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R. A. Jameson, Division Leader, Accelerator Technology Division, Los Alamos "RF Accelerators for Fusion and Strategic Defense."

Introduction

This discussion is intended to relate rf linear accelerators to the symposium's topics of fusion and strategic defense. From this rather large subject, a few central points have been selected.

First, I want to stress that rf linacs are a relatively mature technology and that they are playing direct and auxiliary roles in both of these fields. There is a potential for near-term application of particle accelerators for parts of fusion programs and also for some of the SDI work; in the long-term development, the number of applications continues to grow.

To give a base line for the state of the art of high-intensity rf linacs, we start with the Los Alamos Meson Physics Facility (LAMPF). It is a large machine and runs at 800 MeV, 1-mA average current. As the world's most powerful proton accelerator, it generates more protons than the sum of all other accelerators. In our accelerator technology activities at Los Alamos, the basic figure of merit used for linac performance is the brightness of the beam: the power of the beam that is delivered to the target, divided by the quality of the beam squared. If we can increase the power, the figure of merit goes up directly, but if we can increase the quality, then the leverage is even greater. Therefore, the programs with which we are involved obviously concentrate on these increases. If one uses LAMPF as an example (it runs at about a milliampere average current at an energy of about a gigaelectron volt and has a beam quality of approximately a microradian), then the brightness number that one would need to keep in mind as the present state of the art of rf linac technology is about 10^{18}.

Now to place that figure of merit in the context of SDI, we can discuss one technology against another in terms of a beam brightness number. If we write down the brightness that is required to do destructive damage to some kind of a system, we get a number around 10^{23}. Then we can make a comparison of any particular technology against that, in terms of its present and future capability. (Recall the long-term R&D emphasis of the SDI.) One asks the question, "What will be the situation 10 years from now, after a substantial R&D program goes on, and after there has been opportunity for hardening against any particular device?" We have made that comparison and find that the present capability of an intense particle beam is very significant. And because the particle beam deposits its energy within a target, a particle beam is difficult to harden against. The concept looks like it will also hold up quite well in the long term. Accelerating light ions with an rf accelerator and then converting to a charge-neutral beam appears to be the best way to generate such a beam, capable of being aimed and propagated in space.

There has been an ongoing notion in some of the press reports that particle beams are lagging behind other technologies. The numbers from LAMPF and the argument presented above would suggest that is really not the case. But why does that criticism of particle beam's technology still exist to some extent? I think basically it is because particle accelerators have only recently begun to be applied in great measure to these kinds of problems, either for fusion or to SDI. In the past, these machines were built for physics research; Fig. 1 provides a historical view of the establishment of the technology base. There were two frontiers in accelerator development. One was to go to ever higher energy. That was the main goal of the physics community because they were always interested in pushing back the frontiers of our understanding of basic matter. The other goal was high intensity. In terms of achieving ever higher energies, the efforts started a long time ago, and there has been a steady increase in the energy that can be made available. Up in the top part of the chart, we are talking about a center of mass energy in terms of colliding beams. The energies needed in the weapons systems that we talk about for SDI are rather intermediate. The physics that was needed for these programs was basically all invented a long time ago. Therefore, what has been happening in the last thirty years or so, in a sense, includes (largely) engineering developments, cost reductions, and improvement of the efficiencies. The energy required is really not a problem.

The other frontier is high intensity. As already mentioned, LAMPF was the base line for that. Based on the experience of building LAMPF, we at Los Alamos have been at the forefront of pushing the high-intensity frontier onward through a series of programs, using both ion and electron beams. All the programs are aimed at factors of 100 or better in current above what LAMPF operates at now—we are talking about 100 mA in current for the ion machines—better emittance so that we get that squared improvement in the performance criteria, and also size reduction, more automation, and other things that make the systems more attractive.

Fusion Applications

Let us now discuss the application of the rf accelerator technology to fusion problems. Our main effort has been not to do fusion directly, but to provide an apparatus that can be used to test materials that would be needed in fusion reactor systems, particularly in first wall where there is a lot of neutron damage. A program called the Fusion Material Irradiation Test Facility (FMIT) was to be built at the Hanford Engineering Development Laboratory. It was to be a factory-oriented system with a deuteron beam, generated by a very high intensity linear accelerator, impinging on a lithium target. Neutrons would come out the back of the target into a test chamber where the materials could be exposed to a neutron flux. The idea was to have about a ten-times accelerated test cycle where we could test the material ten times faster than it would be tested in an actual reactor. The challenge to us as accelerator builders was to have a hundred times more intensity than the currently most intense machines, with a plant availability of 85 or 90%, which is better than coal-fired power plants. That availability was supposed to be achieved on the first device we built and meant that we had to have extremely low-beam loss, allowing hands-on maintenance. The machine was to operate cw, posing many mechanical engineering challenges.

