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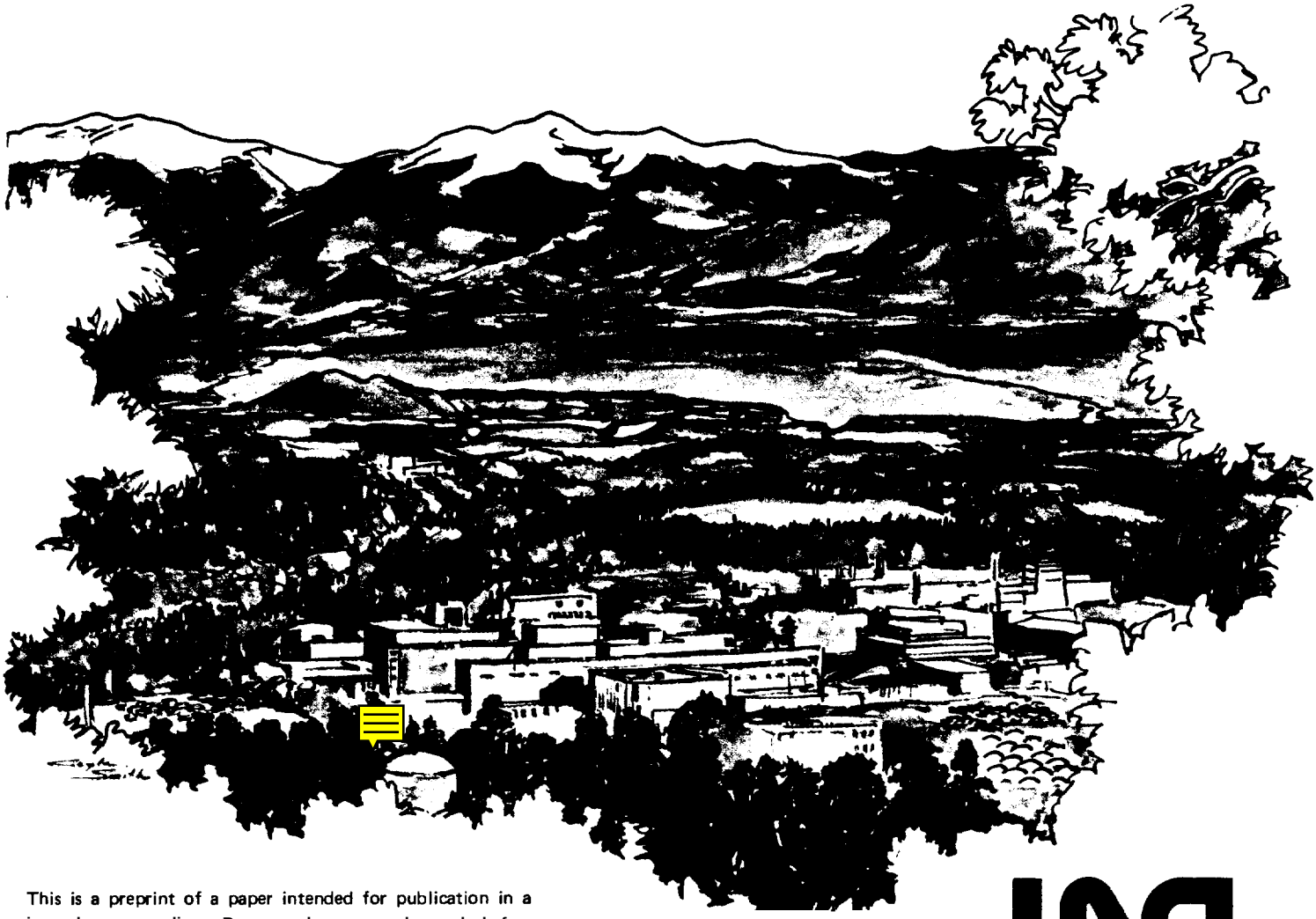

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LOS ALAMOS SCIENTIFIC LABORATORY

POTENTIAL APPLICABILITY OF THE LOS ALAMOS ANTIPROTON RESEARCH PROGRAM TO ADVANCED PROPULSION

by

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ABSTRACT

The Los Alamos National Laboratory currently has a research program in antimatter interactions. The immediate objective of the program is to develop the low energy antiproton production capabilities at LEAR and the technology to store antiprotons. The initial experimental goal is to measure the gravitational mass of antiprotons. The technology required for the experiment, however, may allow high-density storage concepts to be experimentally investigated. Analysis of antiproton production over the last 30 years indicates that milligram quantities of antiprotons could conceivably be produced early in the next century. Thus, antiproton propulsion concepts may begin to be feasible. Some results of preliminary calculations pertinent to antiproton powered rocket engines will be presented.

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1. INTRODUCTION

Within the next 30 years, technological advances may allow systems with a specific impulse (I_{sp}) of 2000-5000 s and with thrusts of around a meganewton to be developed. The effects that such a system could have on planetary missions would be dramatic. For example, a manned Mars mission with a mission profile of 360 days outbound-260 days return and a 100 ton payload, would require about 220 metric tons of mass in Low Earth Orbit (LEO). By comparison, the chemically propelled system (LO_2/LH_2) would require about 1800 metric tons (Ref. 1).

In addition to the tremendous reduction of the required LEO mass, high I_{Sp} systems also offer the possibility of faster transit times. The LEO mass requirements for a 1 yr round trip mission and a 6 month round trip to Mars would be about 308 metric tons and 422 metric tons respectively. Thus, a round trip time of 6 months could be accomplished for less total mass than is currently estimated for the chemically propelled 680-day mission.

The shorter trip time may be necessary to reduce some of the physiological and psychological responses such as those seen by the Russian cosmonauts after 239 days of weightlessness. If less than 100 days of weightlessness were endured, a duration about equal of the U.S. Skylab experience, the requirements for closed environment life support systems (CELSS) and for artificial gravity might be reduced. As a result, the overall complexity of the ship design might be reduced.

