

Techniques

March 27, 1965

Dear Mr. Alvarez:

I have been reading your proposal for "X-raying" the Egyptian pyramids with a great deal of interest indeed. Perhaps, I should explain that it is not really within my competence to judge the physical problems involved even though I am Director of the Applied Science Center for Archaeology (ASCA) here, but it does sound like a straightforward problem with no insurmountable difficulties and the objective is certainly well worth the effort.

John Wilson may have told you that we here have been seeking the necessary permits to begin a long-range excavation at the Dashur site, including the Bent and the North pyramids. In February, in Egypt, I was able to get this permit through all of the committees and up to the Minister for signature, so it looks as though we will be able to begin work at the site during the next winter season. Also, part of our plan in connection with the excavation at Dashur, is to carry out various experiments with new techniques in archaeology. This is a natural outgrowth of our ASCA here (the newsletter is attached). You may also know that there are very considerable difficulties in working in Egypt at the present time. My feeling is that if we can once begin systematic excavations of a major site, in the region of Cairo, we will soon establish a congenial climate for foreign operations there, and can gradually set up our laboratory for experimental techniques at the site.

You may be interested to know that Dr. Fakhry is the one who has seen this permit through many difficulties during the past three years, and

we will certainly rely upon him to clear the way for systematic archaeological research in Egypt.

At the moment there is nothing I can suggest except that we keep in touch and when we get established at Dashur, I should be very happy to assist in your experiment in any way possible.

Most sincerely yours,

Froelich Rainey
Director

Dr. Luis W. Alvarez
Lawrence Radiation Laboratory, University of California
Berkeley, California 94720

FGR/vg

UNIVERSITY OF CALIFORNIA

LAWRENCE RADIATION LABORATORY
BERKELEY, CALIFORNIA 94720

March 10, 1965

Dr. Froelich Rainey
University Museum
University of Pennsylvania
Philadelphia, Pennsylvania

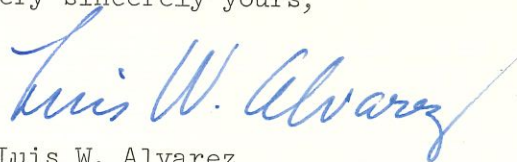
Dear Dr. Rainey:

I had a very interesting visit last week with Dr. John Wilson of the Oriental Institute. I discussed with Dr. Wilson the proposal, a copy of which accompanies this letter. Since I am an alumnus of the University of Chicago Dr. Wilson was familiar with my work in physics, and we were able to discuss the matter in a quite open fashion.

I don't want to try to summarize Dr. Wilson's reaction to my proposal to "x-ray the pyramids", but from an entirely subjective point of view, I was exceedingly pleased by the way he reacted. He said that he would talk with Dr. Ahmed Fakhry in a month or two, when the two of them will meet in Cairo at a meeting of the "Save the Monuments Committee". He gave me your name, and suggested that I send you a copy of my proposal, for your information. He reminded me that you had played an important role in the archeological community, in helping to establish the validity and usefulness of Bill Libby's Carbon Dating Technique.

I will be very pleased to receive any comments or suggestions you might have relative to this proposal. I have of course dispatched a copy to my old friend, Bill Libby, and I am looking forward to receiving his comments.

Very sincerely yours,



Luis W. Alvarez

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encl.

SUBJECT

A Proposal to "X-ray" the Egyptian Pyramids to Search for Presently Unknown Chambers.

NAME

Luis W. Alvarez

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March 1, 1965

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		DATE March 1, 1965		

I. Introduction

The purpose of this proposal is to show that by the use of modern physical methods, it is possible to examine the interiors of the three large pyramids, in search for presently unknown chambers. The author can state quite unequivocally, as a physicist, that if such chambers exist, they can be found by the methods described in this proposal. When he is discussing the reasons for thinking that such chambers might exist, he is of course not speaking with any authority at all, and he begs the indulgence of his archeological friends on those few occasions when he may appear to be injecting his own ideas into what is properly an area for debate only by qualified experts.

The Egyptian pyramids are associated in the lay mind with the name Cheops, the builder of the "Great Pyramid", in about 2600 B. C. We shall be primarily concerned, in this proposal, with three pyramids: the Great Pyramid of Cheops, and the pyramids built by his father and by his son. The "Bent Pyramid" at Dahshur was built by Sneferu, the father of Cheops, and the "Second Pyramid" was built by Chephren, the son of Cheops, adjacent to his father's pyramid, at Gizeh. To a casual student of the pyramids, there is an enormous difference in the presently known complicated internal structure of the two earlier pyramids, as compared with the apparent internal simplicity of the latest of the three (Chephren's pyramid). Figures 1, 2 and 3 show what is known today of the systems of chambers and passages of the three pyramids.

Two contrasting explanations can be given for the qualitative difference observable in the three sets of plans. The one that is apparently favored by modern Egyptologists is that Chephren, who was probably aware that his father's pyramid was robbed almost immediately after the burial ceremony, concluded that his pyramid could not be made secure. He therefore abandoned the attempt to mislead potential robbers, and had himself buried in a chamber centrally located

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"BENT PYRAMID" OF SNEFERU AT DAHSHUR

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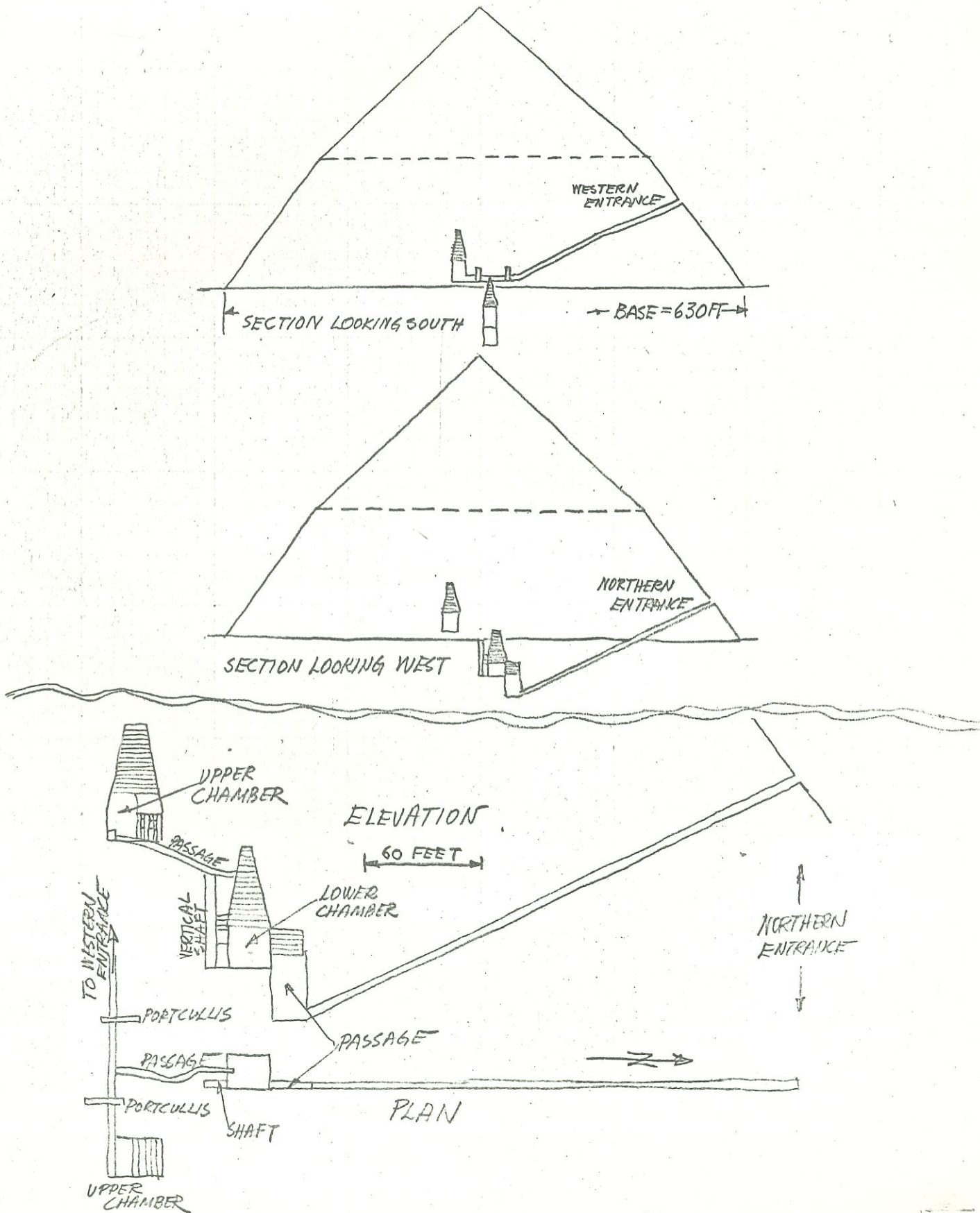


FIGURE 1



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"GREAT PYRAMID" OF CHEOPS AT GIZEH

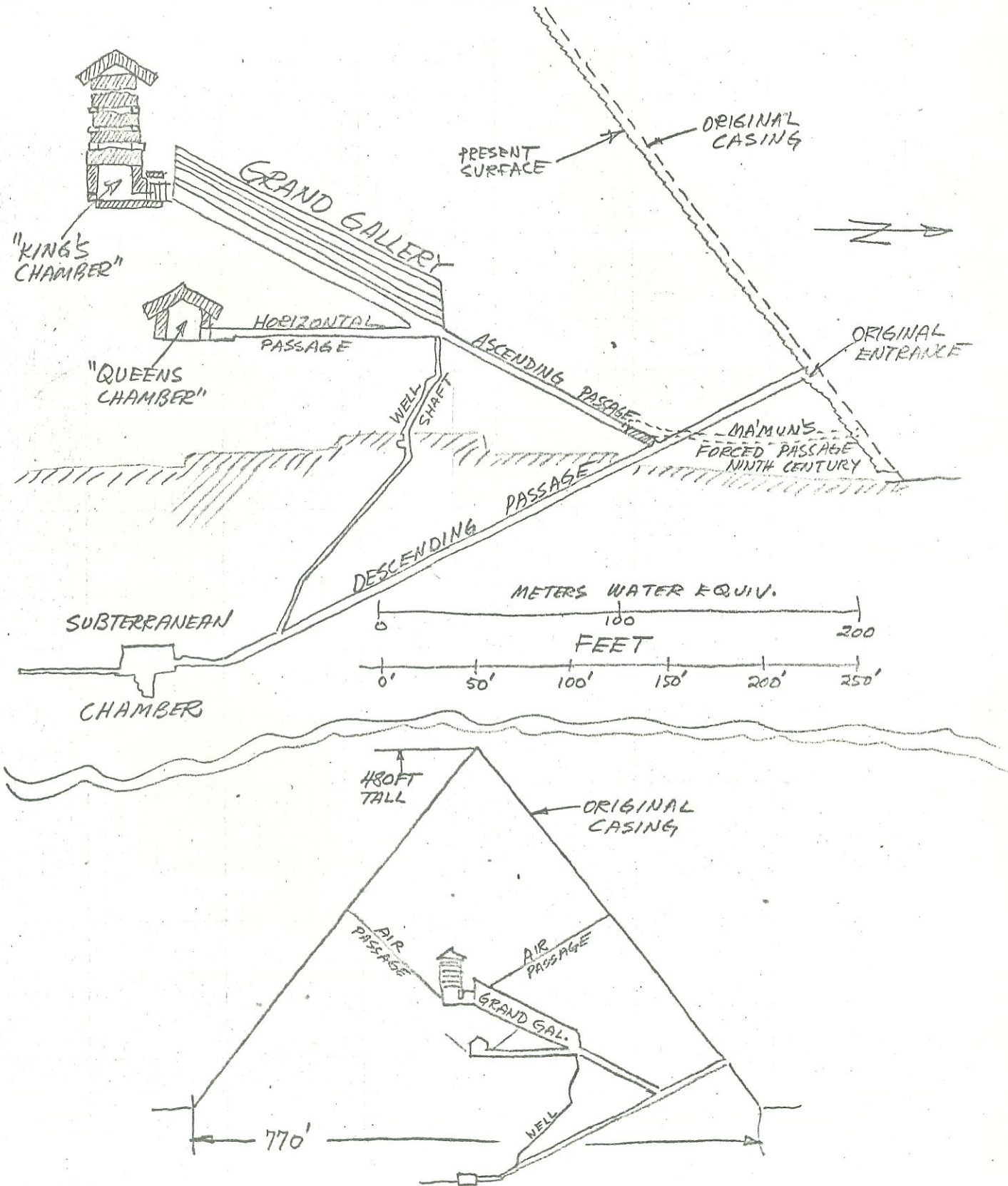


FIGURE 2

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"SECOND PYRAMID", OF CHEPHREN, AT GIZEH