At Los Alamos we have been involved with building a prototype of this accelerator, shown in Fig. 2. The layout is typical of linear ion accelerators; the beam is initially produced in an ion source, given an initial acceleration through a dc potential, then converted into bunches suitable for acceleration by a radio-frequency wave in the radio-frequency quadrupole (RFQ) preaccelerator, and then accelerated further in the well-known drift-tube-linac structure. At the present time, we are operating at 2 MeV with the RFQ. We have several of the parts built for the drift-tube-linac prototype, but unfortunately the status of magnetic fusion in general makes it look like we will not be able to get the last 10% out of this investment to finish up the technology for the critical demonstration to the full 5 MeV. Once we do go through the front end of an accelerator and get the beam on its way at an energy of 5 MeV or so, we will have basically solved most of the challenging physics and engineering problems for any particular application.

The RFQ accelerator is a new way to capture, bunch, and accelerate low-velocity ions. Before the RFQ came along, injection systems, for example at LAMPF, were Cockcroft-Walton-type systems requiring a three-story building to house them. The RFQ accelerator, in a system sense, has the advantage of much smaller size, and also preserves the source beam quality much better—so much so that it makes programs like the FMIT or the SDI applications much more feasible. The idea for how to build an RFQ originated in the USSR. Figure 3 is a picture of the RFQ going together for the FMIT accelerator. The requirements for low beam loss and cw operation in this machine resulted in the choice of a low frequency (80 MHz); this choice makes the device fairly large.

At present, we are operating that system at full power cw rf, which was one of the main development goals. That was a very challenging task, and it has been successfully demonstrated. We are running at 20-mA, cw beam current (with a goal of 100 mA); thus, we are already 20 times more intense than the LAMPF accelerator and well on our way to the final goal of 100 times.

I am not going to discuss heavy-ion fusion (HIF), except to state that at Los Alamos we are now participating in the HIF program, discussed at this meeting by R. Bangerter, in a couple of ways. One is in advanced R&D on basic issues in accelerator beam dynamics and how to develop multiple-beam systems. In particular, we are building a multiple-beam injector. That is another place where we have played on the fusion side.

Strategic Defense Applications

In reference to the SDI programs, at Los Alamos we have been involved in a program called White Horse for about eight or nine years. The goals of that program have always been to explore the technology of rf linacs toward the defense application and to see what possibilities there are. The program really asks for the ultimate performance from ion linacs. How bright can we really make them? The investigation is based, however, on a technology that is mature in terms of being able to run at high power and high repetition rate, and in the understanding of the physics issues. We have recently begun to think more in terms of the system integration aspects and how to do a scale-up for an SDI mission. That is really where the challenge lies. One possibility for space experimentation is to put a small accelerator on a rocket and send it up to learn how to make such a system operate in a space environment, and to propagate the beam to verify the physics of how the beam acts in the upper atmosphere and in space. Other areas of investigation are the development of precise pointing and tracking and an underlying technology base program to work on all the aspects of the engineering and technology in parallel.

A primary advantage of particle beams over laser beams is that particle beams deposit their energy inside the target, whereas lasers deposit their energy on the surface. This deep energy deposition makes hardening against the particle beam more difficult. For this application, the main criteria is beam brightness, leading to the choice of a higher frequency and, therefore, a smaller diameter machine. Figure 4 shows the assembly of a 425-MHz RFQ in our laboratory. This size reduction is advantageous for space application or other uses where a premium is placed on compactness.

Figure 5 shows the RFQ installed in the experimental system. Again, this is a 2-MeV output energy RFQ, but smaller than the FMIT machine of Fig. 3. Here, at 425 MHz, an io linac operating at 100 mA begins to look more like the usual electron linac. The size reduction is really quite significant.

The plan for the next development of this particular activity is to build a facility called an upgrade facility, where we have an accelerator and a beamline, expanding optics, a neutralizer cell, and then a sensing area where pointing experiments can be performed. We are now planning the higher energy accelerator with which to explore the problems of the final beam transport, and pointing and tracking aspects, which have not yet received the kind of attention that the accelerator has.

We turn now to another area where accelerators are playing a role in SDI mission: the free-electron laser (FEL).

The name free-electron laser comes from the fact that the laser is pumped by an electron beam and the medium is a vacuum. The electron beam is propagating in a vacuum; the electrons that are involved in the pumping are therefore not bound in the band structure of either solids or liquids as they are in conventional lasers. The advantage of that has several aspects, including heat removal and tuneability. Thus it is a different concept that has a particular role to play in SDI and also probably in the future of industrial applications to process chemistry.

The program in which we have been involved started with a demonstration that light amplification could be achieved in a single pass interaction of the electron beam with the laser beam. Next, we put mirrors on each end of the experiment and made it lase. The rf-linac-driven device is run as an oscillator to produce the desired output power.