The concept of using antimatter as a power source for propulsion has existed for decades (Ref. 2). Because antimatter annihilation has the highest specific energy of any reaction now known, the potential advantages of an antimatter propulsive system are very great. The obvious problems, however, are whether: 1) sufficient quantities of antimatter can be produced; 2) sufficient quantities can be conveniently stored for long periods; and 3) the products of the annihilation reaction can be converted efficiently into usable thrust.

II. ANTIPROTON PRODUCTION

Although the existence of the antiproton was predicted in the 1930s it was not until 1955 that its existence was experimentally observed. Chamberlain and coworkers (Ref. 3) at the Lawrence Berkeley Laboratory had labored since the late 1940s to build a proton particle accelerator with enough energy to produce antiprotons. To achieve that objective the accelerator design was tailored for the production of antiprotons. Their discovery of this new antiparticle rocked

the world of physics and Chamberlain and Segre were awarded the Nobel Prize in physics for this observation. The award cited specifically the experimental confirmation of the particle-antiparticle symmetry in nature. This work opened the door for cosmologists and astronomers to ask in earnest if there were antimatter in our universe and stimulated a host of other investigations.

Since their discovery, the rate of antiproton production has increased by an order of magnitude every 2.5 years (on the average). This trend line is shown in Fig. 1 where the relevant physics and detector technology are indicated as well (Ref. 3-20), The slope of this trend line is limited by funding and the available accelerator and magnet technology. The LEAR facility, (Ref. 13-16) which recently came on-line at CERN, fits clearly on the trajectory as does a proposed facility at Los Alamos (Ref. 18,19). The early part of this trend line was driven by the advent of the zero gradient synchrotrons (ZGS) (Ref. 8) at the Argonne National Laboratory and the alternating gradient synchroton (AGS) (Ref. 7) at the Brookhaven National Laboratory. The present and future production rates will be driven by a new technology, stochastic and electron cooling (Ref. 21). The faci1ity at the Fermi National Accelerator Laboratory (FNAL) (Ref. 17) is already considerably above the trend line. In addition, a practical antiproton factory, using existing magnet and accelerator technology, could be built by the 1990s and would produce 100 to 1000 times more antiprotons than the conservative Los Alamos proposal. This possible factory is still further above the trend line, which shows that the projected limits of the new cooling technology are not properly indicated. Actual limits could be considerably higher. Nevertheless, if the conservative trend line is followed, the annual production of antiprotons could exceed a gram by the year 2010.

Although the antimatter production process is not totally understood, several empirically derived production cross section formulations describe the limited data available. These empirical formulations have been used to design the collection facilities at CERN and FNAL. Neither of these facilities were designed originally with antiproton production or collection in mind. Their collection facilities were added onto the existing accelerator systems. Nevertheless, the antiproton production capability of these facilities is impressive. At CERN ^{67} antiprotons per second are made available to experiments at low energies whereas at FNAL 10^7 per second is expected soon at high energy. Improving these rates is a high priority at these facilities. An order of magnitude increase can be expected in the short term. In one year at

CERN or FNAL 10^{13} - 10^{14} antiprotons can be produced with 10^{15} per year in the near future.

Two facilities are currently being planned in the free world for producing among other particles, antiprotons: TRIUMF in Canada and a facility at the Los Alamos National Laboratory. The antiproton production rates at these facilities could far exceed those currently available at CERN and FNAL. However, even these facilities are not optimized solely for antiproton production and do not exploit fully the available magnet and accelerator technology. These and all previous antiproton facilities represent the very best that could be done with a fiscally constrained basic research budget. The current Los Alamos plan for example, is a 300M$ project, not including an antiproton collector and cooler. If the fiscal constraint were lifted for the design of an antiproton factory, several orders of magnitude more antiprotons per year could be produced using existing technology. However, before this increase in production can be cooled and accumulated very significant progress needs to be made in accumulator/cooling technology. In addition, before the milligram to gram size quantities, projected for the next decade and beyond, can be produced, very significant progress in accelerator technology needs to be made as well. Increasing the production/cooling rates is a high priority task at antiproton facilities around the world.

IV. STORAGE OF ANTIPROTONS

At the present time the particle physics community stores a significant number of antiprotons for several tens of hours for basic research on particle dynamics at very high energies. The storage technique used is electromagnetic confinement in very large rings inside which the antiprotons are circulated or accelerated to the desired energy. Although well-suited to the requirements of many applications in basic research, this type of storage is not readily adapted to the applications we envision. We have considered two general types of storage: Bulk storage, in which antimatter at low temperature is stored in a high vacuum, and dispersed storage, in which the antimatter is stored in a uniform mix with normal matter. Whether in bulk or dispersed storage, the antimatter can be charged, as in the case of antiprotons or it can be neutral, as in the case of antihydrogen atoms.

A simple and obvious way to prevent antiprotons from impinging upon the walls of a storage vessel is to electrically charge the walls so as to repel them. Storage devices of exactly this sort have been intensively studied both

theoretically and experimentally for the confinement of normal matter ions (Ref. 22). All of this "ion trap" work is directly applicable to the storage of antiprotons. Briefly, the charged particles are stored in a volume defined by a combination of electric and magnetic fields or in an inhomogeneous RF field. In addition, techniques for cooling the confined ions to very low temperatures have been developed (Ref. 23). Estimates indicate that about 10^{11} particles/cm^3 can be stored in an ion trap with a field strength of 6 T.

The principle operating feature of the concept of condensed matter storage involves the long-range van der Waals force, which is attractive for normal matter-matter mixtures and is still attractive for matter-antimatter mixtures. As the matter-antimatter atoms or molecules draw more closely together, the interaction potential grows increasingly more attractive until finally the protons and antiprotons annihilate along with the electrons and positrons. With normal matter-matter interactions, as the two atoms or molecules draw more closely together, the potential also becomes more strongly attractive until the two objects are close enough to start exchanging electrons. At this point a repulsive exchange force overwhelms the attractive force and the two objects can get no closer.