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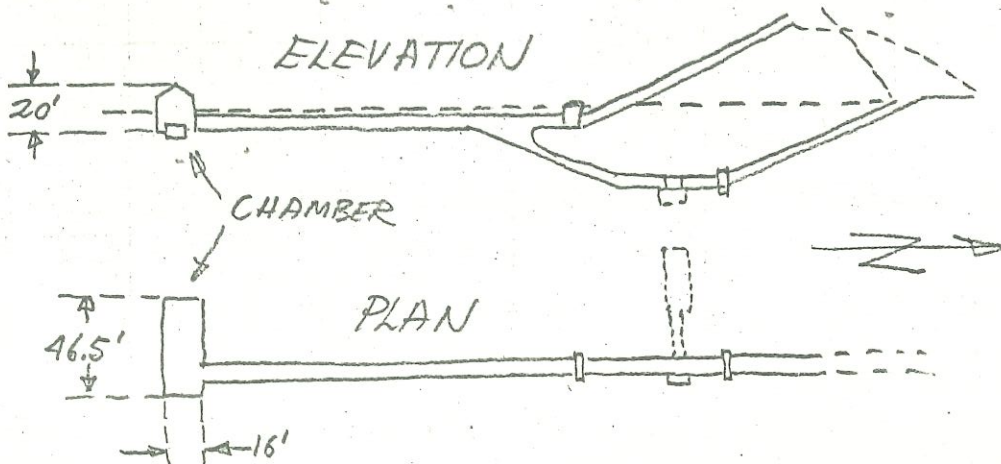
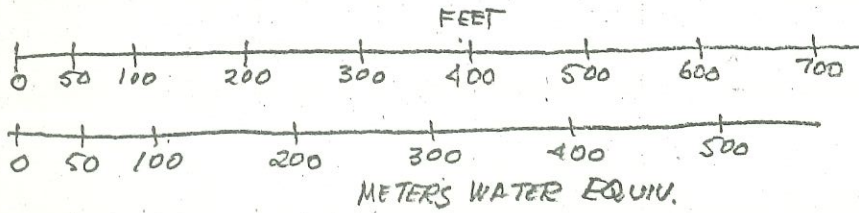
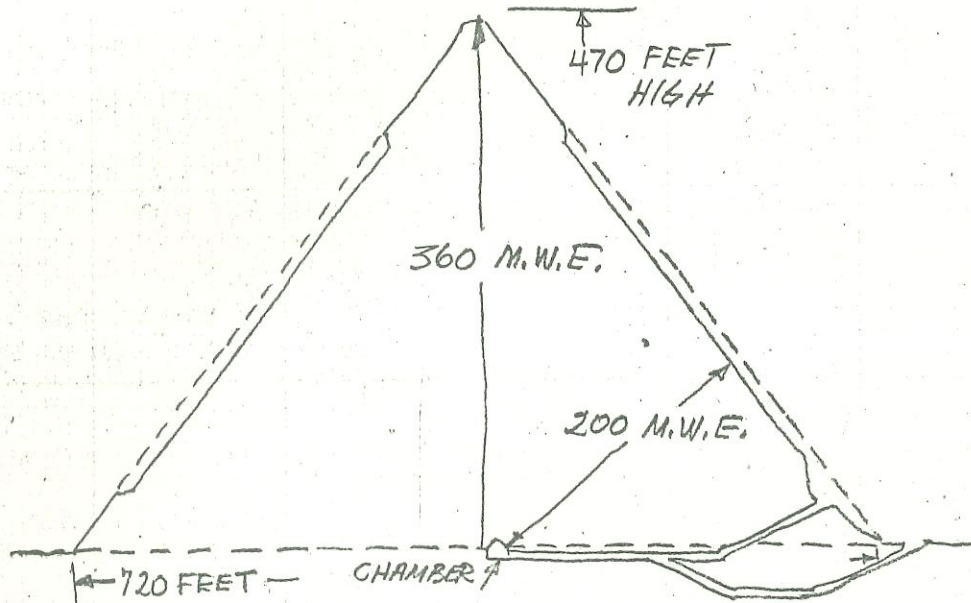


FIGURE 3



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on the "ground floor" of his pyramid. This theory accounts for all the known facts, but it does not answer the question, "Why did Chephren expend the great effort required to erect his pyramid if he did not believe that it would preserve his body for the future life?"

An alternative theory that has had many adherents among past generations of archeologists is that each of the three kings encouraged his pyramid architects to use all their ingenuity to mislead future grave robbers into believing that someone had sacked the burial chamber before they arrived on the scene. This would, of course, convince the robbers that it was useless to probe further into the pyramid structure. One can use the presently known internal structure of the Great Pyramid as evidence for, but certainly not proof of, this second theory. The fact that the subterranean chamber of the Great Pyramid was known to Herodotus in the fifth century B. C., but that the upper two chambers were not discovered until the ninth century A. D., is consistent with the second theory. The passage to the upper chambers was so well concealed that it was only by accident that Ma'mun's tunnelers found it in the ninth century; this is again consistent with the deception hypothesis.

If one adopts this hypothesis, then the apparent barrenness of the Second Pyramid at Gizeh can be attributed to the greater success of Chephren's architects in hiding their upper chambers from grave robbers. If one does not adopt this hypothesis, then he should answer the following difficult question: "Why would Chephren, after a boyhood spent watching his father's slaves erecting a beautiful and complex series of chambers and passages in the Great Pyramid, be content to erect a solid and uninteresting pile of limestone blocks as his own pyramid?"

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As stated in the opening paragraph, the purpose of this proposal is merely to point out that with modern techniques, one can probe the Second Pyramid, and decide unambiguously whether or not there is a presently unknown burial chamber somewhere in the huge volume of the pyramid. If a chamber were observed, its position would be located accurately enough so that tunnelers could dig directly to it on the first attempt.

One could, alternatively, try the device first in the Great Pyramid, to confirm that the detector would find the internal structure known to exist in that pyramid. However, the physics and engineering aspects of the device are so straightforward that such a preliminary test does not appear to be worth the effort. The effort arises from the fact that the equipment must be set up in the subterranean chamber of the pyramid being probed. This chamber in the Second Pyramid is now accessible, and free from debris, and it is not normally visited by tourists. For these reasons, it is ideally suited for the first attempt at "X-raying" a pyramid. There is the additional incentive to probe the Second Pyramid that stems from its complete absence of known structure above the ground level.

The subterranean chamber of the Great Pyramid is largely filled with rocks that were taken from a shaft excavated in the floor of the chamber by Col. Howard Vyse and Perring in 1837. (Incidentally, Howard Vyse and Perring expended a great deal of effort in digging and blasting a series of shafts and tunnels in the Great Pyramid, looking for the "true burial chamber" of Cheops.) If the examination of the Second Pyramid were to reveal the presence of a new Chamber, one would certainly probe the Great Pyramid and the Bent Pyramid in a similar fashion. Under these circumstances, one would be happy to expend the effort

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required to clear Cheop's Subterranean Chamber of its accumulated debris. But until that time, we shall assume that we are planning to probe the interior of the Second Pyramid.

Several criteria must be met before the "Pyramid Project" can be started. First, of course, the project must have the official blessing of the United Arab Republic. One of the reasons for writing this proposal in such detail is so that Egyptian archeologists may have the opportunity to study it at their leisure, and to confer with their colleagues in the field of cosmic ray instrumentation concerning the validity of the calculations. It is to be hoped that if and when they are satisfied with the physical measurements aspects of the project, they would recommend to President Nasser that the project be supported.

The author has discussed the project in some detail with Dr. A. R. Fikry Hassan, an Egyptian high energy physicist with experience at the CERN laboratory in Geneva. Dr. Hassan has worked with spark chambers and electronic data analysis, and he has expressed an interest in the project. He has recently written that he has heard from Dr. F. Bedewi, the Head of the Physics Department, Faculty of Science, Ein Shams University in Egypt. He says, "Dr. Bedewi informed me that Ein Shams University would fully cooperate with your Group in carrying out your Project inside the Pyramid. Dr. Mofty has not written to me yet." (Dr. El Mofty received his Ph.D. degree in Physics at the University of California, for work performed at the Lawrence Radiation Laboratory, and he is a member of the Atomic Energy Commission of the United Arab Republic.)

From what has been said above, it seems that unless some unforeseen difficulty arises, the project apparently appeals to competent Egyptian physicists as an interesting one.

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The present document will also be sent to a number of American archeologists, particularly to those who have access to independent judgements from high energy physicists on their own campuses. (For example, the Oriental Institute and the Enrico Fermi Institute for Nuclear Studies are only a few blocks apart at the University of Chicago.) If the project appears worthwhile to the archeological community, both Egyptian and American, then it is possible that one of the philanthropic foundations might arrange to set up a cooperative project with participation by the University of California and an appropriate organization in the United Arab Republic. It is to this end that this proposal is addressed.

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II. "X-raying" the pyramids.

The English language has no simple word or phrase to describe the process we propose to employ in probing the interiors of the large pyramids. Our use of the word X-ray in quotes come closest to the mark, because the end result of the program will be a photographic transparency showing the known chambers and passages, and hopefully, the presently unknown chambers this proposal is designed to find. (In fact, the program will produce a pair of stereo X-ray photographs, so that the chambers can be located in all three dimensions.) If we constructed an exact scale model of the Bent Pyramid, according to figure 1, and asked to have this model X-rayed by a specialist in industrial radiography, we would be presented with an almost exact duplicate of the "X-ray photographs" mentioned earlier in this paragraph. In figure 4a, the industrial radiologist has placed a small "radioactive source" of X-rays in the Lower Chamber of the model, and the X-ray film is placed so that it touches the apex of the model pyramid. (We use the Bent Pyramid, rather than the Second Pyramid in this example, because the latter has no known upper chambers to show on the X-ray film.) With this technique, we can say that the process of taking the photograph "projects", or "maps" the pyramid onto the X-ray film. Just as there are many ways of mapping the spherical surface of the earth onto a plane surface (e.g. Mercator's projection and conical projection), there are many ways to map the interior structure of a pyramid onto an X-ray film.

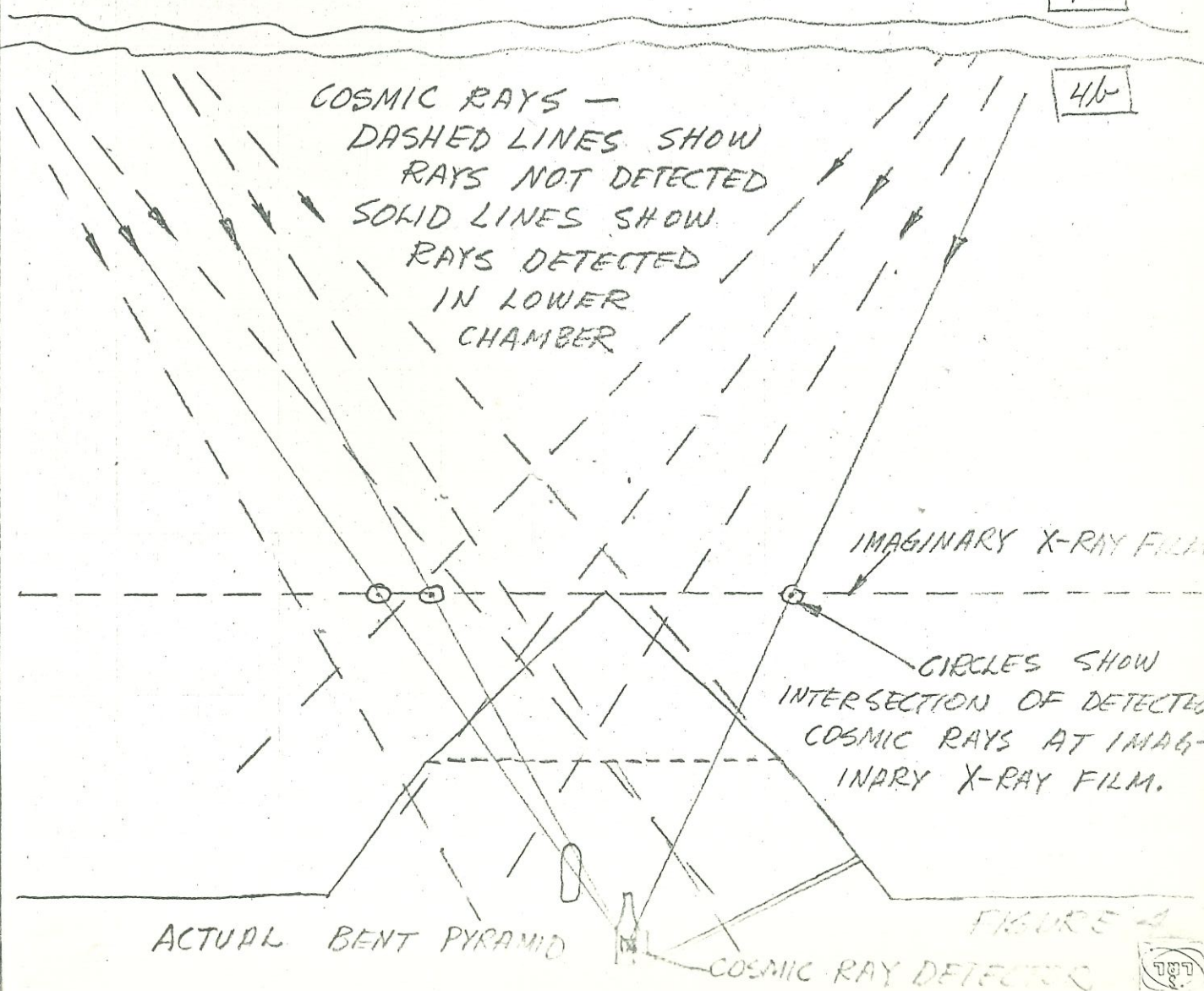
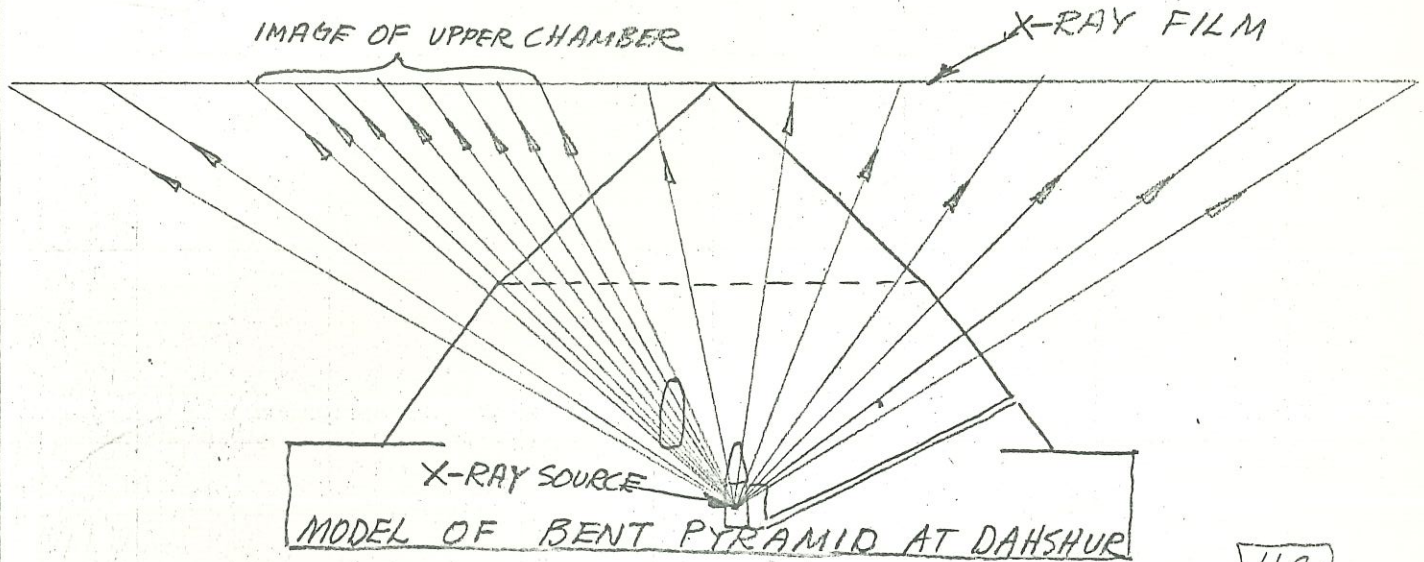
To make a map or projection, we need three things: (1) a point from which to project the "rays", (2) the object to be projected, and (3) the surface on which to make the projection. We are fortunate in having point sources of X-rays available, so we can perform the "projection operation" illustrated