To get the entire system's efficiency up, the energy of the electron beam is recovered after it exits the laser. After the electron beam has been in the laser and we have extracted energy from it, then the energy spread of the electron beam widens to the point where we really cannot reuse it. For example, some FELs have storage rings where the electron beam is recirculated. But they can only take out a very small fraction of the energy each time. We take out an intermediate amount, which is more efficient, but introduces energy spread in the electron beam; therefore, we cannot bring it back around to use it again. We do not want to waste the remaining energy in the electron beam, however, so we plan to decelerate the electron beam in another accelerator structure. That process feeds the power back into the electrical system, basically, and we can get system efficiencies up to 25 to 30%. This capability will be demonstrated during the next year. After that, we will raise the power levels and reduce the wavelength of operation from the present 10 μm down toward the 1-μm region. This technique requires a higher energy electron linac.

For our accelerator group, the challenge of this program is to advance the performance of electron linacs. The requirements are stressing in terms of brightness and power levels, to the same extent that the ion beam requirements are stressing for the ion accelerators. Then there are the same kinds of questions that everybody faces in terms of scale-up to high power, such as providing prime power. Figure 6 shows the present FEL oscillator experiment. We are achieving a rather significant factor in average power above other FELs, because rf linacs are already capable of running at high power levels and repetition rates.

The beam out of a radio-frequency pre-electron laser is characterized by being very nearly perfect optically. The system has a good emittance internally and that makes a good-quality output beam. The tuning range that we have already demonstrated just by changing the electron energy is a factor 4—that is continuous tuning.

Figure 7 shows a picture of the rf-linac part. The structure is called the side-coupled accelerator structure. It was developed for the LAMPF accelerator. A variant is found now in almost every x-ray machine, in every hospital in the country. We are changing the structure now for even higher power, including cw, operation.

One of the research aspects of the program is to achieve even higher power and better quality electron beams. We are working on a photocathode where we generate the initial electron beam by a laser-driven cathode technique.

Magnet wiggler technology is another aspect that requires a large amount of development.

Summary

In summary, we have found that rf linacs do have a place in fusion, either in an auxiliary role for materials testing or for direct drivers in heavy-ion fusion. For SDI, the particle-beam technology is an attractive candidate for discrimination missions and also for lethality missions. The free-electron laser is also a forerunner among the laser candidates.

In many ways, there is less physics development required for these devices and there is an existing high-power technology. But in all of these technologies, in order to scale them up and then space-base them, there is an enormous amount of work yet to be done.