The scale of the barrier needed to confine the antiprotons in condensed matter can be estimated by treating the confinement as a one-dimensional barrier penetration problem (Ref. 24). The transmission coefficient for such a barrier should be in the range 10^{-30} -10-3' in order to realize long-term storage of gram-like quantities. The calculation reveals that transmission coefficients in this range can be obtained with barrier heights of about 0.5 eV and widths of 2 to 4 angstroms for thermal antiprotons (10 - 100K). The scale set by these results are atomic in size. Thus much of our effort in searching for a storage medium for antimatter will necessarily be concentrated in atomic and condensed matter systems.

To explore any of the atomic or condensed matter storage approaches, a thermal source of antiprotons is required. Because of the cooling capability of ion traps these devices can serve as an intermediate technology allowing for the study of more advanced concepts. Currently, ion traps with a volume of around 5×10^4 cm^3 exist in Japan. If the Japanese expertise in large ion traps is applicable to the storage of antiprotons, then around 10 to 10^{16} antiprotons could be stored using this technique. This not only represents more antiprotons than are currently being produced yearly at existing facilities but it also represents an engineeringly significant amount of energy (about 2 megajoules).

V. PLANNED EXPERIMENT

Currently, effort are underway to develop a series of ion traps which will contain up to 10 antiprotons. The antiprotons will be accumulated using the 2 MeV beam at the Low Energy Antiproton Ring (LEAR) at the Cern facility in Europe. The traps will be used in an experiment to test directly the equality of particle and antiparticle gravitational masses in the baryon sector with protons and antiprotons. The experiment will use the time of flight technique pioneered by Witteborn and Fairbank in their measurement of the gravitational force on the electron. In this approach, the particles are launched vertically up a drift tube. The time of flight of the particle up the drift tube together with the initial velocity gives a measure of the gravitational force acting on the particle.

To realize this measurement in sensibly dimensioned equipment and with reasonable timing precision requires ultra-low velocities for the antiprotons. We propose a staged deceleration approach to achieve these velocities. The experimental setup is shown schematically in Fig. 2. In our approach, low energy antiprotons from LEAR will be decelerated in an RFQ and cyclically injected into a series of specially designed pulsed ion traps. In this series of traps, adiabatic, resistive and electron cooling will be used to lower the antiproton energy to the required thermal level. When this is achieved the antiprotons will be transferred, a few at a time, into a launching trap at the base of the drift tube. After launch, the antiprotons will be detected at the top of the drift tube with a microchannel plate. By using an H^- source to calibrate the equipment, a relative measure of the gravitational attraction on the antiproton will be made. The by-product of the experiment will be the development of a mobile, ultra-cold source of large numbers of antiprotons with which to pursue research in high density storage.

VI. APPLICATIONS

The capability to store large numbers of antiprotons at thermal velocities will open many avenues of basic and applied research. Many of the potential applications thatwe envision utilize the very high specific energy characteristic of antimatter annihilation. The fact that antiproton annihilation has a specific energy 10^8 times chemical values and about 10 times fission reactions, indicates the enormous potential of antiprotons as an energy source for space based prime power and propulsion applications where mass is a principle consideration.

Because the energy release modes of antiproton annihilation are vastly different than any other energy source, the questions confronting designers of antiproton propulsion or power sources must be approached from a fundamental viewpoint. The calculated spectra of charged pions and gamma rays resulting from p - $\bar{p}$ annihilation is shown in Fig. 3. The average energies are 200 MeV and 240 MeV for the gamma rays and pions, respectively. Because of the large ranges of these energetic particles, conversion of the annihilation products to useful energy is required. Although in their infancy, several propulsion system concepts have been discussed (Refs. 25-29).

One concept which has not been discussed but which may offer a near term potential is the Solid Core Thermal Rocket (SCTR). The SCTR would utilize the antiprotons by stopping all of the annihilation products in a solid core of high melting temperature material such as tungsten. The core is honeycombed to allow the heat transfer to the propellant. Such a concept is similar to the nuclear rockets developed during the NERVA program in the U.S. (1960-1971) and could possibly utilize many of the non-nuclear components, such as liquid hydrogen (LH_2) turbo pumps, already tested. A schematic diagram of the small nuclear rocket engine (SNRE) designed in 1971 is shown in Fig. 4. This engine would have produced about 16000 lb of thrust and would have weighed about 5887 lb. The figure shows the layout of the liquid hydrogen transport lines, values, and pumps which were tested in the NERVA program.

Preliminary calculations indicate that a tungsten cylinder which has been sized to stop most of the $\bar{p}$ annihilation products would be slightly smaller than the nuclear reactor core designed for the SNRE. These calculations included the 36% void fraction for the hydrogen flow channels used in the SNRE. A source of charged pions and gamma rays with the energy distributions seen in Fig. 3 were built and put into the HETC (Ref. 30) code. Calculations on a homogenized tungsten/hydrogen core were performed using HETC coupled to the MCNP code for low-energy neutron and photon transport. The relative energy deposition as a function of radius in the cylindrical core is shown in Fig. 5. This deposition is the sum of annihilation products and secondary neutrons and gamma rays. The deposition appears rather sharply peaked and is down to around 5% of maximum at about 40-cm radius. The source was deposited in a 20-cm radius by 20-cm long sodium cylinder in the center. The results of these preliminary calculations show that significant quantities of neutrons are produced in the core. Prompt radiation levels are calculated to be about 1 rad at 100 meters for a 0.1 amp beam of antiprotons incident. Further calculations are planned to look at

reducing the external radiation fields and flattening the energy deposition profile.

A $\bar{p}$-NERVA engine based on the most thoroughly tested nuclear rocket, designated NRX, would have a thrust of 4.4 x 10^5 N (100,000 lb), a power level of around 2700 MW, a mass of near 7000 kg, an I of near 1100 s, and a mass flow of antiprotons of around 13 μg/s. Such an engine would require about 400 metric tons of material in LEO to accomplish the previously described, manned Mars mission--a factor of 4.5 times less than a chemically propelled system.

