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NUCLEAR PULSE PROPULSION (ORION) TECHNICAL STATUS SUMMARY AND GROUND-ORIENTED DEVELOPMENT PLAN

by

E. A. Day and J. C. Nance

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NUCLEAR PULSE PROPULSION (ORION) TECHNICAL STATUS SUMMARY AND GROUND-ORIENTED DEVELOPMENT PLAN*

by

E. A. Day and J. C. Nance

Paper to be presented at the American Institute of Aeronautics and Astronautics Propulsion Conference, Colorado Springs, Colorado, June 14-18, 1965.

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May 1, 1965

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CONTENTS

ABSTRACT

A brief background of the history of Project ORION and a discussion of the main technical problem areas connected with nuclear-pulse operation are presented. The inherent separability of many of these problems has been established through the use of computation and experimentation. The technical status of the program is summarized. Based on this theoretical and experimental background, a development plan for a specific engine design is presented. The plan is phased to generate the required data for a project definition phase (PDP) with modest expenditure of time and funds. In the post-PDP phases, the engine components are developed and the completely assembled engine is brought to a preliminary-flight-rating-test (PFRT) condition without space or atmospheric nuclear explosions. During this period, special-purpose underground nuclear tests are carried out and high-explosive (HE) simulation testing is extensively employed. Complete operating-load simulation on the ground with HE is applied to each test engine. The unique pulsing operation of the system permits each test specimen to be reused until destroyed or quality proved, and thus the quantity of test items is kept to a minimum. Space nuclear tests are required only in the final phase to bring the engine to a condition of initial operational capability (IOC).

I. TECHNICAL STATUS

1.1. BACKGROUND

All steady-state nuclear propulsion systems now under development are limited in performance by allowable temperatures in the engine structures, and performance, or I_{sp}, increases as $\sqrt{T}$, other factors remaining equal. In solid-core nuclear rockets the fuel elements must remain structurally intact at temperatures in excess of the maximum propellant temperatures, implying that propellant temperatures never exceed about 3,000°K. The various gas-core concepts propose to circumvent this limitation by insulating the structure from the high-temperature fissioning energy source by means of a gas which when heated becomes the propellant. If any one of the proposed gas-core concepts can be shown to be feasible, a considerable improvement in exhaust temperatures and hence I_{sp} can be expected.

A second approach to improved performance may be achieved by pulsing the nuclear energy source. Early calculations indicated that application of nuclear-pulse techniques would allow the engine "operating" times (or the time during which the propellant created by each explosion interacts with the engine structure) to be reduced to a few hundred microseconds. During this short operating period, useful momentum could be transferred to propel the vehicle, but thermal waves would not have time to penetrate the engine structure.

The general notion that nuclear explosions could be used in this manner for propulsion occurred independently to a number of people shortly after the first nuclear device was detonated in New Mexico in 1945. The idea was particularly attractive because of the enormous energies released in a nuclear explosion for the very small amount of mass expended.

Ten years passed before any consideration serious enough to justify detailed calculations was given to the problem. In 1955, S. J. Ulam and C. J. Everett of the Los Alamos Scientific Laboratory made the first attempt[1] to foresee possible solutions to the problem associated with handling the heat and pressures arising from a nuclear explosion. Their calculations were for a vehicle that would today be considered infeasibly small (12 tons). Furthermore, the mission application was in the ICBM category where the concept is now known to be noncompetitive. Finally, accelerations imposed in the vehicle were computed to be very large--in the neighborhood of 10,000 g's.

Immediately after the successful launch of the first earth satellite by the U.S.S.R., Dr. T. B. Taylor[2] addressed the problem of devising a practical space vehicle employing nuclear explosions which hopefully would surpass the Soviet space effort. The ORION concept as we know it today stemmed from this effort. The major early contributions made by Taylor included the application of the concept to large vehicles (in the 1,000- to 10,000-ton class); the application to far more difficult space missions; a modification of nuclear devices to enhance momentum transfer and specific impulse; the use of an ablating surface on the pusher for heat protection; and the use of shock absorbers between the pusher plate and the vehicle payload compartment to degrade accelerations from the 10,000-g level to less than 10 g's.

