several projections in one translation of the part. The X-ray beam must be fanned out to cover the aperture spanned by all the detectors. A "third generation" scan has sufficient detector array aperture to allow all data to be taken by rotating the part only--no translation is necessary. Finally, a "fourth generation" configuration refers to a ring of 360 degrees of detectors surrounding the part, and only the source moves, encircling the part once to gather an entire data set.

When the data is taken, it must be "reconstructed" into an image. There are various algorithms for this, depending on the nature of the object, scan geometry, and processing computer. A reconstruction may take many minutes on a general purpose minicomputer, or a few seconds on the special-purpose, hardwired, pipeline processors used on the medical scanners. Once a digital image exists, it is displayed using video techniques, and since it is in digital form, it is convenient to apply many "conventional" image processing techniques, such as zoom, psuedocolor, etc.

The medical field is nearly an ideal arena for development of CT technology, in that the objects of interest are roughly the same size, and constructed of well-known materials which don't vary greatly in density. The market is also well established, and many man-years and millions of dollars have gone into development of medical CAT scanners. A typical medical scanner costs from .75 to 2.5 million dollars. Industrial scanners have not become as popular. Unfortunately, the proper radiographic source, detector type and size, and part handling hardware are all very strongly dependent on object material and geometry, making it nearly impossible to build a "general" CT scanner for industrial radiography. This situation implies a rather uncertain market for industrial machines, which causes them to be rather scarce.

LITERATURE SURVEY

There is a large quantity of literature in the medical journals, most of which deals with how to use the medical machines, giving case histories and diagnostics performed with CAT scanning. We have not investigated this category since it does not seem applicable to industrial radiography. We did subscribe to the <u>Journal of Computer Assisted Tomography</u>, which is unfortunately wholly medical in content--we will not renew our subscription. We do have copies of several reports and reprints which are useful. The reports are all status or final reports on government contracts to investigate tomography for specific applications--mostly rocket motor inspection. There appears to be no particular journal towards which technical articles on CT have gravitated, although the November, 1982 issue of

Materials Evaluation was devoted to tomography, as was the March, 1983 issue of Proceedings of the IEEE.

There have been several books published on the subject. Two which we have obtained copies of, and which appear to cover the "how and why" quite adequately, are:

G. T. Herman, Image Reconstruction from Projections, Academic press, 1980.

T. H. Newton and D. G. Potts, ed, Radiology of the Skull and Brain, Volume Five: Technical Aspects of Computed Tomography, C. V. Mosby co., 1981.

Dr. Herman has two other books on the subject, which we have on order:

G. T. Herman, Image Reconstruction from Projections: Implementation and Applications, Springer, 1980.

G. T. Herman, Mathematical Aspects of Computerized Tomography, Springer, 1981.

Dr Herman relied on computer simulation for many of the examples and conclusions in his book. The simulation software, called SNARK77, is evidently in the public domain, and is available from him for a $100 copy fee at the following address:

Dr. G. T. Herman
Radiology Associates
Medical Imaging Section
Hospital of the University of Pennsylvania
3400 Spruce St/G1
Philadelphia, PA 19104
(215) 662-3000

We have ordered a copy of this software.

There is also another public domain software package, available for free:

Donner Algorithms for Reconstruction Tomography
Available from:
Research Medicine Group
Donner Laboratory
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720
Attn: RECLBL library

This package doesn't have as extensive a simulation capability as the SNARK77 package, but it seems to be more commonly used for reconstruction of real data.

There are also some brochures put out by GE which give a very readable introduction to CT, with lots of diagrams (many of which I borrowed for the spoken version of this presentation):

> GE Medical Systems Division, Brochure no. 4691: "Introduction to Computed Tomography"

> IBID, Brochure no. 4870: "Technical Performance of the CT/T System"

CONTACTS AND VISITS

To get the most timely information on who was doing what in industrial CT, and to get a better feel for the magnitude of the task by viewing some hardware, we felt that some visits to various people who were active in the field were in order. The following is a chronoligical list of our tomography related trips, with commentary. Here, JWG refers to Jim Guthrie, and BDH refers to Bruce Hansche, both SNLA Div. 7551.

Mar 17, 1982 JWG, BDH LANL

We spoke with Roger Morris, Ron Strong, and Dick Kruger, and toured their labs. They have a home-built first generation system, under the control of a DEC PDP/11. They do reconstructions on their VAX, and display data on their COMTAL. They have both isotope "pigs" and tube sources, shielded to allow alignment of the system by hand. Their collimator consists of two orthogonal "slits" made of a high density machinable tungsten alloy , each micrometer adjustable, so they can obtain any rectangular aperture down to a few thousandths of an inch.