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X-RAY MAPPING PROJECTIONS

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in figure 4a. But we have no point sources of the very penetrating radiation needed to probe the interior of a large limestone pyramid. For this reason, we can't duplicate the projection of figure 4a, "on full scale". The cosmic radiation with which nature provides us appears to come with "equal brightness" from all points in the sky. Such an "isotropic" radiation can be used in a mapping operation, but only if we measure the direction of approach of each cosmic ray, as it is recorded in the subterranean chamber of figure 4b. The projection operation is mathematically equivalent to that of figure 4a, but the directions of all useful rays are reversed in the two examples.

The details of the cosmic ray detectors are described in sections IV and V, and in more detail, in Appendix C. Section V also describes a modified form of the mapping scheme shown in figure 4, that has the advantage of keeping the map dimensions finite; the map generated in figure 4a extends almost to infinity, if the whole volume of the pyramid is to be recorded on the X-ray film.

For the present, we need only remember that the cosmic ray detector is located near the center of the ground level section of the Second Pyramid (figure 3), and that it is capable of recording the azimuth and elevation angles of approach of each recorded cosmic ray. Fortunately, appropriately located chambers are accessible in each of the three pyramids discussed in the introductory section of this proposal.

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III. Properties of the cosmic radiation.

The "penetrating component" of the cosmic rays is now known to consist of a stream of electrically charged particles of a rare variety - the mu mesons, or muons as they have recently been rechristened. Energetic muons are born high in the earth's atmosphere, as the result of collisions between still more energetic "primary cosmic rays," and the nuclei of air atoms. (The origin of the primary cosmic rays is of great cosmological interest, but it is a bit far afield from pyramids, and so won't be discussed here.)

Muons lose energy by friction, just as a rifle bullet does when it bores its way into a fence post. The laws governing the rate at which a muon loses energy are particularly simple; every time a muon penetrates one meter of water, it loses 200 million electron volts (MeV) of energy. Therefore, if it has 200 MeV to start with, it stops after penetrating one meter of water; a physicist would say "A 200 MeV muon has a range of 1 meter of water." By the same token, a 2000 MeV muon has a range of ten meters of water. If a particular muon is slowed down by passage through rock of density 3, its range will be one third as great as it would have been in water. Conversely, if we find a muon that has a range of 10 meters of such rock, we know that it originally has three times as much energy as the 2000 MeV a muon needs to penetrate 10 meters of water.

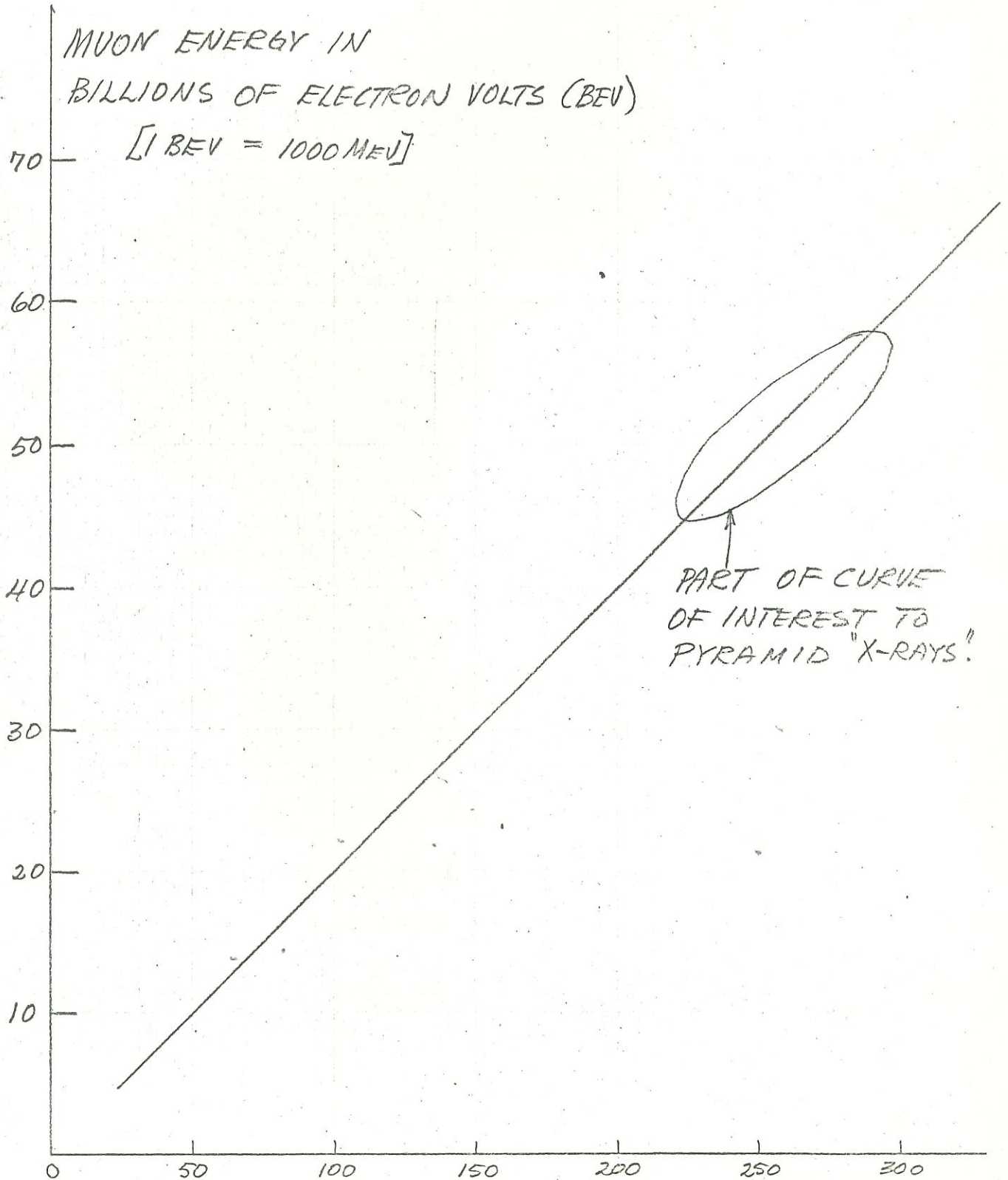
Because of the simplicity of the laws relating energy and range of muons, it is customary to express the range of a muon in "meters of water equivalent" (m.w.e.). (For example, 100 meters of rock with a density of 2.5 has a "thickness" of 250 m.w.e.) We then need only a single range-energy curve (figure 5) to tell us all that is known about the penetration of muons into any material.

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RANGE - ENERGY CURVE FOR MUONS



MUON RANGE IN METERS OF WATER EQUIVALENT

FIGURE 100

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All muons of a particular energy have the same range (if it is measured in m.w.e.), regardless of the density of the material into which they are penetrating. For convenience in designing the pyramid experiment, scales of m.w.e. have been added to figures 2 and 3. The Great Pyramid has a present day height of 137 meters. Since the density of limestone is 2.66, the height of the pyramid, or any other relevant distance through the core to be measured directly, without recourse to calculation.

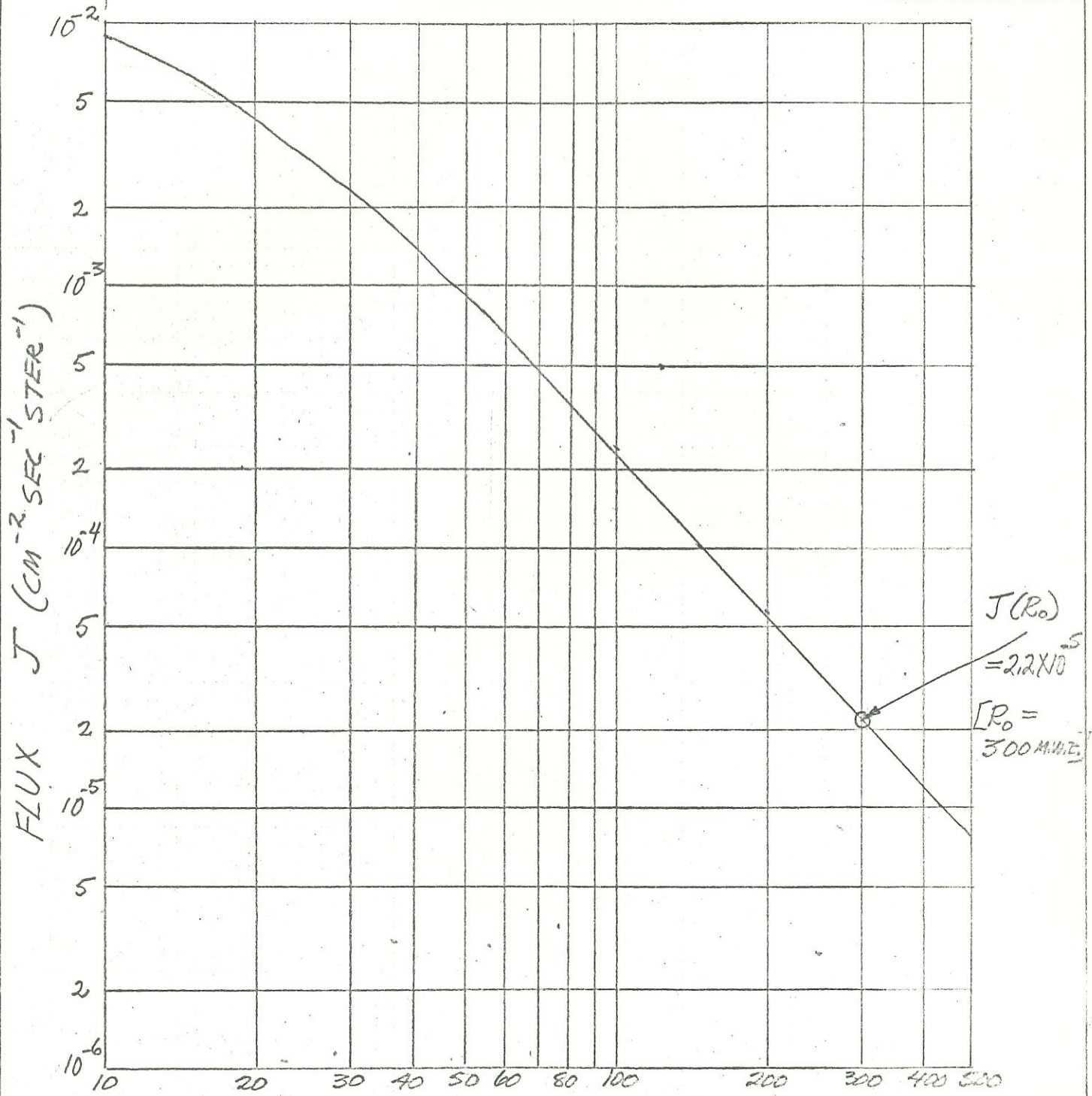
In the 1930's, soon after the Geiger counter had been developed into a reliable detector of electrically charged particles, physicists made the first good measurements of the relationship between cosmic ray intensity, and depth underground, measured in m.w.e. The measurements were often made in the sloping shaft of an abandoned mine. A "Geiger counter telescope," sensitive only to muons from within perhaps a 15 degree cone about the vertical direction, was placed on a mine car, so that the whole apparatus could be moved easily from one depth to another. The result of several months of operation of such an experiment was a curve like that shown in figure 6. (Dr. S. A. Goudsmit a distinguished physicist and amateur archeologist, once proposed making such measurements in the pyramids.)