Early in 1958 General Atomic was granted a contract to pursue the studies initiated by Taylor. In the subsequent seven years, continuous and intenstive analytical and experimental research confirmed the validity of the earlier calculations. Convincing technical arguments can now be made to substantiate the technical feasibility of the nuclear-pulse concept in performance regimes which make manned space travel to practically any part of our solar system economically possible.

1.2. TECHNICAL PROBLEMS OF ENGINE OPERATION

A reference nuclear-pulse-propelled vehicle is shown in Fig. 1. Briefly, the propulsion system operates as follows: A large number of low-yield nuclear pulse systems, which are stored in the engine, are sequentially ejected and detonated external to and below the vehicle. A substantial fraction of the mass (an inert propellant) of each pulse system is directed toward the bottom of the vehicle as a high-velocity, high-density plasma which is intercepted by a large circular metallic plate--the pusher. The propellant momentum is transferred to the pusher and the resulting accelerations are attenuated by shock-absorbing devices to peak levels of a few g's in the upper vehicle--well within human tolerances. A more detailed description is given in Ref. 3.

The operating environments of the engine are shown in Fig. 2, where the major technical problem areas which have been under study are identified. The engine is effectively shielded from the neutron, gamma-ray, and X-ray radiations of the source by the inert propellant, which is an integral part of each pulse system. The fraction of the propellant cloud intercepted by the pusher stagnates against the bottom surface of the pusher, creating plasma temperatures of approximately 200,000°F, or 120,000°K. These thermal conditions at the pusher exist for a few hundred microseconds, during which time the momentum of the propellant is transferred to the pusher. The pusher is driven forward, compressing the shock absorbers, and then it returns to its neutral position, where it is ready for the next impulse. This action occurs in about 1 sec. During the pulsing operation,