Another engine concept would utilize a reaction chamber filled with high pressure gas into which the antiprotons are deposited, The charged annihilation products are trapped by an intense magnetic field, slow down, and heat the gas for expulsion. This engine concept has the advantage of adjusting the ratio of antimatter to matter to produce a wide range of I depending upon the mission. The possible effects of pion and muon thermalization times, wall losses, reaction chamber structural requirements, and losses of pions or muons due to nuclear reactions or decay, need to be evaluated after more fundamental data have been collected and will require complex computational studies.

The amount of antimatter required by either concept will depend upon the mission AV requirements. Typical missions such as launch from earth's surface, orbital transfer to GEO, or a mission to Mars will probably require between tens to hundreds of milligrams. The ship's mass ratios (total mass/payload mass) for these missions would be about 3 to 10.

In general, the antiproton powered engine may allow low mass-ratio ships and/or fast transit-time missions to become possible. These two characteristics may not be simply enhancing but actually enabling to certain space missions such as planetary exploration.

VII. ENHANCEMENT

The specific cost of production of antimatter (dollars per unit mass) is a convenient but misleading quantity. A more significant quantity is the dollars per unit energy. Reduction of these ratios has always been assumed to depend on improving the production and collection efficiency of the antimatter factory accelerator. Use of the latter ratio, however, shows that improvements can be made if the energy output for each incident antiparticle is increased or amplified.

One possibility is to consider the antiproton as a stable repository of negative muons. An average $p\bar{p}$ annihilation will produce about 1.45 negative

pions with an average energy of 250 MeV. If the pions can be either trapped in magnetic field or quickly thermalized by collisional losses, then the negative muons (μ^-) resulting from the pion decay may be generated in a small volume. By thermalizing these muons in a volume containing a mixture of gaseous deuterium and tritium, fusion of the DT atoms can be catalyzed (Refs. 31-35). Recent measurements of $D\mu T$ molecular formation rates (Ref. 36) and of other factors inherent in P^- catalyzed DT fusion have observed up to 180 fusions per muon. The resonant molecular-formation theory which accounts for the observations, predicts that up to 300 fusions per muon could be induced in DT mixtures at appropriate density and temperature. Thus, an upper limit of about 7.8 GeV in fusion energy could be released per antiproton in addition to the 1.8 GeV of annihilation energy--more than a factor of 5 enhancement. Clearly, losses due to pion capture and interactions, muon decay during thermalization, and muon-wall interactions, as examples, will reduce this upper limit in an operating system. Efforts to estimate the magnitude of different loss factors and of a possible reactor geometry are currently underway.

Another method of producing fusion energy using antiprotons is inertial confinement fusion (ICF). This technique relies on stopping the antiprotons in a thin, uranium shelled capsule containing DT gas. The stopped antiprotons annihilate on the uranium nuclei and induce fission. The localized deposition of the fission energy ablates part of the shell and implodes the capsule. Early calculations show that more than 10 GeV/p^- could be released with much higher gains possible. Experiments characterizing the $U(p^-,f)$ reactions are underway at CERN with the ultimate goal of investigating antiproton produced implosions (Ref. 37). The major attraction of the ICF technique is that the incident antiproton energies could be a few keV or less so that the required accelerators would be small. Thus, depending upon the mass of the antiproton storage device, low mass ICF reactors might be possible. Evaluations of pulse structure, implosion symmetry, and optimum capsule design are required and significant work in those areas can be performed with currently existing codes.

VIII. SUMMARY

The antiproton mass-conversion reaction offers the highest potential, the greatest problems, and the most fascination for advanced propulsion. Antiprotons are currently being produced in the world at the rate of about 10^{14} particles per year. Based on the past 30 years of production experience, antiproton production rates have increased by an order of magnitude every 2.5

years. If this trend continues, almost a mg/yr (6×10^{20}) could be produced by the early 2000's. Antiprotons are currently stored in large synchrotrons rings. By lowering the particle energy, storage can be achieved in compact structures known as ion traps. Current experiments plan to decelerate and capture up to 10^{10} antiprotons in such a trap. The storage capability of ion traps is limited. However, these traps will provide a source of sub-thermal $\bar{p}$'s for development of better storage mechanisms suitable for propulsion. The application of antiprotons to propulsion requires the coupling of the energy released in the mass-conversion reaction to thrust producing mechanisms. In addition, there are recent proposals which would enhance the average energy released per $\bar{p}$ used. These proposals entail using the $\bar{p}$'s to produce inertial confinement fusion or to produce negative muons which can catalyze fusion. By increasing the energy released per p, the effective specific cost, (dollars/joule) can be reduced. These proposals and other areas of research can be investigated now. These short term results will be important in assessing the long range feasibility of an antiproton powered engine.

REFERENCES

1. S. D. Howe, Proc. of Manned Mars Mission Workshop, Huntsville, Ala., June 10-14, 1985 (to be published); Los Alamos Report LA-UR-85-2442.

2. E. Sanger, Ing. Arch. 21, 1953, p.231 ff.

3* O. Chamberlain, E. Segre, C. Wiegand, and T. Ypsilanti, phys. Rev. 100, 1947 (1955) .

4. L. E. Agnew, T. Elioff, W. B. Fowler, R. L. Lander, W. M. Powell, E. Segre, H. M. Steiner, et al., Phys. Rev. 118, 1371(1960).

5. C. A. Steinberger, N. Gelfand, U. Nauenberg, M. Nussbaum, J. Schultz, J. Steinberger, H. Brugger, and L. Kirsch, NEVIS Laboratory report NEVIS-126 (1964).

6. N. Barash, P. Franzini, L. Kirsch, D. Miller, J. Steinberger, T. H. Tan, R. Piano, and P. Yaeger, Phys. Rev. 139, B1659(1965).

7. G. M. Bunce, Brook haven National Laboratory report BNL-50874 (1978).

8. "Zero Gradient Synchrotrons Users Manual," Argonne National Laboratory (1969).