Figure 6 is called a range spectrum, or an intensity-depth curve, because it tells how many cosmic ray muons penetrate at least as far as the indicated depth. Until now, we have been treating cosmic rays as though they were a downward stream of almost vertically directed muons. But in fact, we have implicitly been selecting a vertically directed stream from the totality of cosmic rays, by the use of a "telescope" - an arrangement of Geiger counters that is sensitive only to muons arriving nearly parallel to its axis. As long as we make our measurements with nothing but air above the apparatus, we

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 RANGE SPECTRUM OF COSMIC RAYS

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MUON RANGE-METERS OF WATER EQUIVALENT
 (LOG-LOG SCALES)

FIGURE 6



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find that we observe the same counting rate, no matter what direction our "counter telescope" is pointing. (This was suggested in the earlier discussion concerning the mapping procedure.) It is furthermore true that the counting rates in two identical "telescopes" - one pointing vertically and the other inclined at any angle above the horizon, will be the same, not only when there is nothing but air above them, but also when the same thickness of rock is introduced into, and along the two "lines of sight" (Figure 7). It is this fortunate aspect of the cosmic radiation that makes the pyramid project so easy to investigate by mathematical methods. We need only a single curve (figure 6) to tell us what counting rate to expect when "looking through" the pyramid in any direction; it is sufficient to measure the thickness of rock in that direction, from the subterranean chamber to the surface of the pyramid.

A more mathematical description of the properties of cosmic rays will be given in Appendix A. The brief summary given in this section should suffice to show that:

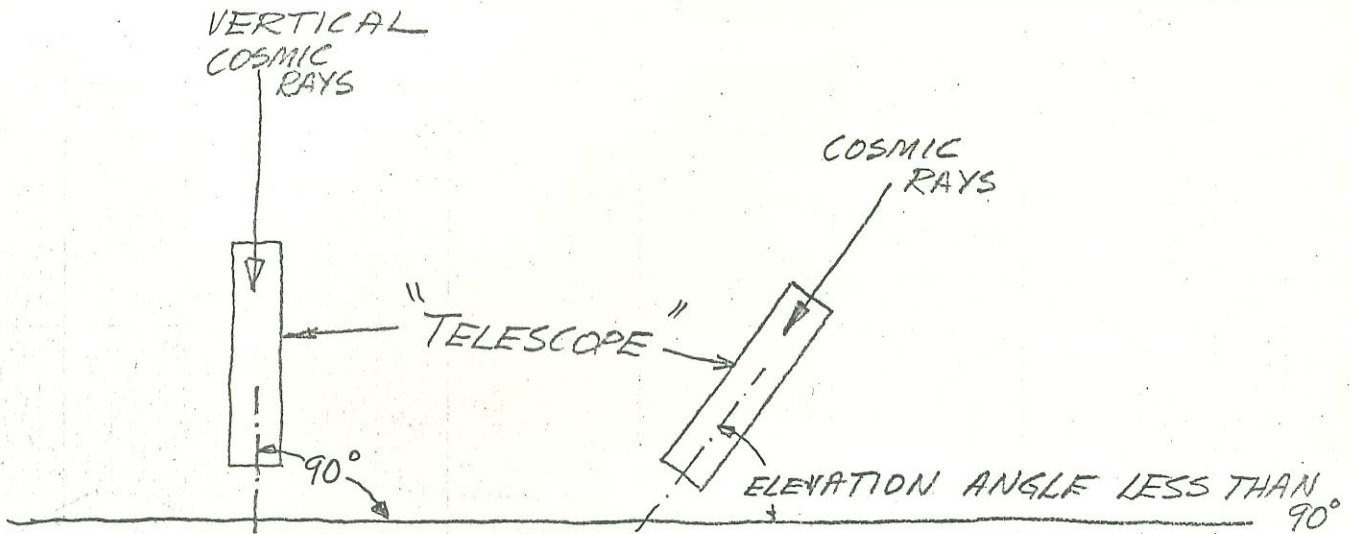
- 1) Cosmic rays are able to penetrate rock thickness as great as those encountered in the pyramids.
- 2) If the rock thickness is decreased (as for example, by creating a hollow chamber in the line of sight) the counting rate increases.
If the method is to be successful, two further criteria must be met:
- 3) The counting rate, in apparatus that can be placed in the subterranean chamber, must be high enough to yield a "grainless" X-ray picture in less than a year of operation. The effects of "statistical fluctuations" in the cosmic ray counting rate will be dealt with in Appendix B, and the conclusion will be reached that the fluctuations will not be large enough to indicate the presence of non-

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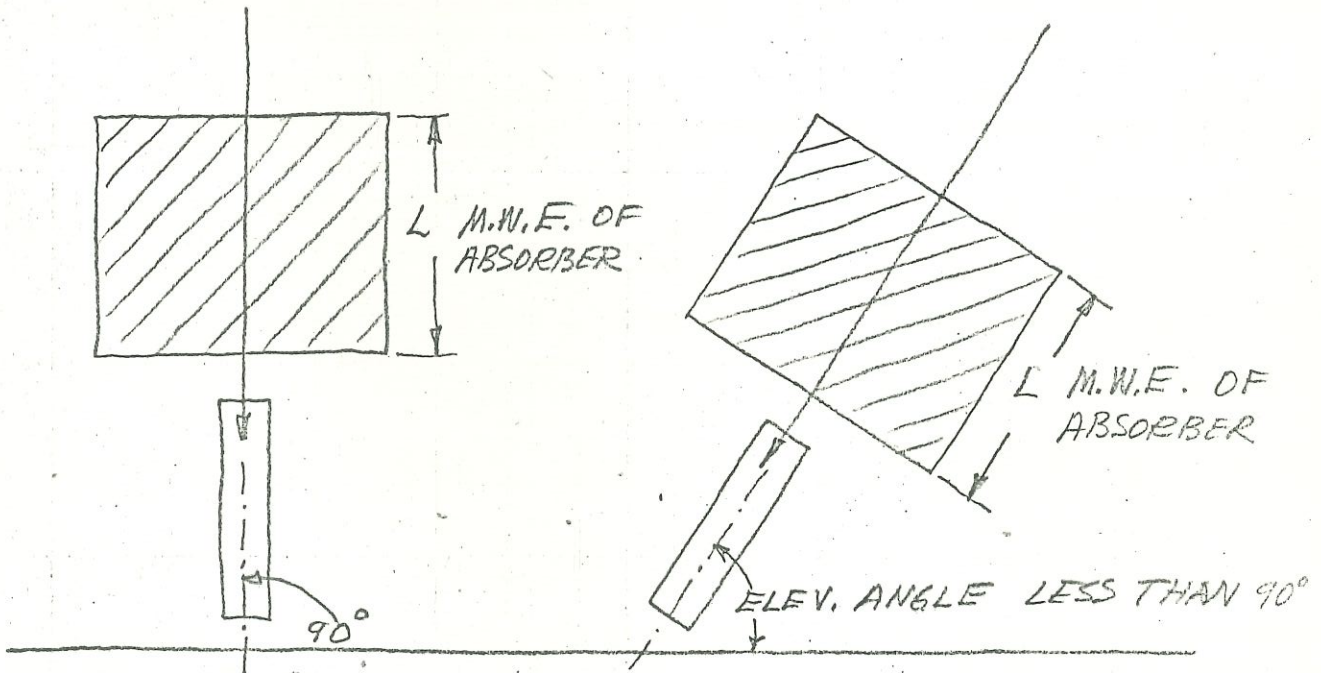
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COSMIC RAY TELESCOPES & ABSORBERS



Two identical counter telescopes pointing at different angles count the same number of muons, independent of the angle, when they are in the open air.



Identical counter telescopes have same counting rate for equal thicknesses of absorber (measured along line of sight) independent of elevation angle.

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existent chambers.

- 4) Random deflections of the cosmic ray muons as they pass through the rock must be small enough to keep the images of the chambers from being "washed out" on the X-ray plates. The random "scattering" of muons is understood mathematically, and although it could give trouble in the simplest kind of apparatus, the trouble is easily eliminated in the proposed design.

We can therefore conclude the non-mathematical sections of this proposal by stating that there are no technical reasons why the proposed experiment would not detect the chambers it is designed to find.

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IV. Cosmic ray detectors.

If we merely had to count cosmic ray muons in the Subterranean Chamber, Geiger counters would do the job admirably. But in order to reconstruct the X-ray picture of figure 4b, we must also measure the two angles that specify the direction of arrival of each muon. The recently invented spark chamber does this job so much better than Geiger counters could possibly do, that we shall confine our attention from here on to spark chambers alone.

The simplest variety of spark chamber consists of two flat metal plates spaced about a centimeter apart. When a muon penetrates the two plates, an electronic circuit suddenly applies a high voltage between the two plates. The high voltage causes a spark to jump between the plates, very nearly along the trajectory of the muon. The spark can easily be seen with the naked eye, and it is customarily recorded by two cameras. The two cameras look into the narrow gap, with their optical axes at right angles to each other, so that the true position of the spark can be located by "stereoscopic reprojection."

Many millions of spark chamber photographs have been taken in the last three years, but the present day trend is toward bypassing the photographic process altogether, and recording the coordinates of the spark directly on magnetic tape. So instead of sensing the recording the light from each spark, we plan to sense the electric current that flows, and record the signal electromagnetically. This procedure obviates the need for the time-consuming and expensive use of technicians to measure and record the positions of millions of individual sparks.

The electrical and mechanical designs of the spark chambers to be employed in X-raying the pyramids are described in some detail in Appendix C.

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Of the various techniques presently available for eliminating photography, we have chosen the "Nickel wire - Magnetostrictive readout." This ingenious method has been developed within the past year at the Lawrence Radiation Laboratory, by Dr. Victor Perez-Mendez and his co-workers. A detailed description of the modus operandi of a Perez-Mendez spark chamber would be out of place in a proposal of this sort. It should suffice to say that if a muon traverses two such spark chambers (both of which are horizontally oriented, and spaced a foot apart in the vertical or Z direction), the x and y coordinates of the sparks in the two planes will automatically be recorded on magnetic tape. The accuracy of each coordinate measurement, (x_1, y_1, x_2, y_2) will be better than one millimeter, so if the two horizontal spark chambers are spaced 12 inches apart, the desired angular information concerning the muon will have errors less than three milliradians - quite small compared to other errors we shall soon discuss.

We shall digress for a moment to the subject of angular errors, because it is important that we be aware of the magnitude of what might be called "tolerable angular errors." The three known "burial chambers" in the two large pyramids are roughly the same size, and it is reasonable to expect that any as yet undiscovered "true burial chambers" in either pyramid would not be very much smaller than these known chambers. The three chambers of interest are the King's and Queen's chambers of the Great Pyramid, and the Subterranean Chamber in the second Pyramid. All three chambers are about 18 feet in height, and 17 feet in width, their lengths are 33 feet (K), 18 feet (Q), and 46 feet (S_2). We shall therefore assume we are looking for a chamber that is 17 feet by 25 feet in floor area, and 18 feet high. We will furthermore assume that this chamber is 300 feet from the subterranean chamber (in either

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pyramid). (The maximum distance containable within the Great Pyramid is about 600 Feet; the corresponding length is about 400 feet for the Second Pyramid.) The angle subtended by the "standard chamber" at the muon detectors is therefore assumed to be about 20 feet/300 feet, or 67 milliradians, or 3.8 degrees.

One would have serious reservations about attempting to probe the pyramids with a detecting device whose ability to certify angles was poor compared to this value of 67 milliradians. But on the other hand, one would not be willing to pay much to improve the angular uncertainty from 20 milliradians to 2 milliradians; with either of these small values, the unknown chamber could be detected unambiguously.

It is a simple matter to design the spark chamber system so that output data supplied to the magnetic tape recorder is accurate to a few milliradians. This is true, if by accuracy, we mean the ability of the apparatus to record the trajectory of the muon as it passed through the two spark chambers, within the quoted angular limits. An additional angular error must now be investigated; it can best be appreciated by asking the question, "How nearly true is it that the muon we record in our spark chambers is still moving along the same straight line that defined its trajectory as it passed through the burial chamber?" Whenever electrically charged particles pass through matter, they suffer random and normally small changes in direction. Such angular dispersions are calculable from what physicists call "Scattering Theory". The comparison of experimental scattering observations with theoretical predictions has been exceedingly fruitful - the atomic nucleus was discovered by Rutherford in this manner, in 1911.