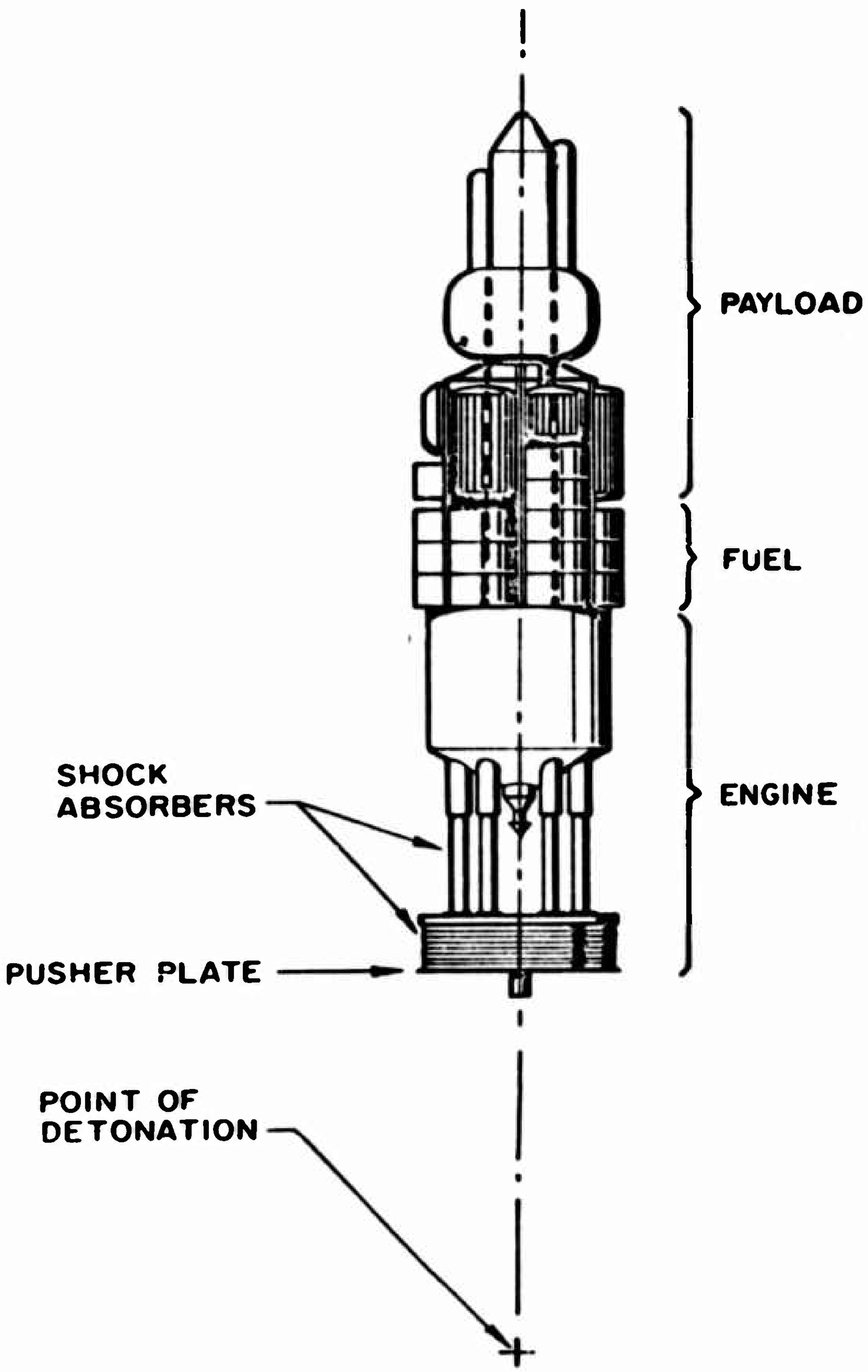

Fig. 1--Reference nuclear-pulse vehicle

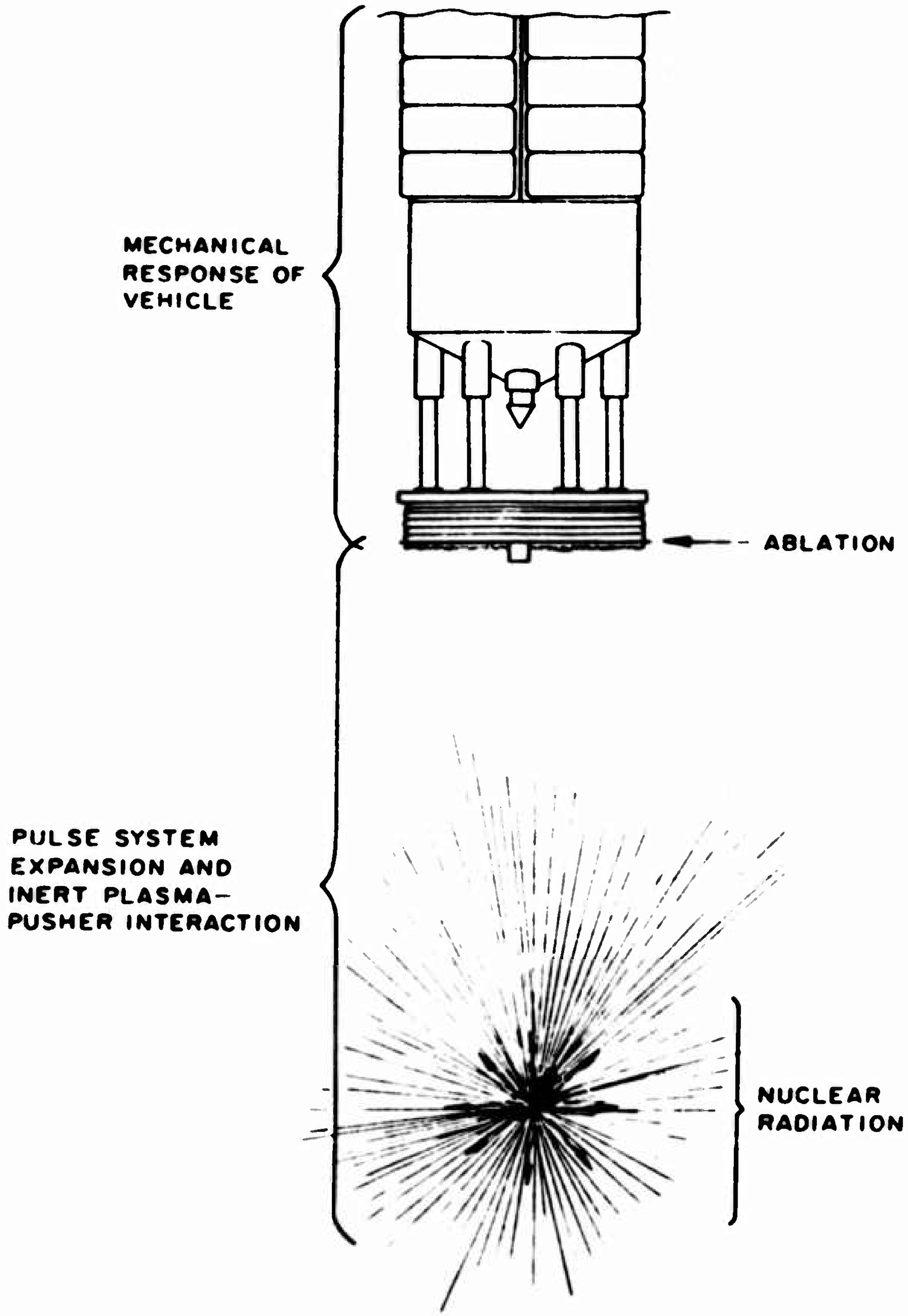

Fig. 2--Separability of nuclear-pulse problems

some energy is dissipated in the shock-absorber system and cooling is required[3,4]; in turn, the coolant vapor is employed to eject the pulse systems.

Any desired total vehicle velocity in a particular operating maneuver is obtained by varying the total number of pulse systems expended. Typical over-all engine "burning" times, at the rate of one impulse per second, may be as long as several hundred seconds, but the propellant—pusher interaction times even for very high-energy missions will be substantially less than <u>one second</u>.

From this general description, it is possible to broadly identify the major technical problem areas inherent to this propulsion concept:

1. Pulse system configuration and expansion characteristics, yield, mass, and radiation levels.

2. Interaction phenomena, temperatures, pressures, and resulting ablation.

3. Mechanical response of pusher and shock-absorber systems to repeated interactions.[4,5]

4. Engine integration, pulse-system delivery system, controls, and stability.[5,6]

In considering these problems, there are certain classical features of ORION that have direct bearing on the operational flexibility and, more importantly, on the research and development philosophy and the technical approach. These features are:

1. Nuclear radiation levels and effects in the engine during operation are low enough that they can be disregarded, or at least they can be considered separately from the thermal and mechanical effects.

2. Nuclear activation levels immediately after operations are such that personnel access to all parts of the engine is permitted.

3. High-temperature (ablation) effects are constrained to a "thin" ablating layer on the pusher surface that is approximately a few thousandths of an inch thick. The remainder of the engine, including the pusher structure, operates at modest steady-state temperatures of less than about 600°F. In studying engine problems, the thermal effects can be directly separated from the mechanical effects.