Kruger has done some studies of reconstruction algorithms, involving both experiment and simulation, which he describes in a paper in the November, 1982 Materials Evaluation. He indicated that he might be leaving LANL soon, and indeed he is now with SAI in Arizona.

Dec 7-9, 1982 JWG Advanced DoD Manufacturing Technology Radiological Planning Workshop, Phoenix, AZ.

This meeting was cosponsored by the DOD Manufacturing Technology Advisory Group (MTAG) and the American Society for Testing and Materials (ASTM). An MTAG report containing general and background information, workshop program, conclusion and recommendations is available.

The workshop program included the following sessions:

Real Time Imaging
Computerized Axial Tomography (CT)
Digital Enhancement
Automatic Image Analysis

The sessions consisted of two state of the art paper presentations and a workshop panel discussion. CT presentations were made by:

1) Tom Kincaid, NDT manager for General Electric Company, Schenectady, New York, who described the CT capability developed for the tri-service funded Integrated Blade Inspection System at GE's Evendale, Ohio jet engine facility. (That system and a visit to Evendale is discussed elsewhere in this report).

2) Harvey Peck, Operations Program Manager, Aerojet Strategic Propulsion Company, Sacramento, California, who described two CT systems under construction at Aerojet which were commissioned by the Materials Laboratory, Air Force Wright Aeronautical Laboratories, Wright Patterson Air Force Base, Ohio. The charter of these systems is to significantly improve the capability to inspect tactical and strategic solid rocket motors and their components.

   A major emphasis of the Aerojet effort was the transition from medical CT applications to industrial CT applications in terms of system design. Design work on the Aerojet CT units was done in conjunction with the Advanced Research and Application Corporation (ARACOR) in Sunnyvale, California.

<u>Jan 26, 1983</u> JWG, BDH Advanced Research and Applications Corp (ARACOR), Sunnyvale, CA.

We met with Jim Stanley, Alan Young, Mike Boyle, and S. Thomas Workman. ARACOR is a major part of the design team for the two large CT systems being installed at AEROJET for the Air Force (AF/ACTS-I and II--see May 12, 1983 below, and Fig. 3). They are a "high-tech consulting" firm, and have had previous dealings with SNLA (R. Schellenbaum, 9252). They have an extensive simulation program which includes beam hardening, scattering, and divergence. We approached them later (May 83) about the possibility of our purchasing this software, but their current decision is not to sell it. They will use it to study individual problems on a consulting basis. The existing scanner is also available for "demonstration projects" through AEROJET.

They indicated that our desire to build a "general purpose" CT scanner was unrealistic, and suggested that we do a more thorough internal "market survey" to set some bounds on object size, material, and required resolution.

They have a design for a high resolution (a few thousandths inch spacing) detector array which they would like to build a system (a "tomographic microscope") around. We intend to follow this up, perhaps joining with LANL to fund a development project.

Jan 27, 1983 JWG, BDH SNLL

We met with Chuck Oien, 8444. Chuck did a Masters thesis in tomography of nuclear fuel bundles using a limited number of views. His thesis advisor operates a consulting firm, and one of their specialties is CT. They are:

John and Claudia Barton
Neutron Radiography Consulting
5709 Waverly Ave.
San Diego, CA
714-459-7604

Chuck has a contract with Scientific Measurement Systems to do CT on hot isostatic pressed (HIP) pressure vessels--they are looking for wall thickness variations (lack of concentricity) on the order of .005 inch. In a follow-up call on June 2 1983, Chuck said that they were happy with the results so far, and would continue the program. (He did feel that there was an unjustifiable delay in processing and reporting on the data.)

Jan 28, 1983 JWG, BDH Science Applications Inc. (SAI), San Diego, CA.

We met with Raulf Polichar, and John Reed. They are designing a CT inspection system for nuclear reactor plumbing systems, funded by the Electric Power Research Institute (EPRI). They have a prototype, but didn't seem inclined to show it to us, nor did they give us a copy of any relevant reports. (We obtained one of the reports later). Some of the preliminary experiments for this work were done at LANL with Dick Kruger, and are described in his paper in Materials Evaluation.

They also suggested that there is no such thing as a "general" CT scanner, which reinforced ARACOR's suggestion that we narrow our field of object types. They would be interested in any type of consulting contract, either hardware or software. We didn't discuss detector hardware at all, and it wasn't clear whether they have any expertise in that area.

Mar 10, 1983 JWG, BDH Scientific Measurement Systems, Austin TX.