The scattering of muons in rock is described by a particularly simple mathematical equation that has been found experimentally to agree with the

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theory. As long as the muon has enough energy to penetrate at least a few tens of meters of water equivalent, its path will almost indistinguishable from a straight line. But as the muon traverses its last few meters of water equivalent, it scatters (on the average) through ever larger angles. Let us now remind ourselves that the muons we are most interested in are those which would have stopped in the rock just above our spark chambers if no burial chamber were present along the "line of sight". The existence of the void in the rock allows these particular muons to pass through the spark chambers, and gives us more counts than we would otherwise have recorded from that direction. We see, then, that all the "useful information" about the burial chamber is carried by muons that are just able to penetrate the spark chamber system, and stop in the rock just below the detectors. Unfortunately these are just the mesons that pass through the spark chambers with the greatest angular scattering from their original direction through the pyramid and from the burial chamber to the subterranean chamber. An optical analogy would be a 35mm colored slide projector that was out of focus. We must therefore, seek a way to "sharpen the focus" of our "muon projector system". We have seen that the scattering difficulty arises from the fact that we are looking at muons very near the "end of their range." We therefore, cure the difficulty by measuring the trajectories of the muons several meters of water equivalent before they end their range. We could do this in principle by moving our spark chambers into a newly excavated chamber some meters above the subterranean chamber. If we made sure that the muons were still able to penetrate down into the original subterranean chamber, we could use the angular information we obtained "up above," with confidence that it represented the true direction

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of the muon, before scattering in the underlying rock had changed that direction.

Fortunately, the subterranean chambers in all three pyramids, are high enough that we needn't cut any more holes in the pyramid. We place our spark chambers near the roof of the subterranean chamber, and stack iron bars between these angle detecting devices and another set of simple ordinary detectors near the floor level. The iron bars and the detector below simply assure us that any muon whose direction we sense in the spark chambers has enough energy left in it to penetrate the several feet of iron, and be counted in the floor level detection device. A physicist would say, "We've 'hardened the beam' with the iron absorber, so it's less subject to scattering errors."

In the mathematical Appendix B, we shall calculate the "mean projected scattering angle", $\langle \theta \rangle$, of a muon that has come from a burial chamber 18 feet tall, located 300 feet from the subterranean chamber. We shall also demand that the muon be able to penetrate at least five feet of iron after its direction has been measured. The result will be that the mean projected scattering angle is 33 milliradians, which is equivalent to saying that at 300 feet, the "fuzziness of the image" of the chamber edges on the simulated X-ray picture would correspond to a linear distance of 10 feet. This result means that there should be no difficulty in observing an unknown burial chamber, by looking at the "X-ray photograph." We would not have been much better off if the "spread" had been 1 foot, but the project would not be worth talking about if this number had turned out to be 100 feet. The scattering of muons in the rock presented the only potential hazard to the theoretical success of the project. As we have just noted, if the scattering had been worse by a single order of magnitude (factor of 10), the pyramids could not have been probed by any presently known radiation.

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V. Operations and data analysis.

In the first two appendices, the basic parameters of the detection apparatus have been discussed, one by one, and their values have been chosen to optimize the overall design: Two square spark chambers, each seven feet on a side, will be mounted horizontally, and spaced a foot apart. Under the lower spark chamber will be a layer of iron about five feet thick, and below the iron will be a simple layer of scintillation counters. The general layout is shown in figures 10 and 11. The detectors will be set up near the western wall of the subterranean chamber in the second pyramid. If the image of an unknown chamber appears on the "X-ray photograph," as it should do in a month's time, if the chamber exists, the detector will be moved about 35 feet eastward, to the far wall of the same chamber. The angular displacement of the chamber image, caused by this detector displacement, will allow the elevation of the new chamber above the subterranean chamber to be determined by a simple trigonometric calculation.

All of the apparatus has been designed so that it can be carried through the entrance passages of the three pyramids of interest. The spark chambers will have to be dismantled and reassembled inside the subterranean chamber. The tape recorders can best be installed in a wooden hut near the entrance to the pyramid, and connected to the detectors by cables which thread the passage to the subterranean chamber.

After all the apparatus has been installed and checked out, the further operations could be carried out by a single individual living in Egypt. He would verify that the equipment was working each day, and would hang a new magnetic tape on the recorder. The inscribed tape would probably be duplicated in Cairo, so the original would be available for analysis by our Egyptian associates; the duplicate would be sent to Berkeley for similar processing.



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Many ways to display the data are available. The most meaningful would be to print out the number of counts obtained in each "elementary unit of solid angle," much like the "pressure map" printed by the weather bureau. In Appendix A, we have suggested that 1600 counts per element of 8.5×8.5 square feet would be adequate to locate a "standard burial chamber." The last digit in this count is certainly of no significance, but the second digit, representing the number of tens of counts is of some significance; we expect to have an extra 160 counts if we are looking through a "standard chamber." The apparent magnitude of the fluctuations can be increased by a simple operation; the computer can subtract some constant number of counts from each sample, or more correctly, some number that varies smoothly from one direction to another, so that the residual number of counts is essentially constant over the whole "map" of the pyramid. It is a simple matter to generate, by the computer, the proper number to be subtracted. This number would be an analytic function of the pyramid geometry and the cosmic ray spectrum. When it was subtracted from the experimentally observed matrix of counts, the resulting matrix would be an almost constant set of individual counts, with an enhanced fractional increase from the direction of an existing burial chamber.

The data analysts in Berkeley and Cairo would devote most of their attention to the printed matrix of "differential counts," looking for small regions in which several neighboring cells had statistically significant counts over the "background." If such a region of interest showed up, it would be a simple matter to convert the matrix of numbers into a simulated X-ray photograph. One would simply program the computer to display the matrix on its cathode ray oscilloscope, and the display would be photographed by a camera.

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Such procedures are common in the author's specialty of high energy physics. The cathode ray oscilloscope spot would be programmed to move over the whole range of x and y variables (North-South and East-West), remaining at each spot for a time proportional to the number of counts recorded from that direction (minus the slowly varying baseline count). The result would hardly be distinguishable from the X-ray photograph of the model pyramid discussed earlier, except that its "contrast" would be considerably enhanced; a smaller chamber would show an amplified change in intensity relative to that from neighboring directions through the pyramid.

This is an appropriate place to discuss in more detail how one would map the pyramid onto a flat photographic film. In figure 4, the X-ray photograph of the model pyramid would extend nearly "out to infinity," if one wished to map regions of the pyramid down to the same altitude as the subterranean chamber, which in the second pyramid is almost at ground level. (This difficulty with some kinds of maps is well known in the Mercator's Projection, where the polar regions are greatly distorted, and the two poles are "plotted on the map at infinity.")

A simple way to map the interior volume of the pyramid onto a finite area of photographic film is to adopt the following procedure: calculate from the angles of arrival of a cosmic ray muon where that muon first penetrated the rock surface of the pyramid; project that point of entry onto the base of the pyramid, to give an x and y "base coordinate." Plot that particular count on the "X-ray film," at those two "base coordinates." From what has just been said, it is obvious that all counted muons will give rise to points plotted within the square base contour of the pyramid. From the x and y coordinates of the sparks in the two spark chambers, plus the stored equations

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of the four flat faces of the pyramid, the computer can calculate the "base coordinates" for each muon in a few millionths of a second. The computer will then immediately add one count to the number of counts previously stored at that "base x and y address" in its memory.

For purposes of orientation, we need to know approximately how many words in the computer memory are required to store all the information in the simulated X-ray photograph. If we use our "resolution area" of 72 square feet ($8\frac{1}{2}$ foot square), we note that the base of the largest pyramid contains 8,300 such unit areas. A typical modern computer has 16,384 words in its "fast memory," each word with 36 binary bits. According to Appendix A we wish to store approximately 1600 counts in each memory location. If we assume we may allow that number to increase to 8,000, we still need only 13 of the 36 bits in each word to accommodate that amount of storage, ($2^{13} = 8,192$). From this we see that there is vastly more storage capability in the computer than we can possibly use; we use less than one third of each word, and about one half of all the available words. There is, therefore, more than enough memory capacity available to store the arithmetic program, the input and output routines, and the display program for the cathode ray oscilloscope.

A typical day at the computer would involve the following operations: The operator would unpack the tape just arrived from Egypt, and would hang it on a tape transport unit at the computer. He would at the same time hang the "library tape," with its complete "memory dump" from the last day's computer run. The library tape would then be "read into core," so that the state of the memory on the previous day would be recreated, just as though no time had elapsed between the previous run and the present one. The program in the memory

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would "step the new tape forward," looking for coordinates of spark chamber sparks - the "end of record" mark on the previous day's tape would have told the computer that no more spark coordinates were available, and that it was time to "dump the memory" onto the library tape, and let some other user have the computer. Now, with a new tape to read, a "start" instruction from the operator will put the computer to digesting a new day's accumulation of data on the direction of arrival of muons at the pyramid.

It is probable that the operator would not be able to restrain his curiosity, so he would ask for a print-out of the numbers in the memory "bins." It would take only a few minutes to print all the information available in the memory, so the operator would have a day by day record showing the growth of any "suspicious enhancement" to a statistically significant signal, as more data arrived from Cairo, with the passage of time.

Until now, it has been assumed that the spark chamber trays are oriented horizontally. This is certainly the way one would start operating, but it is also likely that if no burial chamber was found overhead, the spark chambers would be reoriented with their perpendicular axes pointing successively at about 30° from the horizon along the 4 cardinal compass directions. The effective detecting area of the spark chamber system for muons coming in at large angles to its perpendicular axis is greatly reduced from its geometrical area. But by looking successively in five directions, with overlapping coverage (Vertical plus N, E, S and W at 30°), the whole volume of the pyramid can be probed for unknown chambers in any possible location.

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Appendix A

Mathematical description of the penetrating cosmic rays.

Figure 6, the intensity depth curve, has been discussed qualitatively in section III. The intensity as plotted in figure 6 is more properly called the "integral flux," where the word "integral" comes from the fact that at a particular depth, we plot the flux of particles with ranges from that depth all the way to infinity. The flux is defined as the number of particles crossing a square centimeter per second, and per unit solid angle.

The curve in figure 6 is seen to be approximately straight, and certainly quite straight in the range of interest to pyramid probing. As long as the curve can be considered to be straight, it can be approximated by the power law

$$J(R) = J(R_0) \left(\frac{R_0}{R} \right)^n$$

where n is called the "spectral index." We can assign R_0 the value of 300 m.w.e., since that is some sort of mean range of interest to a "pyramid prober," as can be ascertained by inspection of figures 2 and 3. The index of the distribution in the neighborhood of 300 m.w.e. is close to 2, and we shall assume it to be exactly 2 in the calculations to follow.

We can now obtain a mathematical formula that closely approximates the integral flux in the interval of range given by 300 m.w.e. \pm a factor of 2, i.e. from 150 m.w.e. to 600 m.w.e. This expression is obviously the first term in the Taylor expansion about the point $R_0 = 300$ m.w.e. From figure 6, we then have:

$$J(R) = 2.2 \times 10^{-5} \left(\frac{300 \text{ m.w.e.}}{R} \right)^2 \quad (\text{A-2})$$

$$J(R) = \frac{2.0}{R^2} \quad (\text{A-3})$$

where R is in m.w.e., and $J(R)$ is in $\text{cm}^{-2} \text{sec}^{-1} \text{ster}^{-1}$.

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It is now important to note that if we decrease R by a small fraction (for example 10 %), the flux will increase by twice that fraction (for example 20 %). This relationship comes from the definition of n:

$$n = \frac{-d \log J}{d \log R} \quad (\text{A-4})$$

Since $d \log J = \frac{dJ}{J}$, and $d \log R = \frac{dR}{R}$,

$$\frac{dJ}{J} = \frac{-2dR}{R}, \quad (\text{A-5})$$

as noted in the example. The spectral index is fortunately greater than 1, so that a given fractional change in range (caused by the presence of a burial chamber) is turned into a fractional intensity change that is twice as large. If one were greedy, he might wish for a larger index, to yield a higher "magnification factor." But if the index were higher, the intensity at 300 m.w.e. would be less, and one would have fewer counts in a given interval of time; he would therefore be troubled with statistical problems. Fortunately, nature has provided us with a cosmic ray spectrum that is admirably suited to the job at hand, and it is idle to speculate on its improvement.

We shall now calculate how large a spark chamber we need to accumulate a statistically significant increase in the number of counts from the direction of a suspected "void," or chamber in the otherwise solid rock. In the next appendix, we assume that we are looking for a "standard chamber" with a size that is found three times in the two large pyramids. The "standard chamber" has a floor area of 25 feet x 17 feet, and a height of 18 feet. We further assume that the chamber is physically 300 feet from the cosmic ray detector. For statistical redundancy, we shall assume that we are looking for six "sub-chambers," each one being part of the main chamber, and each having a floor area of 8.5 feet x 8.5 feet. The chance that any observed increase in intensity along a particular direction is due to a statistical fluctuation is greatly decreased if we can say, "We have six independent indications that a chamber exists in a particular direction, and each of these indications is larger than the

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statistical fluctuations we see in any other direction." (The fact that we may be looking diagonally through a burial chamber does not invalidate the argument just given-- the "signal" observed by the detecting device actually depends almost entirely on the volume of rock missing from the solid pyramid, and scarcely at all on its distribution in height and floor area.)