9. E. Col ton, Nucl. Instrum. Methods 138, 599(1976).

10. H. Hirabayashi, S. Kurokawa, A. Yamamoto, and A. Kusumegi, IEEE Trans. Nucl. Sci. NS-26, 3191(1979).

11. A. Yamamoto, H. Ikeda, S. Kurokawa, M. Takasaki, M. Taino, Y. Zuzuki, H. Ishii, etal., Nucl. Instrum. Methods 203, 35(1982).

12. S. Kurokawa and H. Hirabayashi, Nucl. Instrum. Methods 212, 91(1983).

13. "Design Study pp Facility," CERN report, CERN/PS/AA 78-3.

14. U. Gastaldi, K. Kilian, and D. Mohl, Proc. 10th Int. Conf. on High-Energy Acc., Protvino (IHEP, Serpukov, 1977).

15. U. Gastaldi, Proc. 4th European Antiproton Conf., A. Fridman, Ed., 8arr, France (CNRS, 1979).

16. W. Hardt, 5th European Symposium on Nucleon Antinucleon Interactions, Bressanone, Italy (Instituo Nazionale De Nuclear, Padova, 1980).

17. E. R. Gray, D. E. Johnson, F. R. Huson, F. E. Mills, L. C. Teng, G. S. Tool, P. M. McIntyre, et al., IEEE Trans. Nucl. Sci. NS-24, 1854(1977).

18. F..E. Mills, Proc. 2nd LAMPFII Workshop, Los Alamos, New Mexico, July 19-22, 1982, Los Alamos National Laboratory report LA-9572-C, Vol. 11 (November 1982).

19. T. E. Kalogeropoulos, Proc. Workshop Nucl. Part. Phys. at Energies up to 31 GeV: New and Future Aspects, Los National Laboratory report LA-8775-C, Vol. II (March 1981) and Los Alamos National Laboratory report LA-9572-C, Vol. II (November 1982).

20. H. Brown, AGS/EPS Technical Note (1980).

21. F. P. Cole and F. E. Mills, Ann. Rev. Nucl. Part. Sci. 31, 295(1981).

22. D. J. Wineland, W. M. Itano, and R. S. Van Dyck, Jr., Adv. At. Mol. Phys. 19, 135(1983).

23. D. J, Wineland and W. M. Itano, Phys. Rev. A20, 1521(1979).

24. M. V. Hynes, Physics with Antiprotons at LEAR in the ACOL Era, Jan. 15-22, 1984, Tignes, France, Editions Frontiers, 1985.

25. D. D. Papailliou, E. J. Roschke, A. A. Vetter, J. S. Zmuidzinas, T. M. Haich, and D. F. Dipprey, JPL Tech. Memo 33-722, NASA, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California (1975).

26. D. L. Morgan, JPL Contractor report CC-571769, Jet Propulsion Laboratory, Pasadena, California (1975).

27. D. L. Morgan, JPL Contract report JS-651111(1976).

28. D. L. Morgan, J. Brit. Int. Sot. 35, 405(1982).

29. B. N. Cassenti, J. Brit. Int. Sot. 35, 396(1982).

30. R. G Alsmiller, Jr., etal., Nut. Sci. Eng. 36, 291 (1969).

31. F. Frank, Nature 160, 525(1947).

32. E. Vesman, Sov. Phys. JETP Lett. 5 113(1967).

33. Ya. B. Zeldovich and S. S. Gershtein, Usp. Fiz. Nauk. 71, 581(1960) [Eng. trans. Sov. Phys. Usp. 3, 593(1961)].

34. V. M. Bystritsky, etal, Phy. Lett. 94B, 476(1980).

35. J. Cohen and M. Leon, Phy. Rev. Lett., ~, 1(1985).

36. S. Jones, etal, Phys. Rev. Lett. 56, 588(1986).

37. S. Polikanov, Proc. Work. on Phys. at LEAR with Low Energy cooled Antiprotons, May 9-16, 1982, Erice, Sicily, Plenum Press, 1984.