We met with I. Lon Morgan (President) and Hunter Ellinger. They gave us a tour of their facility, and showed us pieces of detector arrays being assembled. Their detector is based on a plastic (NE102) scintillator coupled to a cheap photomultiplier. The individual channels are rather bulky, with an aperture of perhaps .5cm by 2cm. Their current "workhorse" CT system employs 31 active detectors, and one reference channel. They use a variable aperture lead collimator in front of the detectors, and a modified second or third generation scan which involves indexing the detector array between scans to decrease distance between sample points. They feel that they are adequately covered by patents on thier detector system, and the typical "proprietary paranoia" seemed absent.

They were in the process of scanning Chuck Oien's HIP pressure vessels when we were there. They operate a "job shop" scanning operation, supply components and systems, and do consulting work. They have also done some scans of a safe transport trailer for R. H. Yoshimura (9783). They have a simulation program which allegedly models scattering, beam hardening, and beam shape, and they indicated that they would be interested in selling this software. It's not clear what relationship this software bears to the SNARK77 code, if any.

They will also sell their detector array in increments of 8 channels. A 32 channel unit would cost about $40k, excluding the CAMAC crate (which is necessary to interface their hardware to a computer).

Apr 19, 1983 JWG, BDH Aircraft Engine Group, GE Cincinnati.

We met with Chuck Wojciechowski, and Hank Scudder. Hank is from the GE research labs in Schenectady, and was visiting at the time. GE's prominent position in the medical field is largely a result of work done at the Schenectady labs. Incidentally, GE has apparently made a large commitment to production of NMR medical scanners.

The Cincinnati lab is within the IBIS program (Integrated Blade Inspection System), which is a joint military funded program for inspection of turbine blades by visual, dye penetrant, x-ray (including CT) and infrared means. The CT system they are currently using is totally company funded, however, so detector development efforts are not in the public domain.

They are designing an ionization chamber detector for industrial CT application. While they weren't interested in selling detectors "off the shelf", they would be interested in a development contract for high resolution detectors.

They were debugging a new feature in their system on the day of our visit, so we saw no scans done, but they displayed some stored images of turbine blades for us. They were impressive, the cooling channels being visible. They claim .010 inch resolution, but we saw no resolution calibrations.

May 4, 1983 BDH American Science and Engineering (AS&E), Cambridge, MA.

I met with Ted Kirchner (Vice Pres., Program Development) and Paul Burstein (Senior Staff Scientist). They showed me some slides overviewing the company, and some specific to CT. They also gave me a tour, and I saw the handler for the CT prototype they built for the Navy. They have about 200 employees, about 20 in CT work (including the Trident program).

They were in medical CT for a while--they built about 25 4th generation scanners, but sold that part of the business to Pfizer. They still make a scanning X-ray system called "Microdose", which uses a rotating aperture and a single large detector. They make both medical and baggage inspection systems (no baggage systems in use in the US). The images on one of their baggage systems were quite impressive--we might look at one for electronic radiography applications in the future.

They built a prototype CT scanner for the Navy, to scan Trident rocket motors. This was reported in the November 1982 Materials Evaluation. Their images are among the best I have seen. The Navy program is continuing, with the development of a full-scale Trident motor scanner (Fig. 2).

They will not sell or reveal details about their components or software--they are only interested in systems, or prototypes which could lead to big (many hundred k$) contracts. They do not do "job shop" CT, but seemed somewhat interested in getting involved in that aspect--perhaps working with a testing lab or other company which would actually do the testing. They have a high resolution detector design (10 lp/mm) which they would incorporate into a system, but would not sell it as a component.

They are interested in development contract and prototype work. A program like the Trident prototype might cost around $400k, while they have done prototypes for as little as $10k.

May 5 1983 BDH TFI Corp., New Haven CT

I met with Gary Burroughs, (Marketing Mgr.) and James Stamatien (Computer Systems). TFI is allied with Andrex in Copenhagen, and all their CT work is done in Copenhagen. Their main business here is mfg and sale of filmless radiography systems, and a microfocus tube. They had only a few examples of CT which were not too impressive, and didn't know any of the details (detector type, etc.)

May 12, 1983 JWG, BDH Aerojet Strategic Propulsion Co., Sacramento, CA.

This was the "official christening" of the AF/ACTS-I CT scanner (Fig. 3). There were 3 "shows" on consecutive days for military, other government, and industry. We were invited on the "industry" day. (L. W. Dahlke, SNLL div 8444, also attended.) Many of the other contacts we had made were there also, and several of the "follow-ups" mentioned above were made here. The contract provides for technology transfer, and this meeting came under that heading.