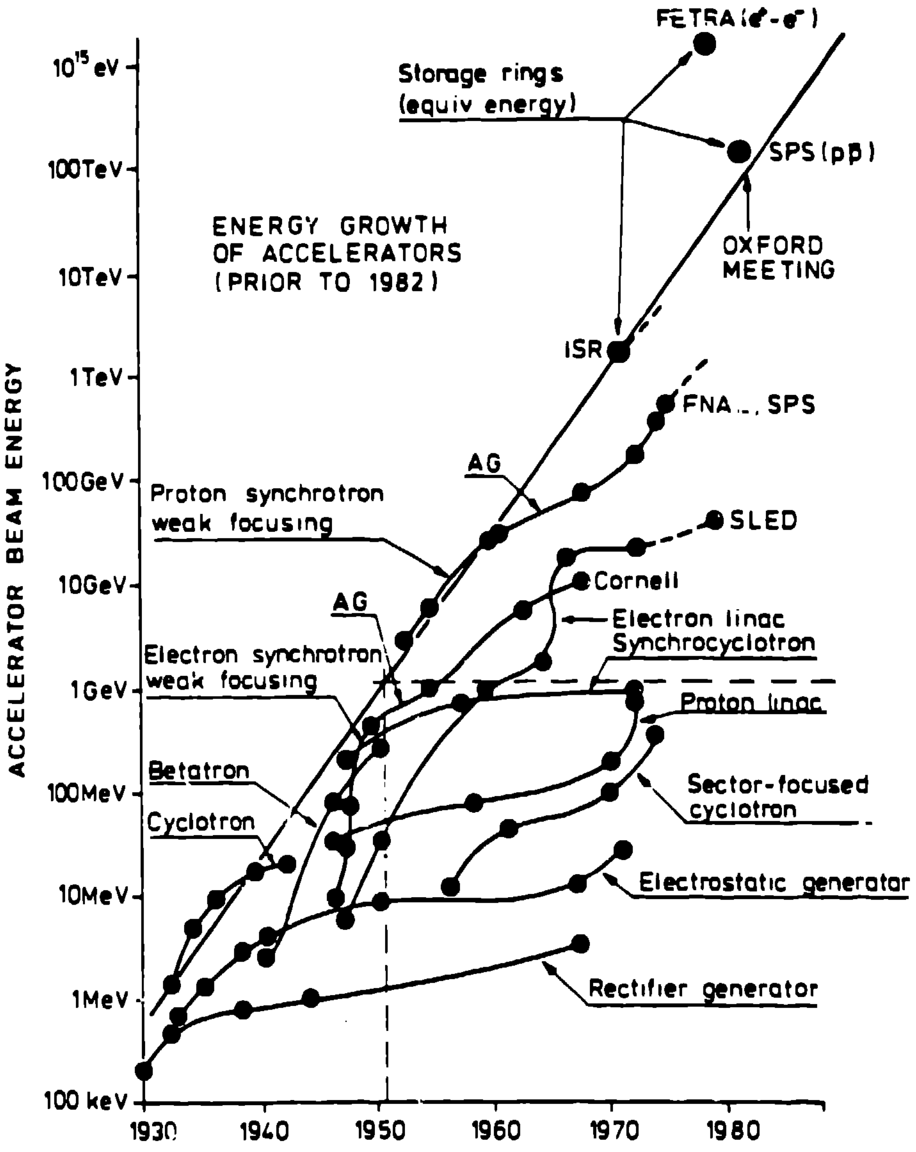
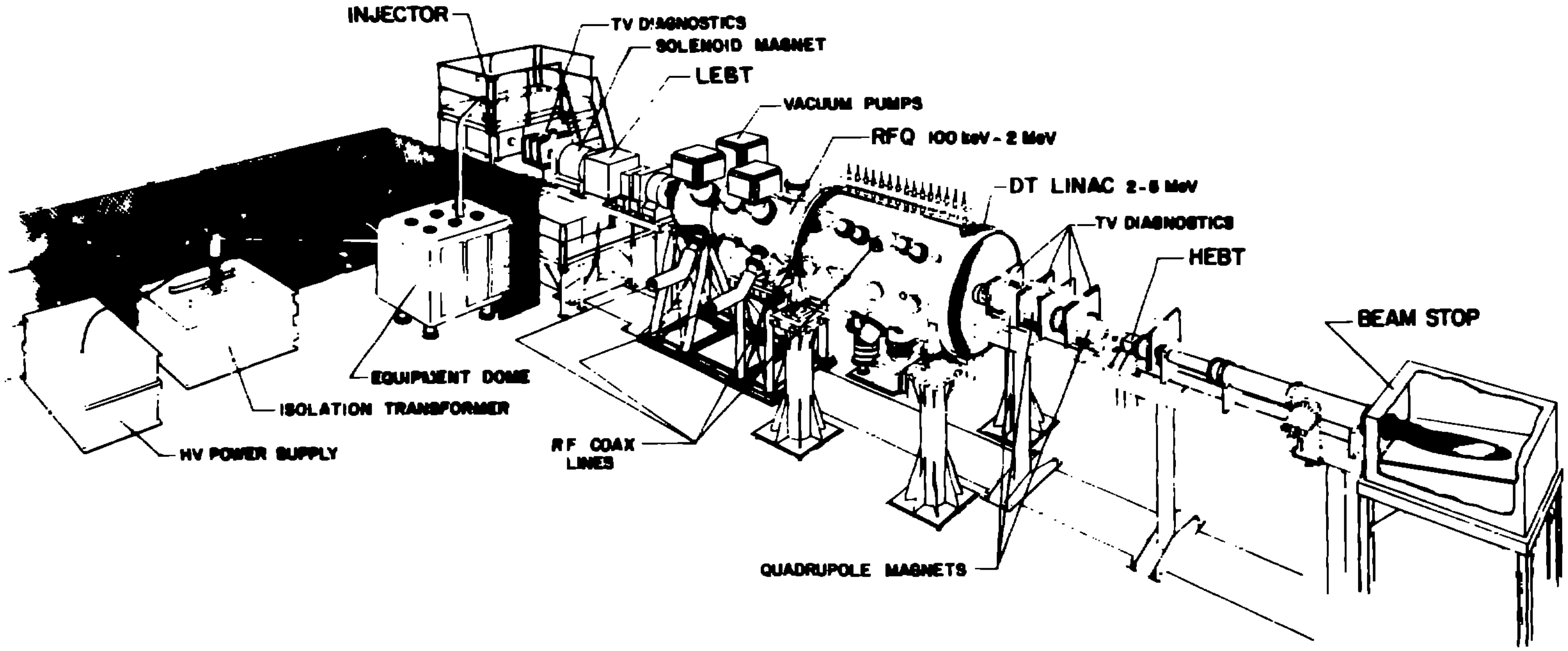


Fig. 1 Livingston Chart



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FMIT PROTOTYPE ACCELERATOR

Figure 2.