The separability of the nuclear, thermal, and mechanical problems and the relative insensitivity of the engine to the nuclear and thermal environments are significant factors in the development program. As will be described later, the mechanical impulse transmitted to the pusher by the stagnating propellant can be accurately simulated in spatial and temporal detail at full scale and at the required frequency with high-explosive (HE) techniques. Thus, in future development activities, non-nuclear testing techniques and facilities should result in gross simplification and savings and will permit phased development of the engine to an advanced preliminary flight rating test (PFRT) status short of commitment to a major flight test program.

1.3. TECHNICAL MILESTONES

The principal milestones of the technology programs to data are summarized in Fig. 3. Research in the early years was concentrated heavily on the basic systems physics. By 1960 theoretical descriptions of pulse-system behavior were obtained with the aid of a two-dimensional digital computer code.[7]

A most important milestone was achieved when this calculation technique was used to describe the observed unusual and unanticipated hydrodynamic behavior of a high-altitude nuclear experiment in the 1962 Pacific test series. The correlation of the analytical description to the observed results verified the validity of the calculational technique. In 1963 a simplified analytical model of this quite elaborate and complicated computer code was developed and is currently used to provide information more rapidly on pulse-system behavior.

The development of a one-dimensional code (SPUTTER), which can be used to describe the propellant—pusher interaction, occupied a major fraction of the effort in the early years. By early 1961 SPUTTER was operational and it confirmed earlier calculations that ablation at the pusher would be tolerable. By early 1962 gross confirmation of this code had been achieved experimentally from high-explosive-driven plasma—target interactions. By 1964 the plasma-source technique and instrumentation had been developed to the point that a time-resolved check on the SPUTTER code with microsecond resolution was achieved. Although the plasma source currently in use provides a relatively good simulation of pressure, temperature, and interaction times, it does not reach plasma velocities in the range of interest.