Gary Cawood, Aerojet program manager, began by giving an introduction to Aerojet, and an overview of the program. The program began in 1981, and is a 46 month program. The goal is to build, and test in a production environment, two systems, the smaller of which was on display here. The program team members and their responsibilities are:

- Aerojet: Provide the source, the facility to house the systems, and operate them in a production environment.
- ARACOR: Provide the detector array, system electronics, and reconstruction hardware and algorithms.
- Eimeldingen: Provide fixture and handlers.

System I uses a 420 Kv X-ray source, and is capable of scanning objects up to 1 m diameter and 2.5 m tall, weighing up to 2,5 ton. System II is to use a 15 Mev linatron, and be capable of scanning objects up to 2.5 m diameter and 5 m tall. System II is due to be running in early 1984. While no specific figures were given, we understand that the total program funding is in the $10M range.

Gary Cawood, at (916) 355-4005 (Sacramento) is the contact for technology transfer, and plans to take the presentation we saw "on the road", plus arrange for demonstration scans of appropriate objects.

The next speaker was Lee Gulley, of Wright Patterson AFB in Dayton. Lee is the contract administrator for this program, and he summarized the Air Force Manufacturing Technology (MANTECH) program, under which this program is funded. The MANTECH program funds establishment of new technology, and technology transfer. It does not fund capital investments nor proprietary development. Its total 1982 funding was $89.1 Million. The main CT applications they are interested in are rocket motors, carbon/carbon ITE's (rocket throats), castings, electronics, and turbine blades. They are also partially funding the IBIS program, described above (GE).

Finally, Jim Stanley of ARACOR described some system details. System I uses 160 solid state detectors spanning 36 degrees from the source. They use a variable aperture collimator, 1 to 4 mm wide, up to 15 mm high. The source is a 420 Kvp tube. The test control and reconstruction is done on a Data General s-250 computer, with a Data General array processor. Display is on a 512 X 512 pixel commercially available unit, for which they (ARACOR) wrote the software. Output is available on mag tape or floppy disk, as well as video.

Their normal scan geometry is 2nd generation, but for small enough objects they can do 3rd generation. They take up to 2000 samples per traverse (projection). Scan time is 5-10 min., and reconstruct time is 1-15 min. depending on array size.

CT AT SNLA.

Prototype Scanners

We have "cobbled together" a prototype CT scanner from parts we had on hand, in order to gain some experience with actual hardware. Our system operates in "first generation" mode. Our initial source was a 100KVP tube with regulated power supply which was part of the DXT fixture. That source proved to be too low a voltage for most of the test parts we wanted to scan, so we have converted to a standard 300KVP tube. This tube does not have a regulated supply, so we have been forced to include a reference detector, and another channel of electronics to support it. We are currently working on calibrating the reference channel to best remove artifacts caused by variations in tube output. We went through several iterations on detector electronics, and are currently using some commercial pulse shaping and energy discrimination electronics, and integrating the output pulse train. This gives us the capability to discriminate against low energy photons (which have a high probability of being undesirable scattered photons), but avoid the complexity of actual photon counting.

We have tried several types of collimators, and have developed a technique for casting them from lead which will allow us to make a very small (.002 inch approximately) collimator if we need to (Fig. 4). By holding a piece of music wire taught in the center of a mold, then breaking it to remove it, we can make a very clean hole. We are currently operating with a .010 dia. round collimator, about 1.5 inches long. Our X/Y translator is from the DXT equipment, and our rotator is a special unit we built for this application.

We are using a filtered back projection reconstruction program we got from C. V. Jakowatz (SNLA Div. 0315). We have modified it sufficiently to facilitate transfer of data from our scanner, but have done no other work on the reconstruction algorithms. We have done all reconstructions so far on the VAX, using the COMTAL to display the results. We are currently implementing the DONNER codes to reconstruct our data.

Figure 5 shows some typical results. Included are a photograph of a phantom that Jakowatz supplied, a conventional X-ray of it, and two scans through it at different planes. We have scanned several test pieces of various types for our own education, but have only done one customer test to date.

We have had a fixture built to accomodate commercial stepping motor X/Y and rotate devices (Fig. 7). We are currently working to make this fixture operational, which should happen late this year. We will then have the capability to scan parts up to 10 inches in diameter, at 300KVP. This should allow us to do some customer work on a regular basis, while further developing the technique.