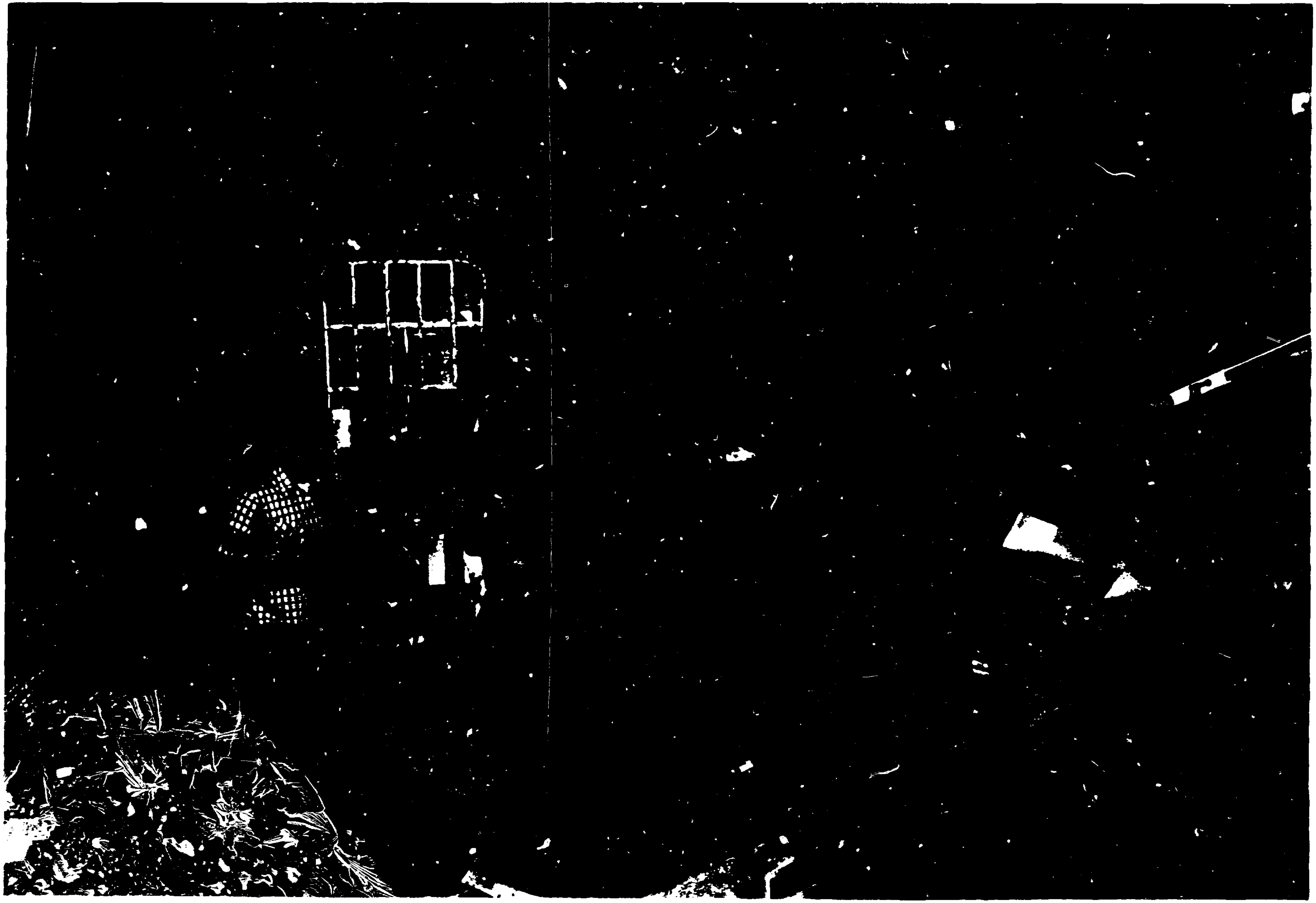

Figure 3.