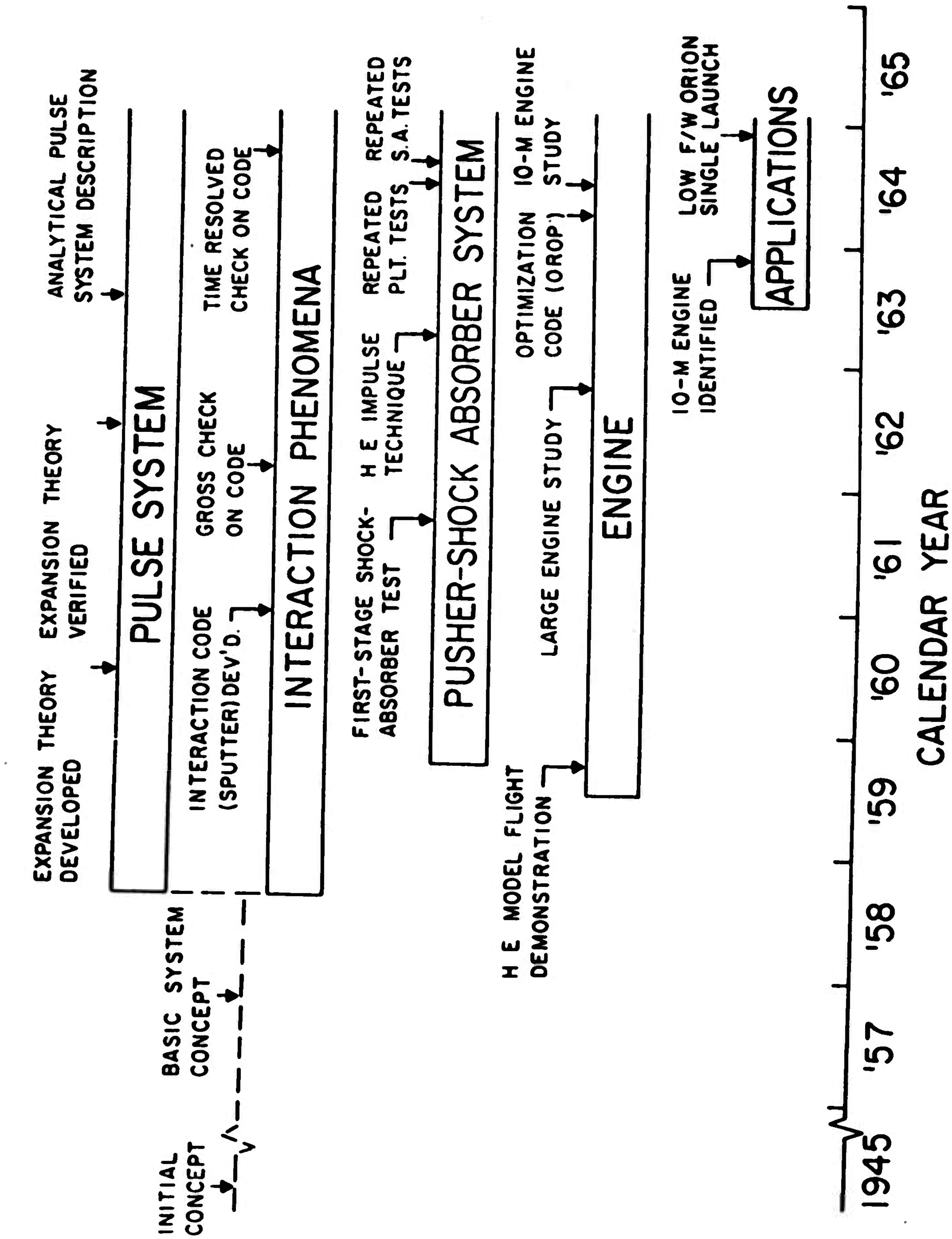

Fig. 3--Principal milestones

Small nuclear underground experiments will be needed to resolve the ablation problem in the required detail. By late 1959 sufficient confidence had been established in the basic physics to justify initiation of preliminary engineering studies on the pusher—shock-absorber system. Early calculations, supported by measurements from tests of bulk high explosives, indicated that the energy-storage capabilities of simple shock-absorbing systems appeared adequate. Effort was then directed toward development of a high-explosive technique for generating impulses which accurately reproduce the pressure-time and pressure-radius profiles on the pusher.

Since bulk high explosives will not reproduce the desired impulse profile, the technique of exploding sheet HE through a foam attenuator was developed.[8, 9] During 1964, repeated mechanical impulse tests were successfully performed on pusher-plate test specimens of medium-strength steel (USS T1) and on primary shock-absorber systems.[9]

Experiments to date have been on scaled engineering test specimens, but the pressures, accelerations, and stress levels for full-scale nuclear engines were used. Empirical results from these experiments indicate that high-explosive impulse techniques are scalable up to full-size pusher—shock-absorber assemblies. Design studies of test facilities indicate further that it is feasible to produce such impulses at the proper cyclic frequencies (i. e., one per second).[10] This testing technique would provide a powerful developmental tool as the response of the entire engine would be the same whether high-explosive impulse generators or nuclear explosions are used to deliver an impulse.

Very early in the ORION research program, an HE-driven flight demonstration model was constructed and flown to demonstrate inherent system stability. The model, which weighed about 300 lb, was propelled by a series of five TNT charges to altitudes of approximately 200 ft. The model consisted of an aluminum pusher plate, dissipative shock absorbers, and a charge storage, delivery, and firing system.[11]

Little effort was expended on integral propulsion engine designs until 1961, when sufficient physics and engineering knowledge had been assimilated to permit meaningful weight estimates and predictions of gross performance characteristics. The first vehicle for which a set of internally consistent engineering and physics calculations was performed had a gross weight of approximately 4,000 tons, an effective I_{sp} of approximately 4,000 sec, and a thrust of approximately 10,000,000 lb. The lengthy calculations and iterations involved in performing this design study made the problem amenable to semianalytical treatment. Therefore, a code was developed for use on a high-speed digital computer for rapidly generating engine designs based on known engineering and physics inputs and constraints. This code (OROP) became operational in early 1964.[12]

In 1963 serious attention was for the first time directed toward specific mission applications of nuclear-pulse engines in an effort to determine their most desirable regimes of operation.[13] Prior to that time ORION had been considered only in terms of very large and extremely high-performance vehicles. The reluctance to consider smaller systems was based on two arguments:

1. I_{sp} decreases as the engine size becomes smaller, and

2. Suborbital start-ups, which were the only type considered, were believed to require over-all vehicle thrust-to-weight ratios in excess of 1.0, resulting in low payload fractions.