Outside Contractor Demonstration Projects

Sandia has had a few tomograms made at Scientific Measurement Systems (SMS) on a "job-shop" basis. Richard Yoshimura (9783) had some scans done of a sample section of an overpack used to transport radioactive waste containers. The phantom consisted of a steel box, about 20 inches square by about 10 inches deep, filled with a low density foam (about 0.1g/cc). The foam had voids in it, and the object was to find the voids. With conventional CT, all the voids were visible, down to a size of 1 cubic inch. Since the overpack which must actually be inspected is too large to scan all at once, a limited angular range would have to be used to scan it (neither the source nor the detector may penetrate the wall, so only 120 degrees of data could be taken.) This situation was simulated by restricting data to 120 and 90 degrees in some of the reconstructions. Some predictable artifacts were introduced in this mode, but the presence of voids was still indicated.

Chuck Oien (SNLL Div. 8444) also had an experiment run at SMS. His object was a pressure vessel, a few inches in diameter, with about 0.25 inch walls. He was interested in wall thickness variations of .005 inches. Scans of a phantom made of a pipe of similar dimensions with shims placed on the inner wall indicated that the required resolution could be met.

Future Efforts

We intend to get our new prototype scanner running late this year, and get some experience working with it. We would then like to upgrade to a multiple detector system--presumably at high resolution (.005 inch range). This multi-channel detector will probably be the result of a development contract, perhaps joint with LANL.

We may want to obtain a good package of simulation software. We had an RFQ out for a package, before we were aware of the SNARK77 codes. We must determine whether they will be adequate for our needs, and if not, whether to write or purchase additional software.

FIGURE CAPTIONS

Figure 1. CT scan geometries. a): First generation, b): Second generation, c): Third generation, d): Fourth generation. sou: source, det: detector(s).

Figure 2. Proposed AS&E Trident rocket motor scanner.

Figure 3. AF/ACTS-I scanner at AEROJET.

Figure 4. Taught-wire collimator casting fixture.

Figure 5. CT results from Sandia prototype scanner. a): photograph of clear potted component phantom. b): conventional X-ray. c,d): slices at different levels.

Figure 6. New CT fixture.