We may now assume that we are looking at a series of "cells in solid angle," each subtended by an 8.5 foot square at a distance of 300 feet. The element in solid angle is then

$$\Delta\Omega = \frac{8.5^2}{300^2} = 8 \times 10^{-4} \text{ steradians.} \quad (\text{A-6})$$

From equation (A-2) we find the integral flux at 300 m.w.e. to be

$$J(300) = 2.2 \times 10^{-5} \text{ cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1} \quad (\text{A-7})$$

In the solid angle given by (A-6), and assuming a detector with an area of $A \text{ cm}^2$, we have a counting rate given by

$$M = 8 \times 10^{-4} \times 2.2 \times 10^{-5} A \text{ counts/sec} \quad (\text{A-8})$$

$$M = 1.75 \times 10^{-8} A \text{ counts/sec.} \quad (\text{A-9})$$

We must now determine the product of the area A and the observation time T , that will yield a statistically significant number of counts, N , from the small element of solid angle defined by 1 "sub-chamber." We first estimate the "magnitude of the signal," from equation (A-5); we take the thickness of rock that the cosmic rays have traversed to be 350 feet, and the height of the burial chamber to be 18 feet. Therefore $\Delta R/R = 18/350 = 5.1 \%$. Consequently, the increase in counting rate along this line will be about 10 %. If the expected number of muons in a counted sample is 100, we expect a "standard deviation" of 10 counts in a family of many such counted samples. If we wish to be more and more sure that our observed "10 % signal" is real, and not of statistical origin, we must accumulate a larger sample of counts-- the standard deviation, expressed as a fraction of the total counts, is given by

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$$\frac{\Delta N}{N} = \frac{1}{\sqrt{N}} \quad (\text{A-10})$$

Tables of the "Probability of occurrence of deviations" shows the following probability, p_m , of finding a deviation larger than n standard deviations:

n	3	4	5	6	7
p_m	2.7×10^{-3}	6×10^{-5}	6×10^{-7}	2×10^{-9}	3×10^{-12}

If we were unprotected by the redundancy of the 6 "sub-chambers" and had to be quite sure that an observed 10 % increase in counting rate was due to a real void, we might be tempted to make p_m less than 10^{-8} . But with the redundancy, it seems perfectly safe to ask that n be only about 4, so p_m is one chance in 16,000 for each sub-chamber. A closer look at the statistical problem shows that the main gain in designing to look at "sub-chambers," is that we insist on having enough spatial resolution to see the finite extent of the burial chamber--we actually don't gain anything significant in insurance against statistical fluctuation; the 6 times larger number of counts for the complete chamber would reduce the standard deviation by a factor of $\sqrt{6} = 2.45$. Therefore we would pass from 4 standard deviations on each of the six sub-chambers to 10 standard deviations for the chamber as a whole. As one can see from the table, a 10 standard deviation effect can always be taken to be real; the probability against a statistical fluctuation is less than 1 in 10^{23} !

Now that we want our signal to be 4 times the standard deviation, we need $4^2 = 16$ times our original count of 100 per "element of solid angle." From this fact, and equation (A-9), we may now write

$$N = 1600 = 1.75 \times 10^{-8} AT \quad (\text{A-11})$$

where T is the total time of observation (in seconds). The product AT is now

$$AT = 10^{11} \text{ cm}^2 \text{ sec.} \quad (\text{A-12})$$

If A is 1 square meter = 10^4 cm^2 , $T = 10^7 \text{ sec} = 4 \text{ months}$. If $A = 4$ square meters, $T = 1 \text{ month}$. This seems to be a good compromise; if we make A less than

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$1/3$ square meter, the observation time is greater than a year, which appears to be going in the wrong direction. At the other extreme, if we try to shorten the observation time to one week, the counter area becomes larger than the "resolution area," which we have chosen to be a square 8.5 feet on a side. We therefore see reasons against making A too large or too small, and a reasonable compromise seems to be to use a pair of square spark chambers each about 2 meters on a side.

We are most fortunate that the intensity of the naturally occurring cosmic rays fit our needs so well. A two order of magnitude decrease (factor of 100) in intensity at 300 m.w.e. would have made the experiment quite impossible, and a one order of magnitude decrease (factor of 10) would have made it exceedingly difficult.

Appendix B.

Mathematical analysis of the scattering problem.

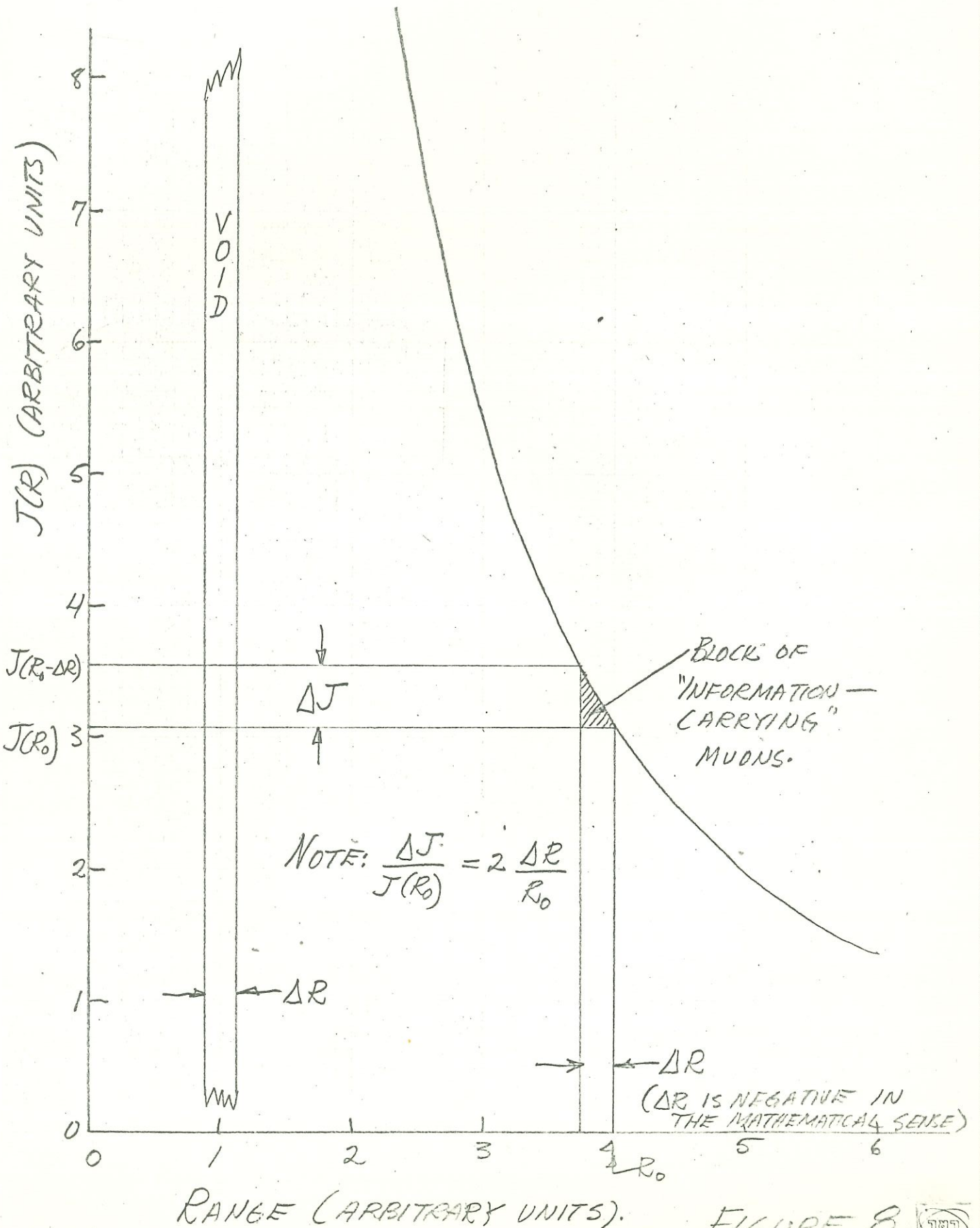
Before attacking the problem of the "multiple scattering" of muons in the pyramidal limestone, it will be profitable to understand in a bit more detail the "signal" modulated onto the cosmic ray beam by the presence of a burial chamber. Figure 8 shows a portion of the intensity-depth curve (figure 6), plotted on linear graph paper, as distinguished from the log-log paper employed in the original figure. Figure 8 shows that $J(R)$ varies as R^{-2} near R_0 , which we have defined in Appendix A to be 300 m.w.e. We also check that $\Delta J/J(R_0) = -2 \Delta R/R_0$, as demanded by equation (A-5).

We now assume a detector with an area of 1 cm^2 , subtending a solid angle of 1 steradian, and a counting period of 1 second; under these conditions, every unit of $J(R)$ corresponds to a single muon. In the absence of a void, and assuming the rock thickness to be R_0 , the number of muons passing through the spark chambers is $J(R_0)$. With the void excavated, we count an additional number of muons equal to ΔJ , the altitude of the shaded triangle. The muons with range less than $R_0 - \Delta R$

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never reach the spark chambers, either with or without the void. The muons with range greater than R_0 always pass through the spark chambers, with or without the void.

The analysis just presented shows that we can divide the muon flux into three components: one we never see because its range is always too short; the third we always see, regardless of the existence of a void, so it can be considered to be a background that tells us nothing about the internal structure of the pyramid. The middle class of muons either registers in our detector, or is prevented from reaching it, depending on the existence of a burial chamber. Under such circumstances, it is useful to postulate that this flux of muons originates in the void, and to treat it as if it were a new flux superimposed on the constant background of muons with a range greater than R_0 .

We can now inquire into the properties of this "new flux" of muons, which carries all the information concerning the void in the rock. We see immediately that this component has a distribution in range in rock below the detector that is uniform from zero to a distance equal to the height of the burial chamber. The two extremes are the following: a) a muon with a range just larger than R_0 would have missed the detector in the absence of the void, but a void of height ΔR will endow the muon with a range of ΔR beyond the detector. b) A muon with a range $R - \Delta R$ will just reach the detector if the void is present, and consequently its extra range in the rock below the detector is zero. In the linear approximation we are using, the range distribution of "new muons" in the rock below the detector is "flat" from zero to a value equal to the height of the void.

We must now investigate the scattering of the "new muons" in their passage from the burial chamber to the detector. (One might think that the scattering should be calculated from the surface of the pyramid to the detector, but any scattering between the surface and the burial chamber is of no significance--the "geometry is poor," so that as many muons "scatter in" as "scatter out," and we can take the flux

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of muons at the depth of the burial chamber to be the random "parent population." In addition to what has just been said, the scattering of these high energy muons is so small as to be inconsequential.)

As was discussed in section IV, we shall reduce the scattering of the "new muons", by not allowing any of them to approach closer than 11.5 m.w.e. to the end of their range. In this appendix, we shall show that 11.5 m.w.e. (5 feet of iron) is a reasonable amount of absorber to use as a "beam hardener," by calculating the mean scattering angle as a function of "hardener thickness."

The "multiple scattering" of muons in passing through rock is a random process, consisting of millions of small deflections, each of which adds to or subtracts from the scattering angle already accumulated. The magnitude of such a sum of random but inherently equal deflections will increase as the square root of the thickness of the rock. But as the muon approaches the end of its range, it becomes "softer," and the individual scattering events cannot be treated as "inherently equal;" each succeeding scattering event becomes larger as the muon approaches the end of its range, so the mean angle increases faster than the square root of the thickness of rock.

The basic formula applicable to the multiple scattering of muons is the following:

$$\langle \theta \rangle_{\text{proj}} = \frac{15 \text{ Mev.}}{E (\text{Mev})} \sqrt{\frac{L}{L (\text{RAD})}} \quad (\text{B-1})$$

$\langle \theta \rangle_{\text{proj}}$ is the mean scattering angle (in radians) projected onto a single coordinate axis. E is the energy of the muon, measured in millions of electron volts. L is the thickness of a thin "slab" of material, so the muon energy can be considered to be constant as it traverses the slab. L (rad) is the "radiation length" of the material. For limestone (CaCO_3), $L(\text{rad}) = 0.26 \text{ m.w.e.}$

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From the published range-energy curves for muons¹, we find that it is sufficiently accurate to use the expression:

$$E(\text{MeV}) = 200 R (\text{m.w.e.}) \quad (\text{B-2})$$

which was introduced in section III. If we measure all distances, χ , in m.w.e., we may make the following substitutions into equation (B-1):

$$E = 200 \chi$$

$$L = \Delta \chi$$

$$L(\text{rad}) = 0.26$$

Furthermore, since both E and 15 MeV are in the same units, we can ignore the dimensions, MeV. Finally, we can square both sides of the equation, preparatory to integration

$$\langle \theta^2 \rangle_{\text{proj}} = 2.16 \times 10^{-2} \frac{\Delta \chi}{\chi^2} \quad (\text{B-3})$$

Equation (B-3) gives the mean square projected angle of scattering of a muon with range χ , when it traverses a thin slab of thickness $\Delta \chi$. If we wish to find the scattering of a muon in a thick absorber, we must integrate (B-3) between the limits χ_1 , and χ_2 , the residual ranges the muon has when it enters and leaves the thick absorber. Thus,

$$\langle \theta^2 \rangle_p = 2.16 \times 10^{-2} \int_{\chi_1}^{\chi_2} \frac{d\chi}{\chi^2} \quad (\text{B-4})$$

$$\langle \theta \rangle_p = 0.147 \sqrt{\frac{1}{\chi_1} - \frac{1}{\chi_2}} \quad (\text{B-5})$$

We shall now evaluate equation (B-5), numerically, assuming χ_2 to be equal to 200 m.w.e. (Within the accuracy of the experimentally available numbers, we might as well have taken χ_2 to be infinite; this confirms the earlier statements

1 A. Buhler, T. Massam, Th. Muller and A. Zichichi. Range Measurements for muons in the GeV (10^3 MeV) Region, CERN preprint 64-31 NP Division, 24, June 1964.