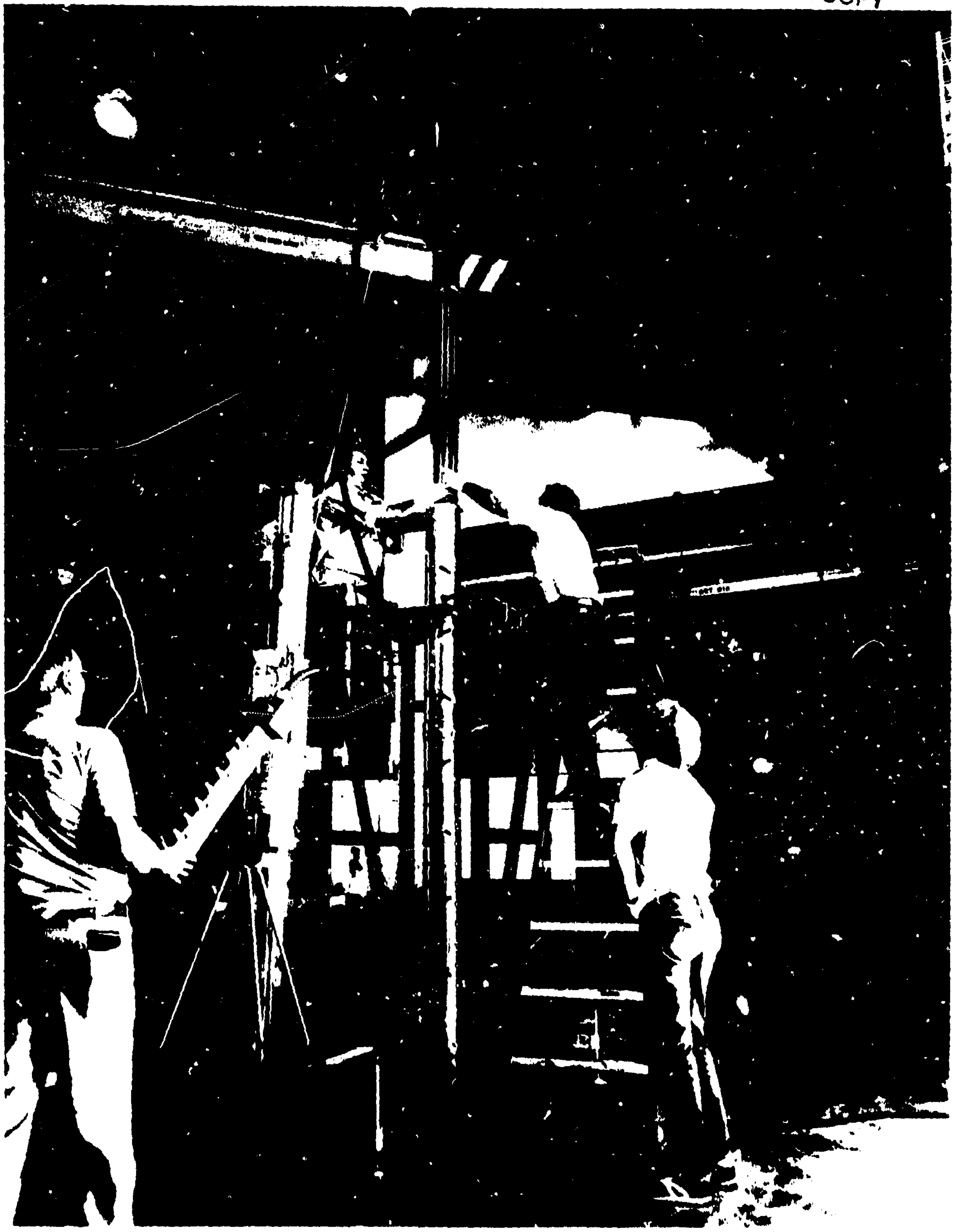

Figure 4.