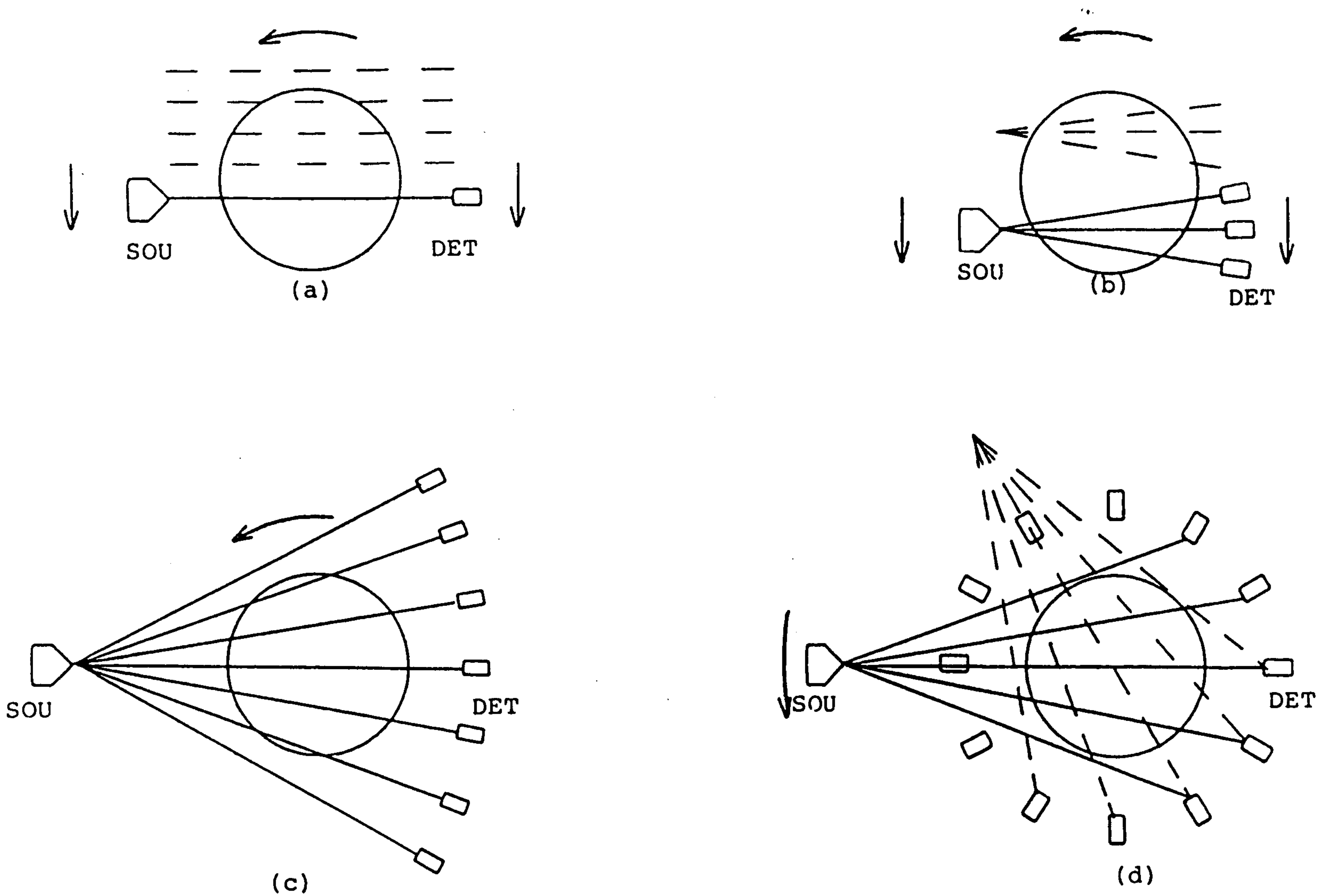
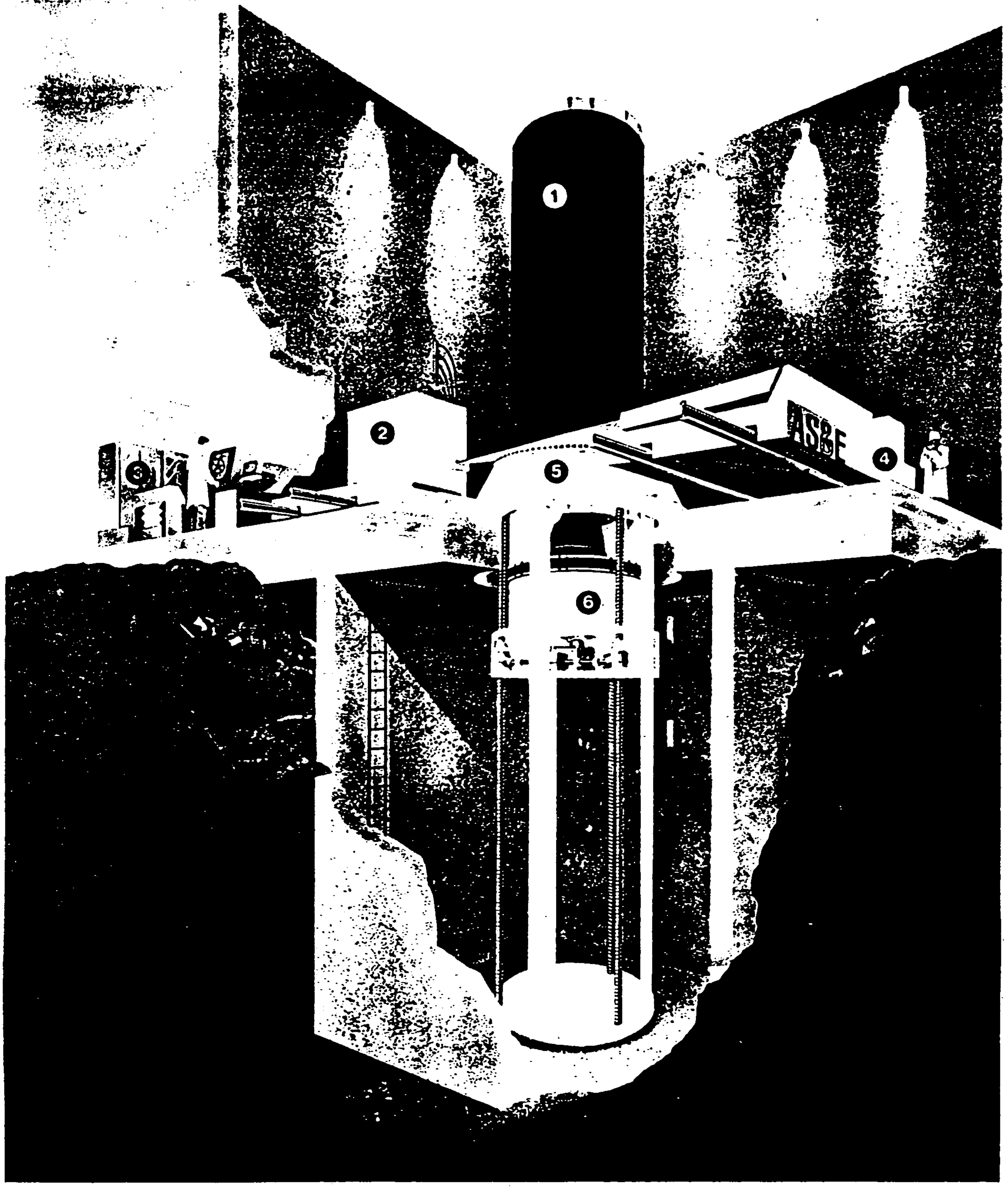