The mission-applications study opened the possibility of orbital start-up, which would permit substantially smaller vehicle thrust-to-weight ratios and correspondingly larger payload fractions. In spite of the fact that the I_{sp} decreased, smaller engine modules thus suddenly became very attractive. A specific engine design, referred to as the "10-m" (for 10-meter diameter) engine, was identified which appeared to be more or less optimum for a broad class of interplanetary and lunar objectives. Early estimates of the performance of the 10-m engine were confirmed in mid-1964 by an integral propulsion-system design study employing OROP. This study indicated that if restricted to current materials and current nuclear technology, the propulsion system could deliver an I_{sp} between 1,800 and 2,500 sec with a total thrust of about 450,000 lb. The engine would weigh under 200,000 lb and thus would be compatible with a Saturn V launch vehicle for boosting the ORION engine to an earth orbit.

Subsequent design studies were completed in late 1964, again employing OROP but embodying conservative estimates of potential improvements in material capabilities and nuclear technology. These studies were based primarily on the 10-m design and treat potential improvements, such as lifting or removal of the basic engine design constraints.

II. DEVELOPMENT PLANNING

2.1. INTRODUCTION

The philosophy employed in the development plan of the ORION system may best be described by citing (1) the important goals, (2) the major development problems, and (3) the practical solution to these problems by methods that are either commonly known or unique to the principle, the order and extent of the solutions being phased to permit an orderly expenditure or effort and funds.

The primary goal of the development plan is, of course, to bring a nuclear-pulse engine, specifically a 10-m-diam (33-ft) engine weighing less than 100 tons, to initial operating capability (IOC) for manned interplanetary mission. One important goal is to defer space nuclear tests until the last stages of development. (Atmospheric nuclear start-up is not considered in the proposed operational mode and hence atmospheric nuclear tests are not planned.) Another important goal is a development plan which by design provides for the step-by-step generation of data so that the commitment of large-scale development funds will occur only after a well-defined program, based on adequate technical and cost information, has been established, e.g., the project definition phase (PDP)* of the DOD.

The major development problems parallel the technical problems discussed briefly in Section 1.2. Each of these development problems has been analyzed in considerable detail, not only individually but also as a part of the over-all engine operation. Because of the very short interaction time (~ 100 μsec) between the high-energy propellant and the pusher, many of the conditions of operation which are assumed to be development problems are decoupled and may be treated to some degree separately from others. Techniques are available for treatment of all technical problems that have been identified. Furthermore, these techniques are compatible with the goals of the phased plan in which nuclear space tests occur late in the development program well after the technical and economic practicability has been confirmed and the decision to proceed with the full development of the system has been made. Space tests will be required only after complete engine modules have been ground-tested with HE impulses at full load (per pulse) and at the design repetition rate (~ 1 per sec). In the preparation of this plan, it has been assumed that (1) orbital rendezvous and assembly in orbit will be routine operations and (2) space survival and operation by man will have been well established by the time the final operations--manned orbital tests--are required.

2.2. PROBLEMS UNIQUE TO ORION

ORION does present some unique technical problems. But since there is essentially complete freedom in post-test handling of all test hardware for inspection and reuse, fewer copies of test hardware are required, turn-around time between tests is minimized, and preflight testing on the ground of all flight hardware is practical. The major problems are described below. Many questions connected with these problems have been answered analytically, all must be confirmed or answered experimentally.