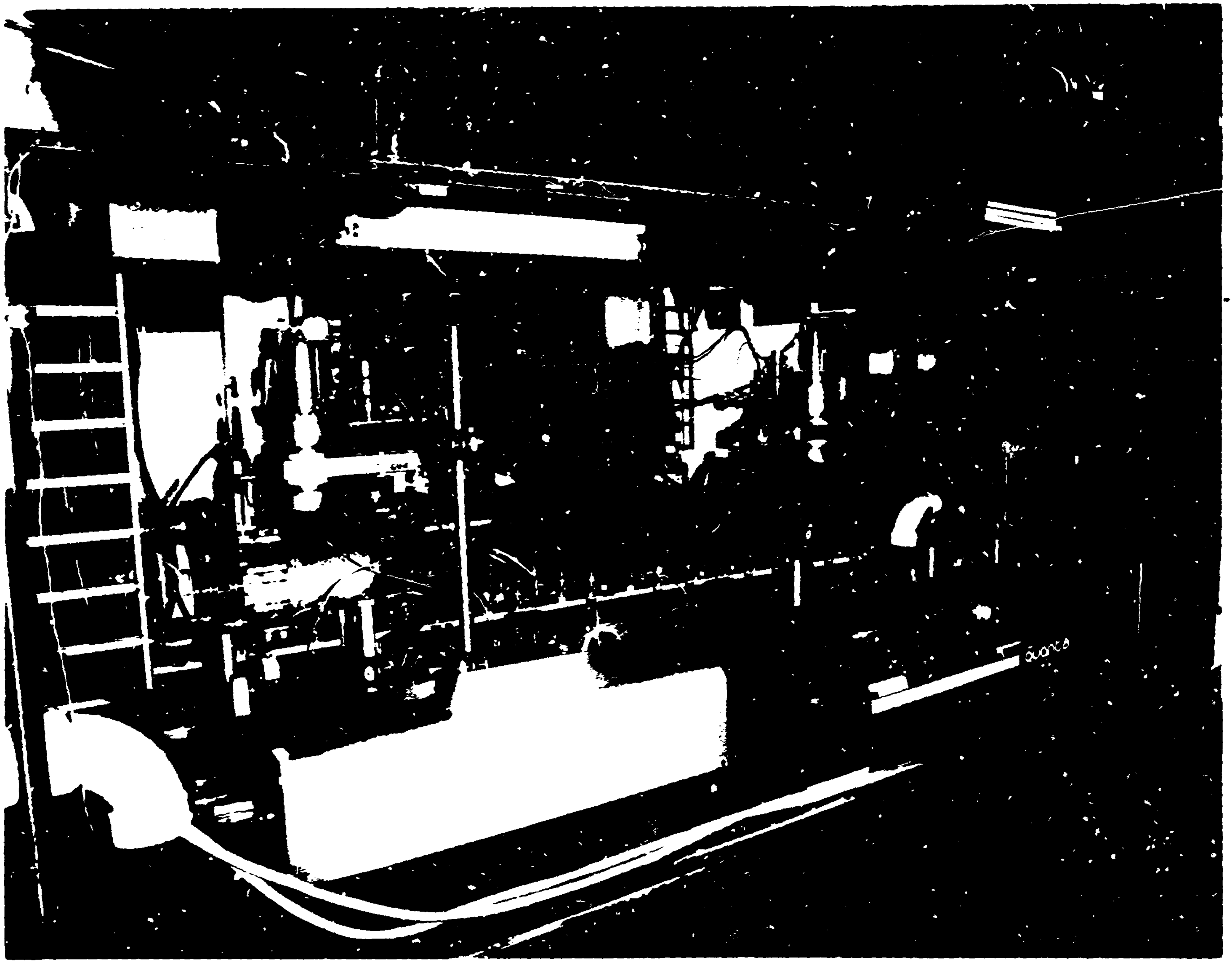

Figure 5.