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that the scattering contributed by the energetic muons is quite negligible).

Figure 9 is the result of the numerical evaluation of equation (B-5); it shows $\langle \theta \rangle_{\text{proj}}$ as a function of χ_1 , the residual range of a muon. As numerical examples, we see that a muon whose direction of travel is measured while it still has a residual range of 22 m.w.e., can be expected to show its original direction to within a mean uncertainty of 30 milliradians. If we didn't measure its direction until it had only 1 m.w.e. of residual range, the measured angle would depart from the original direction by an average angle of 143 milliradians, or 8.2 degrees. The marked effect of the 5 feet of iron absorber is easily seen in figure 9. The somewhat unexpected effect of the chamber height in hardening the muons can also be seen. If the burial chamber being postulated were only 1 m.w.e. in height (rather than 14.5 m.w.e), the value of $\langle \theta \rangle_p$ in the presence of the iron hardener would be 40 mr., rather than 33 mr. But in the absence of the iron hardener, the values of $\langle \theta \rangle_p$ for high and low chambers would differ by about a factor of two.

There is no way to determine the optimum value for the thickness of the iron hardener. The value of $\langle \theta \rangle_p$ would drop from 33 to 25 mr., if the iron thickness was doubled to 10 feet. This does not appear to be a worthwhile return on the invested iron. One would probably start the measurements with one or two feet of iron under the spark chambers, and gradually pile in more iron, until the thickness was five or six feet.

One might suppose that a given thickness of lead would be more effective in reducing scattering, than is the proposed iron. But in fact, the two materials are almost equally effective; the increased density of lead just makes up for an effect we have so far been able to overlook in the present analysis--elements of higher atomic weight are slightly less effective absorbers, on a m.w.e. basis, than are lighter elements.

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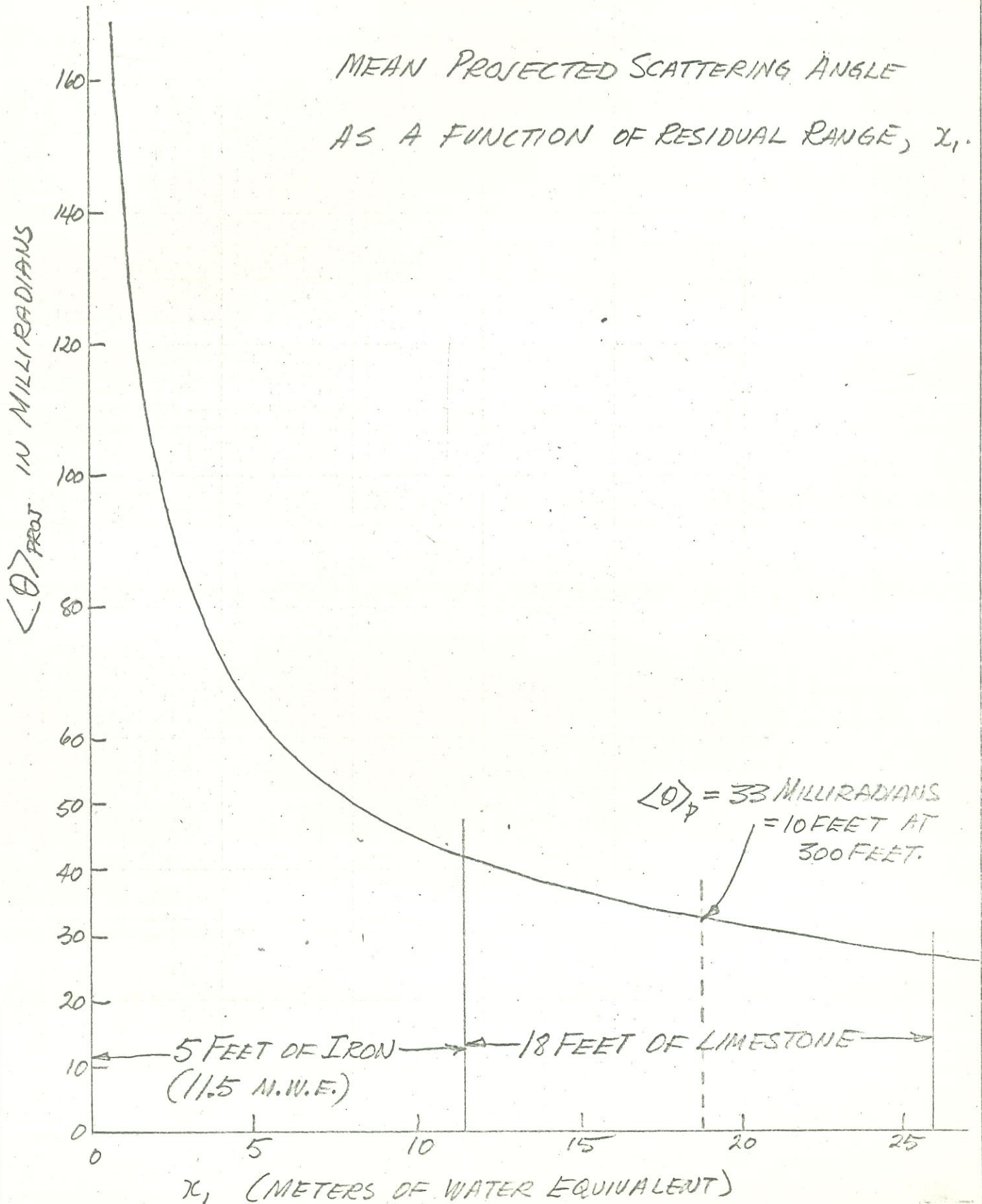


FIGURE 9



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Appendix C.

Mechanical and electronic design studies, and cost estimates.

The main body of this appendix is a paper prepared by two members of the Physics Instrumentation Group at the Lawrence Radiation Laboratory, Dick A. Mack, and Fred Kirsten. The author is very grateful to them for their comprehensive and authoritative estimate of the cost of mounting the experimental program outlined in this proposal. Their costs were estimated on the assumption that considerably larger spark chambers were to be used--5 meters on a side rather than the 2 meter design that finally emerged from the main study. An examination of the detailed cost figures does not show that very substantial savings result from the change in size. The chamber costs are reduced by about \$4,000, and the scintillator costs are reduced by \$15,000. All other costs are unchanged. The total savings are thus about 10 % of the estimated cost, which is less than the "20 % Contingency" of \$27,400, and the "15 % Miscellaneous Items" of \$20,500. We shall therefore quote the estimated cost, under the following assumptions, to be \$170,000.

The cost estimates of Mack and Kirsten were based on the assumption that the equipment was designed and fabricated in the (non-profit) shops of the Lawrence Radiation Laboratory. Since most of the mechanical and electronic devices are standard laboratory "off-the-shelf items", the estimates are certainly realistic. Similar equipment is available commercially from a number of suppliers, so the commercial prices have been kept competitive with those of the laboratory.

An alternative method of cost estimation can be contemplated if for some reason, the Atomic Energy Commission might authorize the Lawrence Radiation Laboratory to lend the (standard) electronic equipment to the "Pyramid Project". Such loans have been authorized in the past, when the receiving agency has been a Government-supported university project, with interests paralleling those of the Lawrence Radiation Laboratory. (Such university loans are of course not restricted to the University of California.) In the event that such a loan program might be implemented the estimated cost of the program would drop below \$100,000.

October 6, 1964

MEMORANDUM

TO: L. W. Alvarez

FROM: Dick A. Mack and Fred Kirsten

RE: Cost Estimate for Pyramid Spark Chamber and Electronics

Based on the discussions we have had, the following estimates the cost of a spark-chamber array and the associated pulsing and readout circuits to be used in your proposed experiment in Egypt. Each part of the system is based upon known experimental techniques which have been used at this Laboratory. We believe the extrapolations that have been made for the larger chambers and scintillation counters are entirely feasible. A block diagram is shown in Fig. 1.

It is assumed that the equipment would operate around the clock for approximately a year, and that once a day local personnel would change magnetic tapes and make routine operational checks. All electronic circuits would be constructed in modular form so that the required maintenance and repair skill would be a minimum. One spare chassis or printed circuit board has been included for each function. If a spare unit is placed in service, the original unit can presumably be returned either to Cairo or Berkeley for service.

All material, components and test equipment have been estimated at the present net cost to the Laboratory. Labor charges have been estimated at \$12 per hour. Certain assumptions that have been made in the estimate are given in the last paragraph.

The grand total is estimated to be \$184,800
 (THIS TOTAL IS REDUCED TO \$170,000,
 ON THE BASIS OF REDUCED
 CHAMBER SIZE - L.W. ALVAREZ.)
 FEB 28, 1965

Dick A. Mack
 Dick A. Mack
 Physics Instrumentation Group

DAM:mt

Fred Kirsten/m.
 Fred Kirsten
 Physics Instrumentation
 Systems Group



A. SPARK-CHAMBER CONSTRUCTION

It is proposed that the spark-chamber array consist of two chambers each capable of yielding both the X and Y coordinate position for each spark. The construction must lend itself to rapid assembly and disassembly in the field. (Auxiliary electronic circuits will ignore events where a) each chamber does not fire or b) more than one spark occurs in a chamber.)

The best chamber construction appears to be that of using etched (or if necessary milled) copper strips on long mylar sheets, as described by Victor Perez-Mendez and others. This method of construction for a large demountable chamber is less fragile and appears preferable to a chamber with wires strung from supports.

Rectangular coordinates for each spark could be obtained by running the etched wires at the top and bottom of the chamber transverse to each other. This method has been described by Neumann for stretched wire chambers. See Fig. 2.

Several methods of readout might be employed:

1. A memory core attached to each chamber wire and subsequently scanned in a coincident-current readout system, or
2. Coded arrays of cores yielding the spark address with a smaller amount of scanning required than required in (1), or
3. A magnetostrictive wire transverse to each set of chamber wires and giving a single-coordinate address for each spark.

Method 3, first described by Gianelli and refined by Perez-Mendez, appears to offer the simplest system and is recommended for this set-up.

For two 5 x 5 meter, etched-wire chambers the construction costs have been estimated as follows:

Master etching template	\$ 500
* Etching costs (\$50 for a 1.5' x 1.5' sheet)	2400
* Copper-clad mylar cost (\$3/ft ²)	3300
Material cost for chamber frames	200
5 Magnetostrictive readout transducers and high-voltage connectors	300
Design time of chambers	2000
* Machining and assembly costs for 2 demountable chambers each 5 x 5 meters	2000
	<u>\$10,700</u>

* For chambers of different dimensions these costs can be pro-rated.



B. SCINTILLATION COUNTER CONSTRUCTION

It is proposed that two scintillation counters be employed to encompass the same solid angle as subtended by the spark chamber array and used to trigger the spark-chamber pulser.

COSTS:

Pilot Y Scintillator

- * 1) 5 x 5 meters x 0.625 cm thick (\$125 for 1 x 4 feet x 1/4")
- * 2) 5 x 5 meters x 0.625 cm thick plus 4 sections 2 x 5 meters around edges of iron shield.

Total of 90 m ² .	$\frac{10.8 \text{ ft.}^2}{\text{m}^2}$	· \$31.25/ft ²	\$30,400
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- * Machining edges of scintillator (assume 1 x 4' sheets require 1.5 hours machining each) \$ 4,400
- * Gluing scintillator to make 5 m long strips \$ 900

Light proofing to be done with aluminum foil and black cardboard at site --	<u>\$35,700</u>
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*For scintillators of different dimensions these costs can be pro-rated.



C. ELECTRONICS EQUIPMENT

1. Spark-chamber pulser and power supplies.

The Spark Chamber pulsers can be triggered with a scintillation-counter coincidence circuit, see Fig. 1. The following standard units (including spares) are recommended for this use:

18 Phototubes and shields	\$4400
18 Phototube bases	3600
4 Pulse OR Circuits	800
2 Pulse AND Circuits	300
2 Spark-chamber trigger amplifiers	6400
3 Spark-chamber distribution boxes	1800
2 High-voltage power supplies for spark chambers	800
2 Clearing field power supplies	400
2 High-voltage power supplies for phototubes	1200
2 Phototube voltage - divider panels	500
2 Bins and power supplies for fast electronics	1000
Assembly and checkout time for pulser and coincidence system.	4000
	<u>\$25,200</u>

2. Spark-chamber Read-out Equipment - per Fred Kirsten

To record the coordinates of each event it is proposed that the magnetostrictive readout signals be used to gate time-interval scalers. The spark-chamber trigger signal would gate on each of four scalers with a capacity of 1024 counts. The magnetostrictive readout would gate each scaler off at a time corresponding to the position of the spark in that chamber. For a time base the scalers would count from a 1-Mc clock oscillator.

The following readout logic circuits (including spares) would be required:

Amplifier and discriminator circuits	\$1400
4 Scales of 1024	1700
Tape transport control circuits	1400
Spare boards	3000
Test routine equipment	2300
Power supplies	1200
2 Incremental magnetic tape transports with drive electronics.	12,000
Engineering design and checkout of individual chassis	7500
	<u>\$30,500</u>



C. ELECTRONICS EQUIPMENT (Continued)

3. Magnetic Tape

It is estimated that in the most compact data format, one 2500 ft. reel of tape would be required per day. At \$25/reel, tape costs for 200 day's operation would be -- \$5000

(The tape is, of course, reusable as soon as the raw data data have been read into a computer.) \$5000



D. ELECTRIC POWER AND LINE REGULATORS

Adequate power with sufficiently good regulation may be available at the site. However, for this estimate it is assumed that we would have to generate our own power. A diesel generator with an output of 10 kVA, 115/230 volts, 1 phase, 60 cycle with $\pm 10\%$ load regulation should be adequate.