FIGURE 1 - CT SCAN GEOMETRIES - (a) FIRST GENERATION; (b) SECOND GENERATION; (c) THIRD GENERATION; (d) FOURTH GENERATION. SOU: SOURCE, DET: DETECTORS.



1. First Stage Trident D-5 Rocket Motor
2. 15 MeV X-Ray Source
3. Control Room and CT Reconstruction Center
4. Scanning Detector Assembly
5. Rotary Table
6. Elevator

FIGURE 2 - PROPOSED AS&E TRIDENT ROCKET MOTOR SCANNER

Figure 3. AF/ACTS-I scanner at AEROJET.

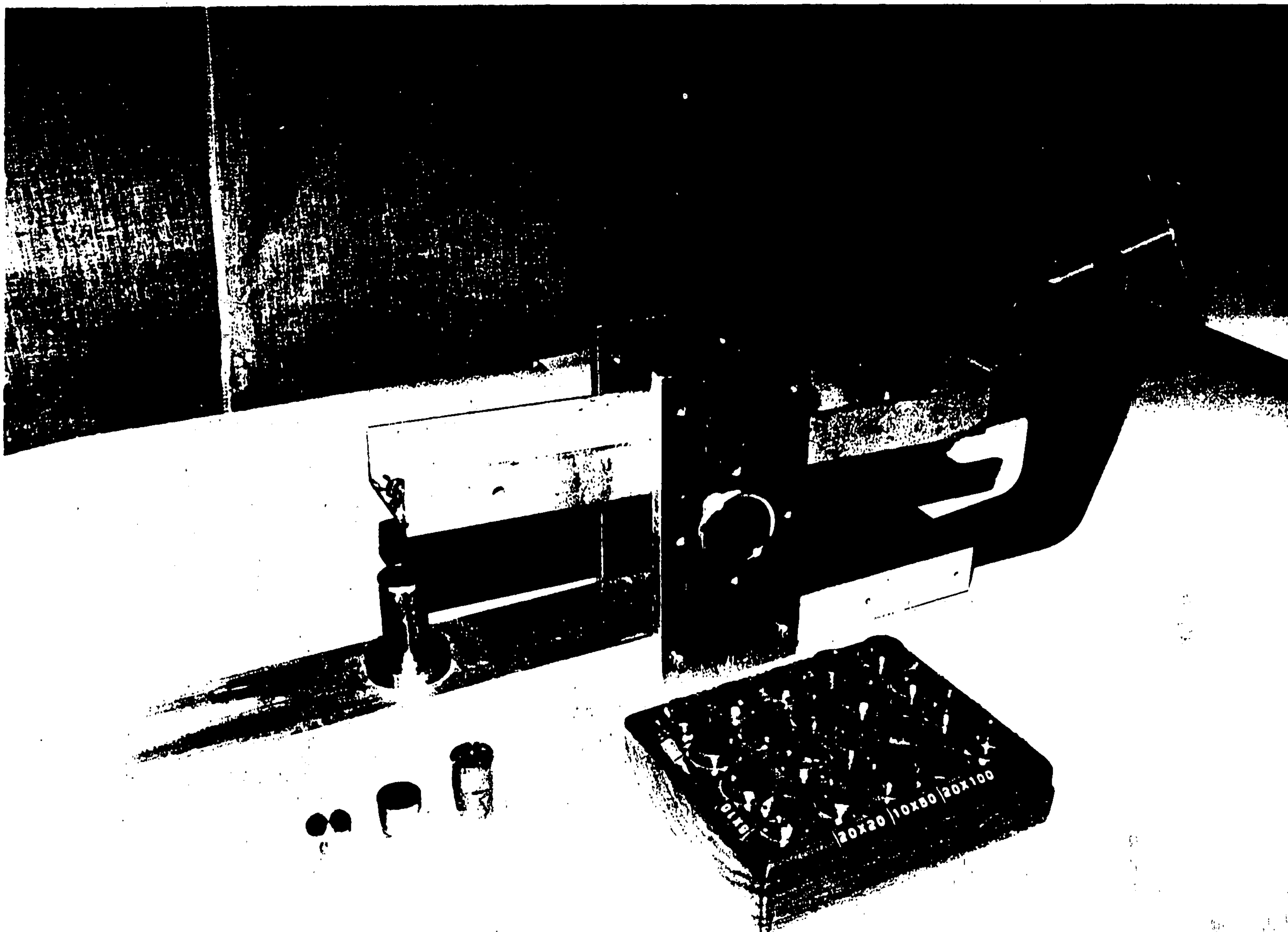


Figure 4. Taut-wire collimator casting fixture.