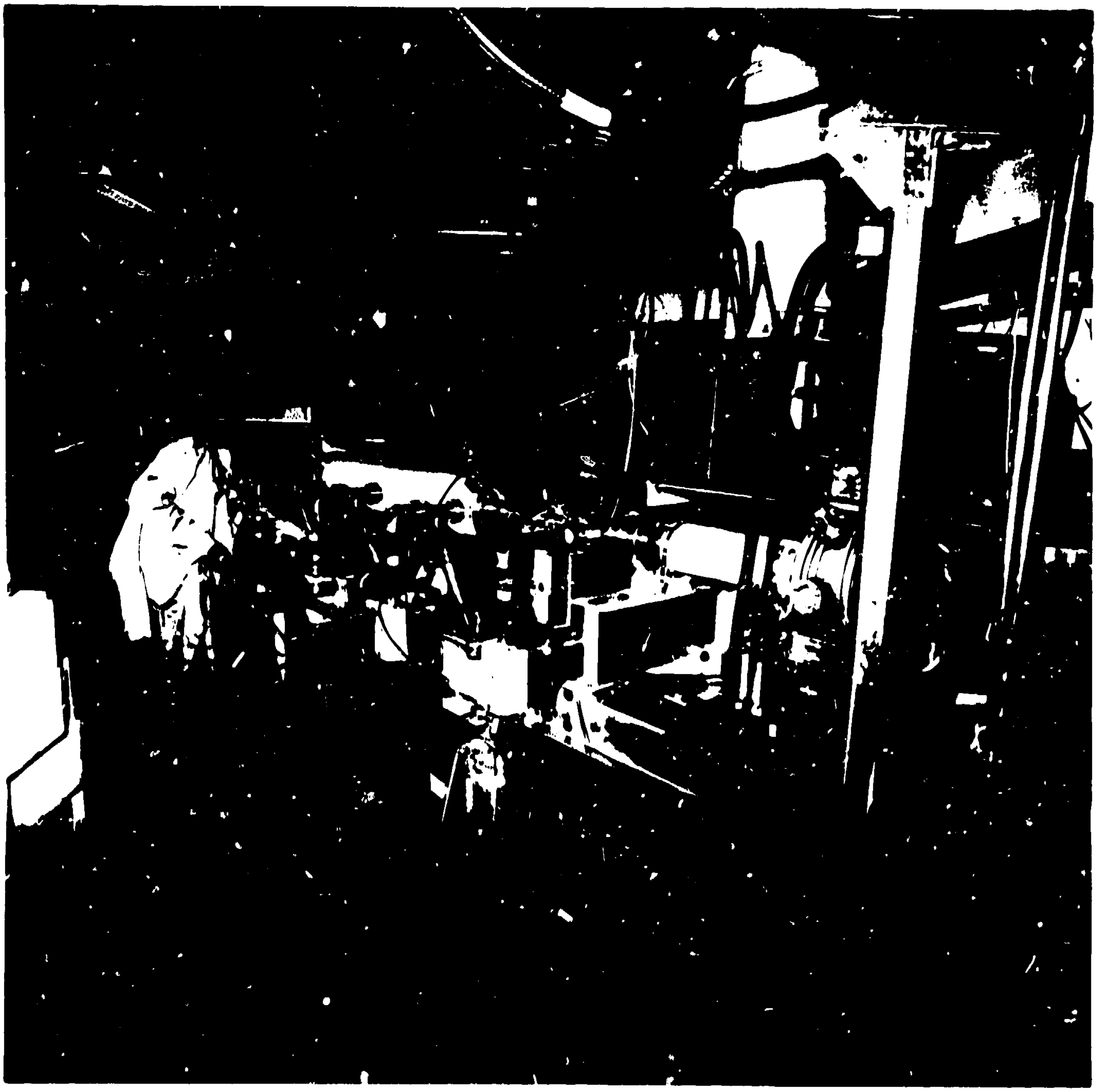

Figure 6.

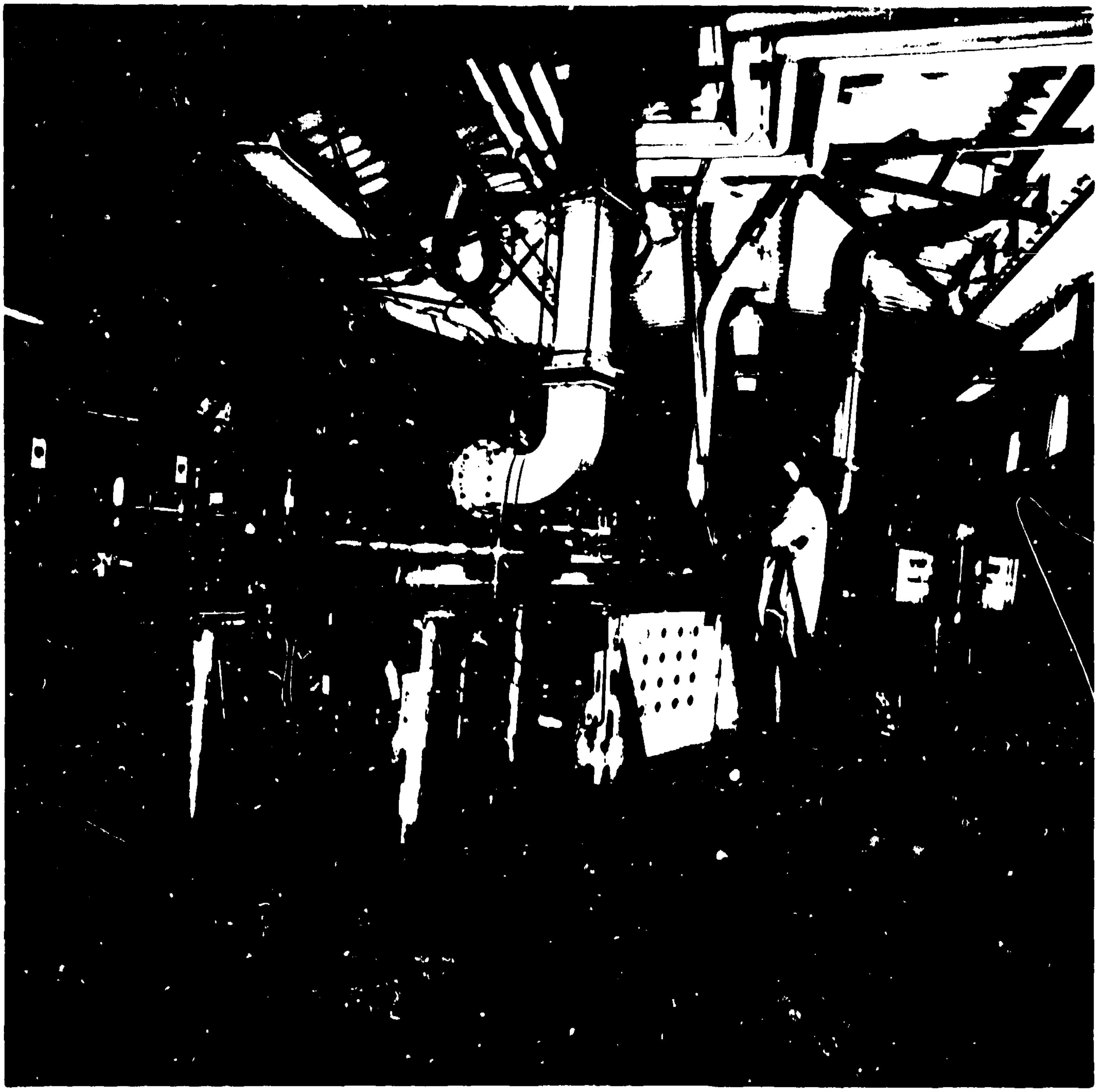

Figure 7.