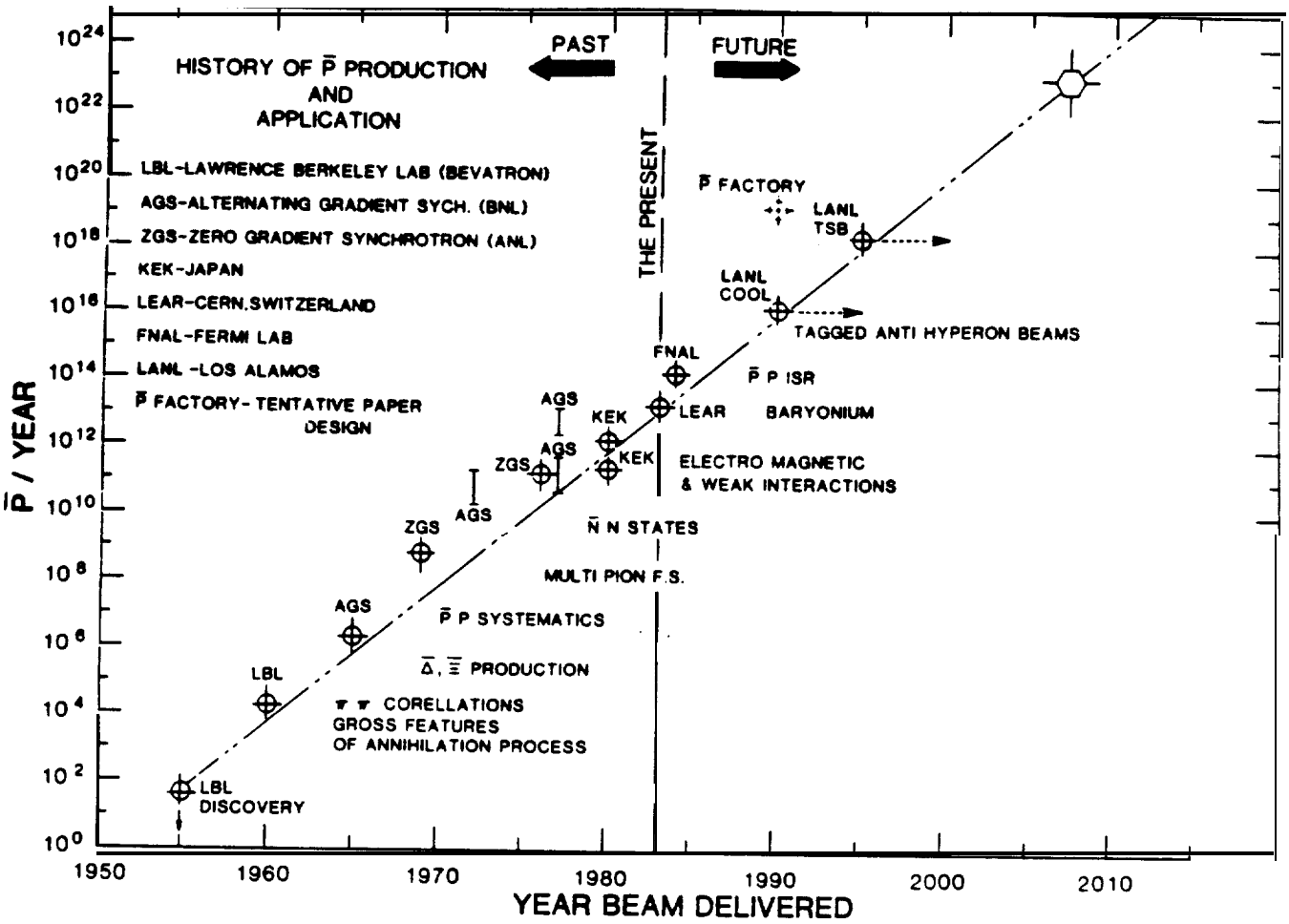

Fig. 1. Annual antiproton production versus year for most high-energy physics facilities around the world. The circled points represent the published flux value; the vertical bar indicates the range of fluxes cited in the literature (Refs. 3-20). The point labeled p factory represents a practical design using existing magnet and accelerator technology. The physics of interest for each era is also noted.

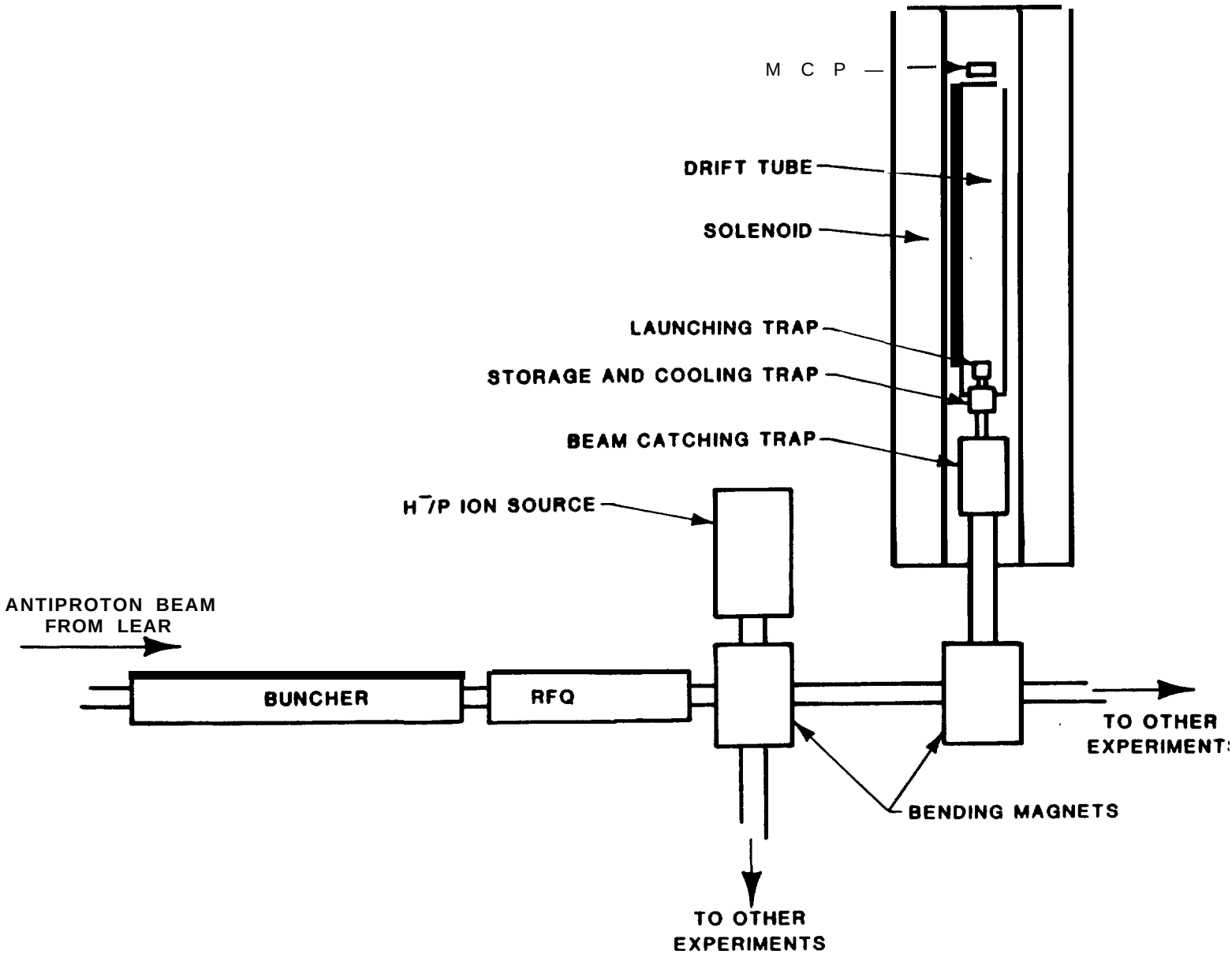

Fig. 2. Schematic diagram of the experiment to measure the gravitational mass of the antiproton. The staged ion traps are designed to operate over different temperature regimes of the contained antiproton pulse. The drift tube is housed in a superconducting solenoid with a field strength of 6 T.