FIGURE 5: CT SCANS OF POTTED COMPONENT

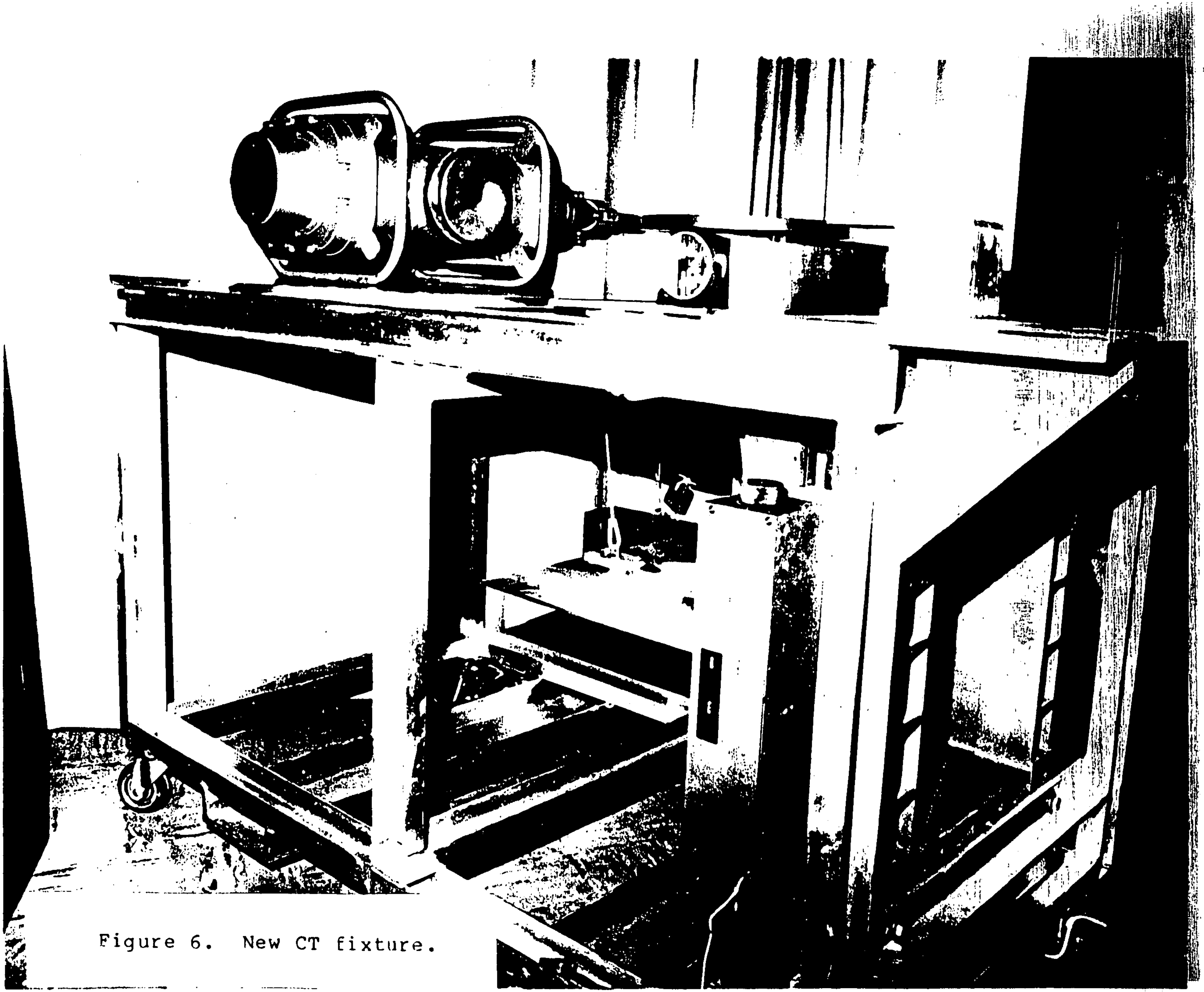


Figure 6. New CT fixture.