Paul Breitenbach supplied the following figures:

Diesel-generator	5 kVA	\$1200	
	10 kVA	1800	\$1800
	15 kVA	2600	
	30 kVA	5000	

Operating costs including fuel, maintenance and depreciation \$.054/kWh.

This assumes fuel costs \$.50/gal., the usage is 0.1 gal/kWh, and depreciation is 20%/year.

= For 1 year's operation at an average power consumption of 5 kVA, the power cost is --- \$ 500

A 5 kVA line voltage regulator is essential for the correct operation of the electronics equipment; a second unit would be used for standby operation.

Stabiline line voltage regulators with protection and control circuits, \$3200 each --- \$6400.

Cabling, coaxial and power -- \$2000

\$10,700



E. TEST EQUIPMENT, TOOLS, SPARE PARTS

1. It is recommended that the following test equipment be assigned to the experiment:
 - 1 - 30-Mc bandwidth oscilloscope with 2 plug-in amplifiers, high voltage and low voltage probes.
 - 2 - High impedance voltmeters with HV probes.
 - 2 - Volt-ohm milliammeters.
 - 1 - Pulse generator. Total \$3600
 - 1 - Radioactive source for checking scintillation counters.- Borrowed

 2. It is recommended that the following amount be included for hand tools, electric drills and associated equipment \$ 300

 3. It is recommended that some spare electronic components (e.g., transistors and tubes) be included for repair of chassis in Egypt ---- \$ 500
- \$4400

F. TESTING

It is recommended that the entire spark-chamber, scintillation counter and electronics array be first checked out at LRL and then be field tested at an underground location nearby. It is estimated that 12 man weeks of time would be required for these tests. \$6000

G. SETUP AND INITIAL OPERATION

It is recommended that one man from LRL go to the site to assist in unpacking, assembly and early operation. A maximum of three months has been estimated for this period. \$87000



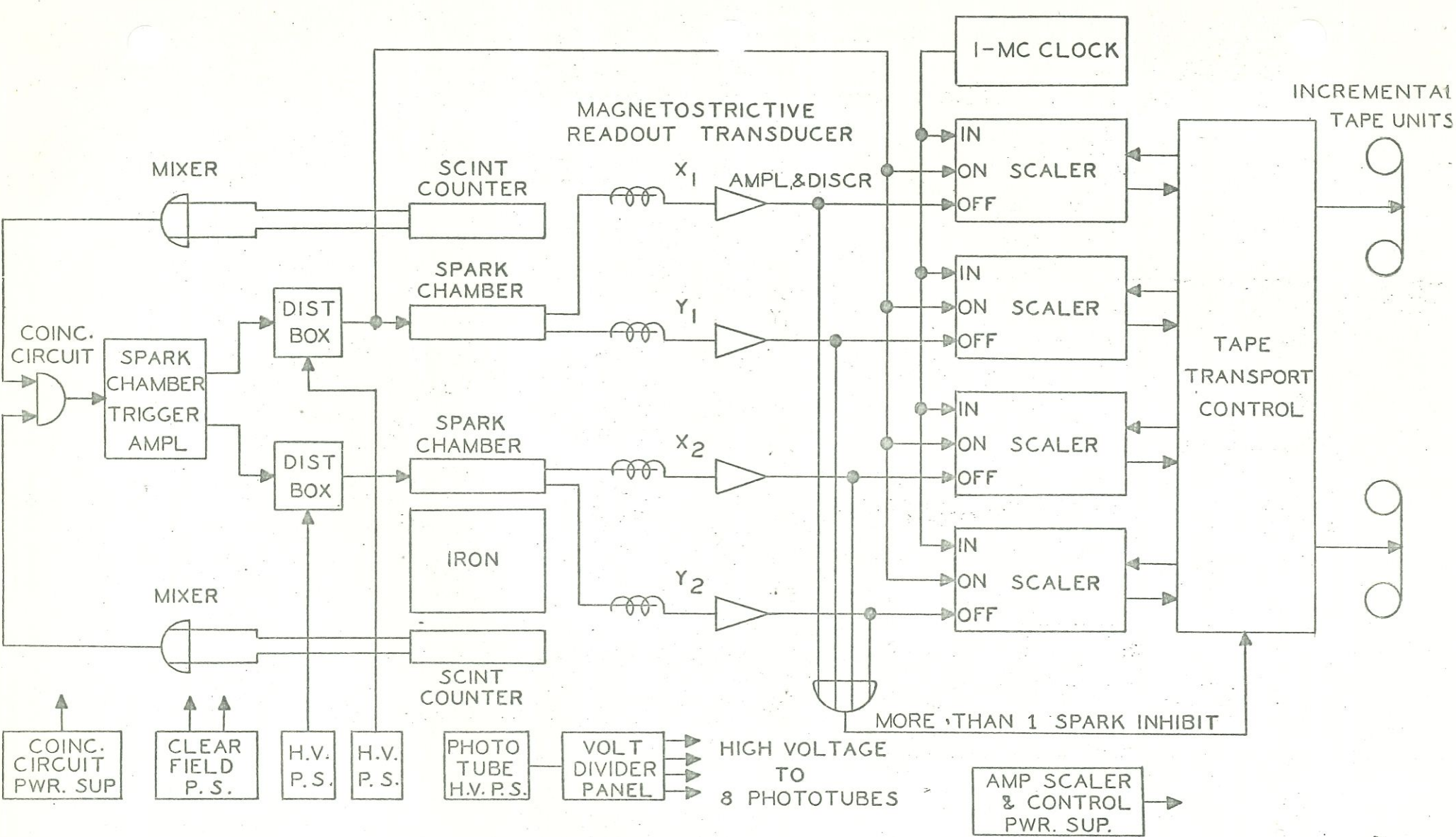
H. EXCEPTIONS

The following items have not been included in this estimate and are assumed to be covered elsewhere:

1. Transportation of equipment and personnel to site.
2. Packing and insurance for equipment.
3. Any procurement costs of equipment and components.
4. Storage and equipment operating hut.
5. Iron shield in spark-chamber array.
6. Air-conditioning for equipment.
7. Electric lights at site; however, 5 kVA of power is available for this purpose.
8. Gas supplies for spark chambers.
9. Fresh-air supply in spark chamber area.
10. Operating personnel at site beyond one electronics man for 3 months to supervise unpacking, assembly, and initial checkout of equipment.

I. <u>TOTAL</u>	-----	\$136,900
20% Contingency		27,400
15% Miscellaneous items		20,500
		<hr/>
GRAND TOTAL	-----	\$184,800

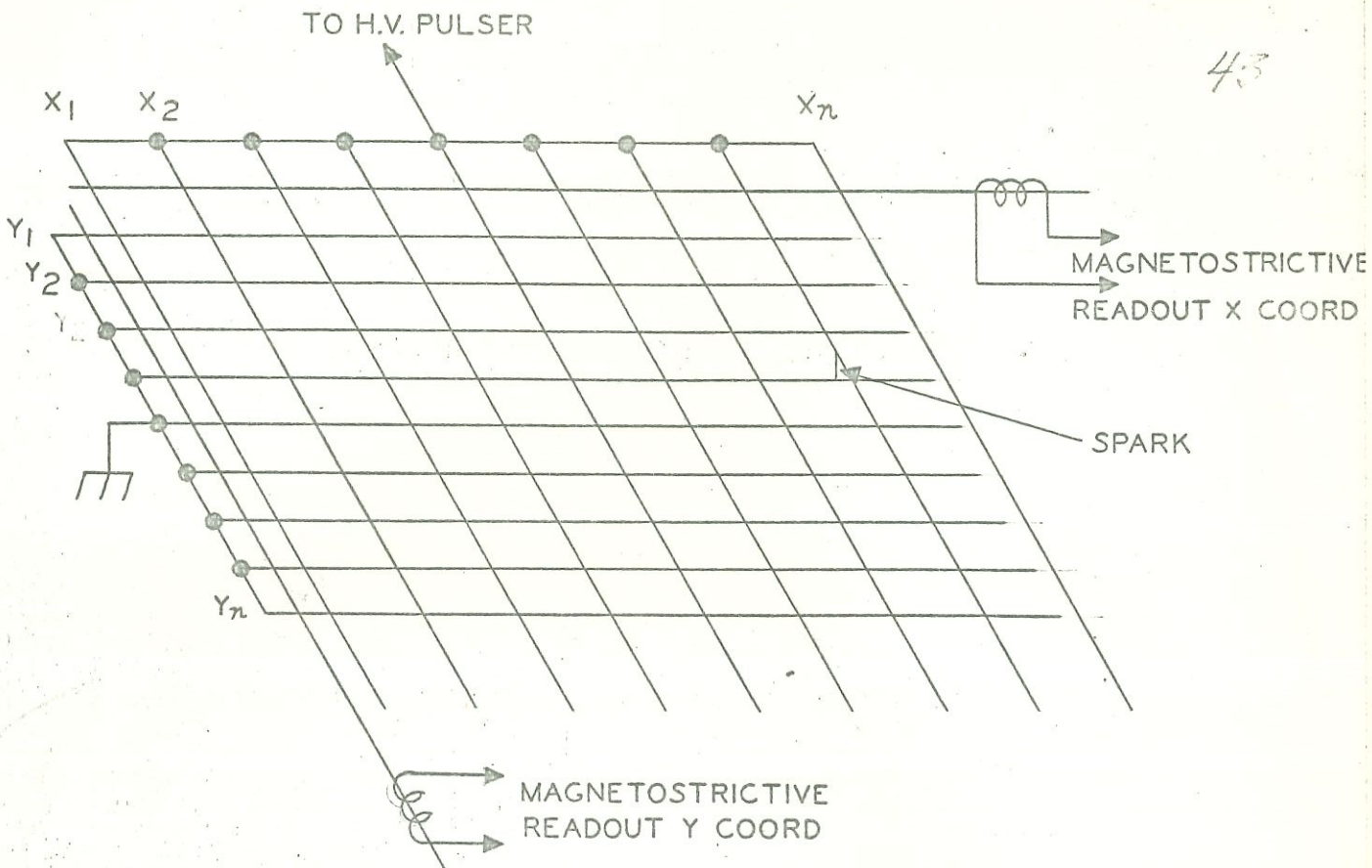




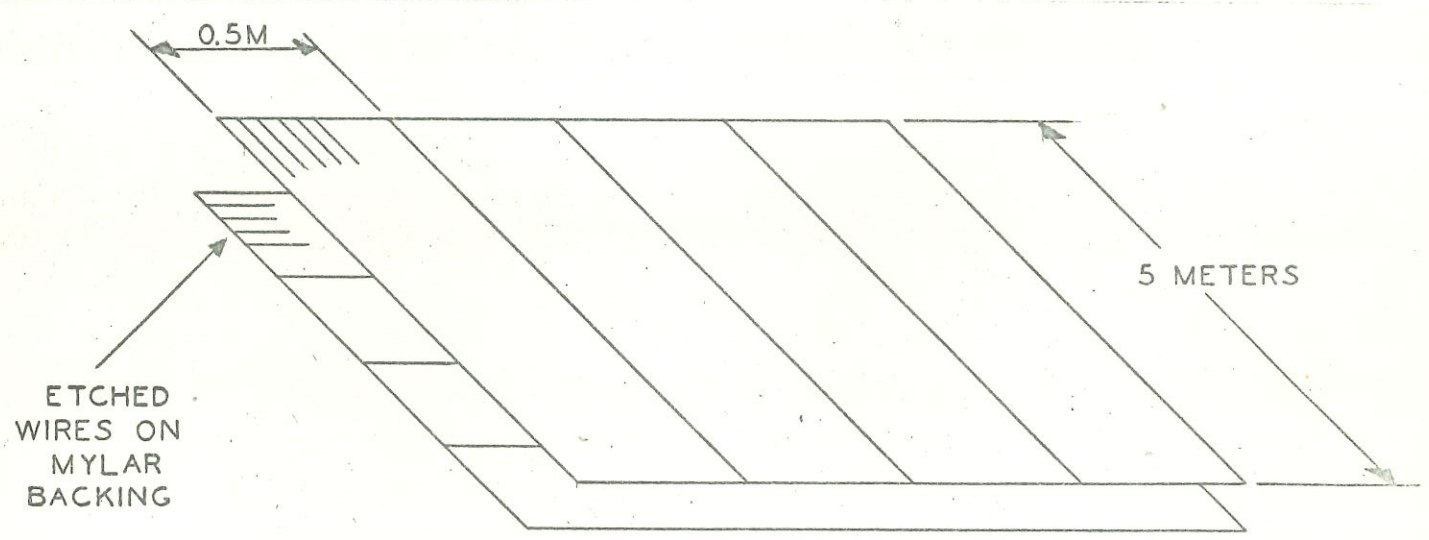
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SPARK CHAMBER & READOUT ELECTRONICS

FIG. 10



MAGNETOSTRICTIVE READOUT
FIG. 2A 11



SPARK CHAMBER CONSTRUCTION

FIG. 2B 12