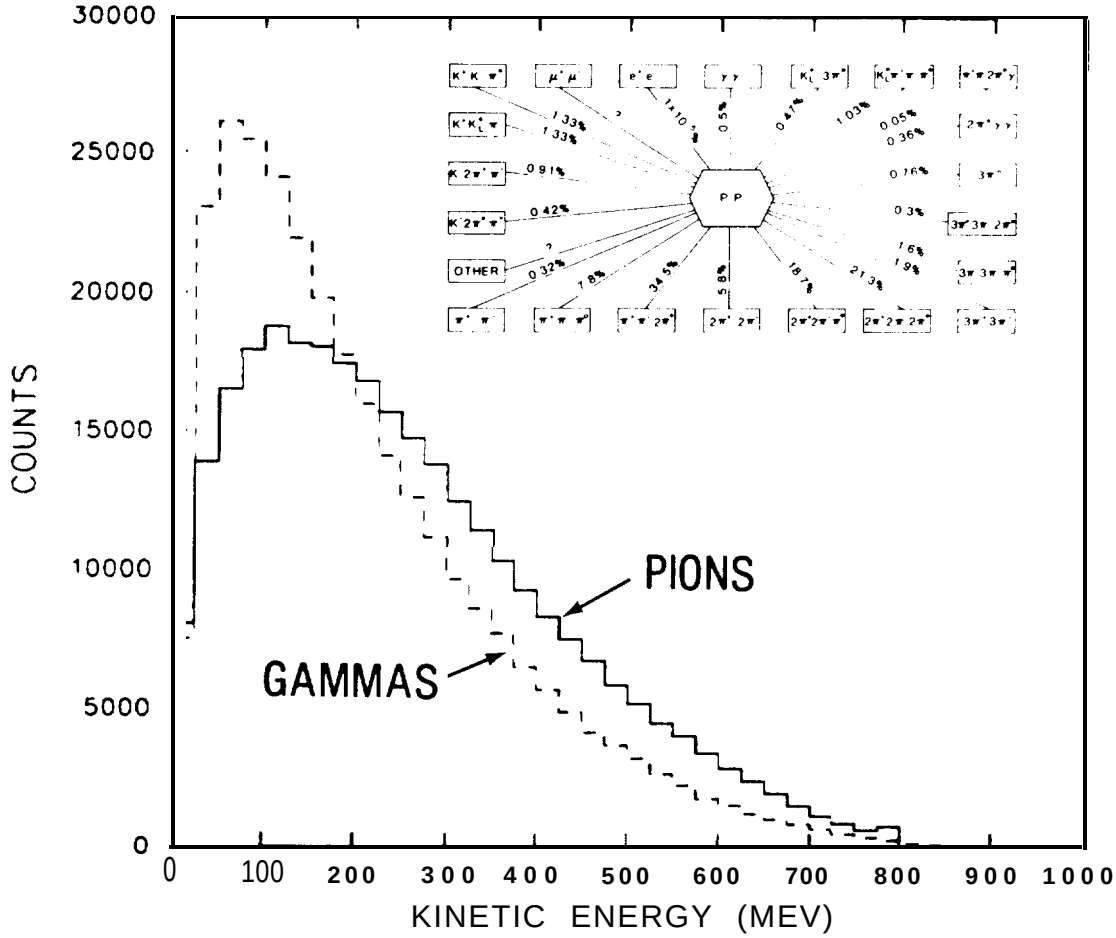

Fig. 3. Calculated spectra of charged pions and gamma rays resulting from the p - p annihilation. The reaction channels used to produce the spectra are also shown. The spectra resulted from 93,000 events which produced an average of 3.12 pions/eventand 3.08 gamma/event.

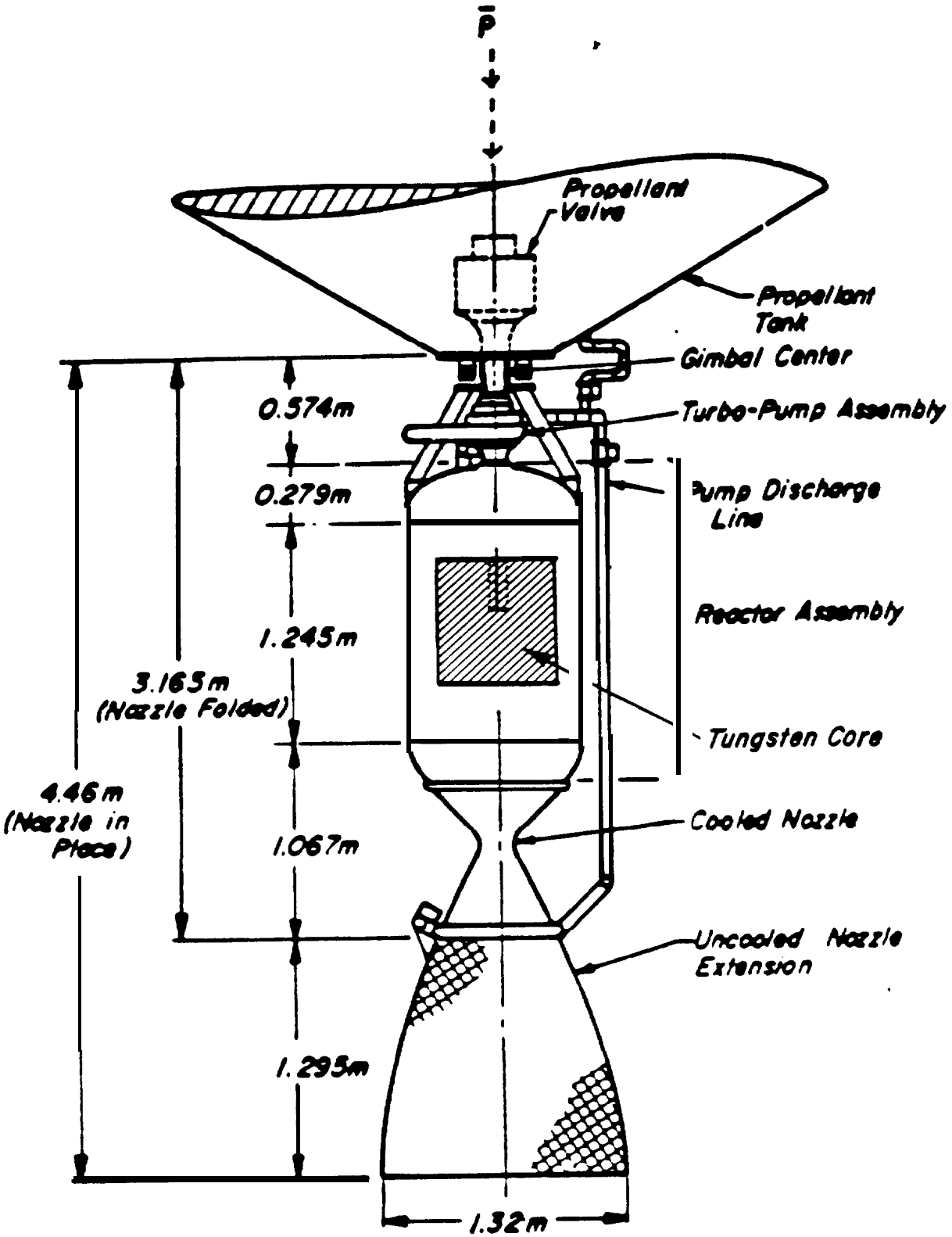

Fig. 4. Schematic diagram of the Small Nuclear Rocket Engine designed during the NERVA program. The nuclear reactor core has been replaced with a possible configuration of the metal-honeycomb used to convert the antimatter annihilation energy into heat.

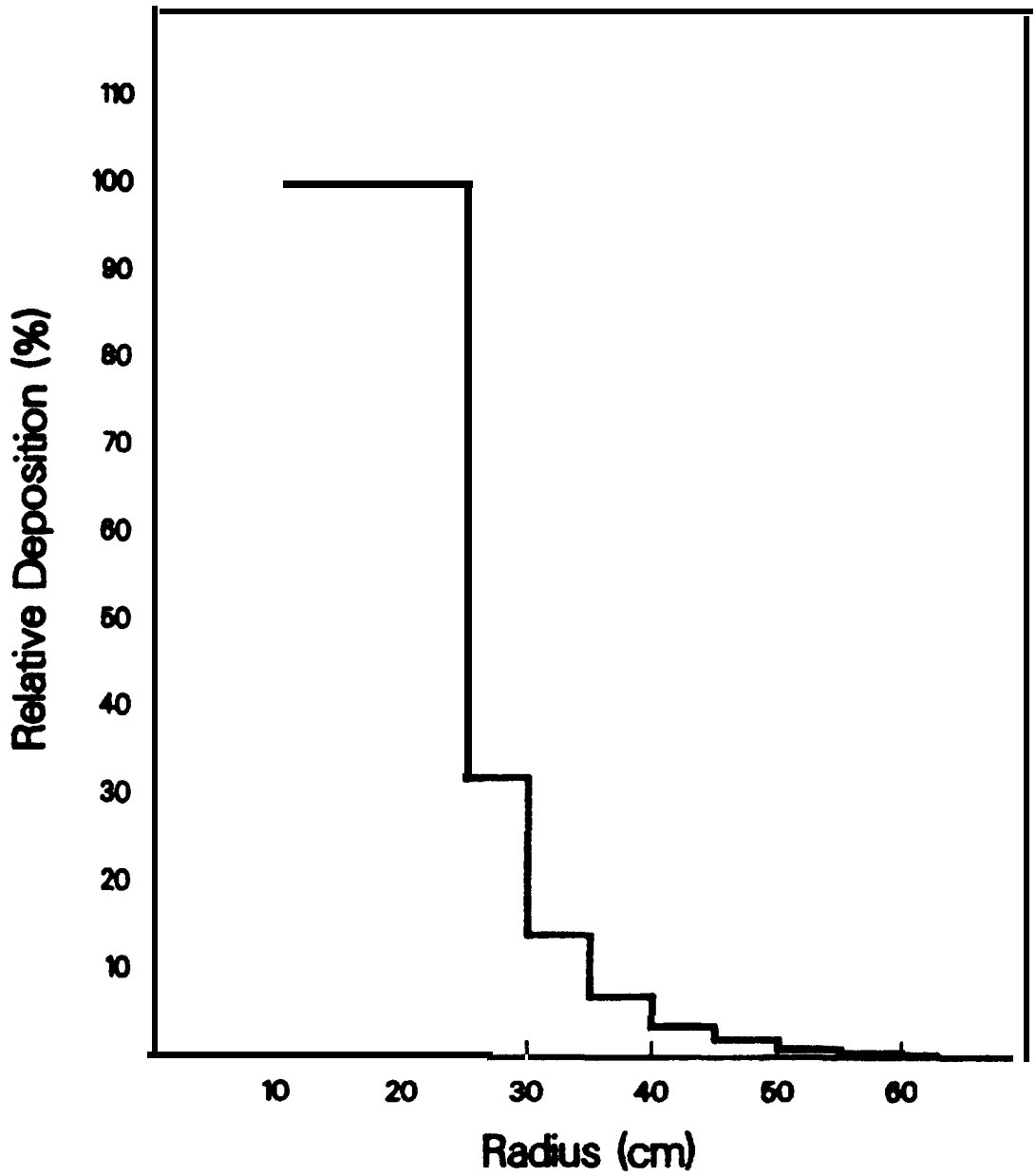

Fig. 5. Relative energy deposition as a function of radius in the solid core thermal rocket. The Monte Carlo transport calculations were made using HETC and MCNP. The core was a homogeneous mix of tungsten and hydrogen. The deposition was normalized to the peak value in the region adjacent to the cell where the antiproton were deposited.