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*PDP is defined by Department of Defense Directive No. 32009, February 26, 1964.

2.2.1. <u>The Nuclear-pulse System</u>

The energy source of ORION is a nuclear device with highly controlled expansion characteristics. The following questions concerning this device may be asked and must be answered during the development program: Can a pulse system be designed and built which will produce an impulse of acceptable characteristics? Can the operation of a pulse system be made reliable and reproducible within the required tolerances? Can the pulse system be designed so that the radiation fluxes in the vicinity of the vehicle and the amount of fission products in the area of operation be kept below acceptable levels? Is the nuclear fuel required compatible with available sources? Will quantity production costs be sufficiently low to make the over-all ORION system economically attractive?

2.2.2. <u>Thermal Condition of Interaction at Pusher</u>

That portion of the pulse system that is intercepted by the pusher is called the propellant, and for efficiency of operation, the propellant must travel at high velocities. Consequently, upon interaction with the pusher, this propellant stagnates in the form of a high-density, high-temperature cloud or plasma, radiates most of its energy to space, and re-expands. This whole interaction process normally takes place in approximately 100 μsec. Considering this very short interval and the materials involved, basic questions arise, such as: What are the conditions of energy transport and what heat remains in the structural portion of the pusher plate? Does this heat have sufficient intensity to vary conditions for subsequent pulses? Are additive effects constant over the range of repetitive pulsing? Is the quantity of heat sufficient to require cooling for a burst of many pulses? The necessary research is planned to obtain answers to these problems.

2.2.3. <u>Mechanical Aspects</u>

The following problem areas concerning the mechanical aspects of the system will require specific tests and will be a major part of the development program: What are the unique aspects of the mechanical and structural response of a system designed to attenuate the pressure pulse from the nuclear pulse system to a level acceptable to engine components or payload? Can a pusher be designed and manufactured so that it can repeatedly accept peak pulse pressures of such magnitude that system efficiency is not seriously limited and, at the same time, be attached to a shock-attenuating system (shock absorbers)? Can the shock-absorbing system accept and attenuate the repeated pulse loads in such a way that the pusher is controlled relative to the rest of the vehicle?

2.2.4. Auxiliary Systems

Optional requirements of the major auxiliary systems may present some difficult development problems. Anticipated possible problem areas are (1) the satisfactory handling and accurate delivery of the pulse systems; (2) the arming, positioning discrimination, and firing of the pulse systems and the disarming and destruction of them in the event of misfire; (3) the general operation of the engine control system, which must coordinate and/or direct the operations of the pusher and shock-absorber systems, the pulse-system handling and delivery system, fire control system, attitude control system, antiablation fluid distribution system, and miscellaneous cooling systems; and (4) the operation of the antiablation-oil distribution system.

2.3. SEPARABILITY OF LOADING CONDITIONS

For a single ORION pulse, the over-all conditions of loading and environment are nuclear radiation, pulse-system expansion and inert-propellant—pusher interaction, ablation at the pusher surface, and mechanical response of the vehicle.

The nuclear, thermal, and mechanical effects are separate, but related, problems of the propulsion-system development. These were schematically illustrated in Fig. 2 and discussed in Section I.

2.3.1. Nuclear Radiation

The nuclear-radiation patterns have been calculated for specific designs by using well-established nuclear-shielding techniques.[4] The accumulated radiation doses for thousands of pulses in the various levels of the engine are well below values at which onset of measurable degradation of structural properties can be expected. The radiation level per individual pulse is so low that there appears to be no mechanism which would cause coupling of effects from one pulse to the next beyond the possible straight addition of nuclear structural damage and heating. The nuclear heating of structural parts is low and is deposited somewhat uniformly throughout the mass of any given part; thus no thermal stress condition is induced. It can be strongly argued that the nuclear radiation effects do not affect the mechanical response of the engine beyond that of gradual heating of some elements.

2.3.2. Pulse System Expansion and Inert-propellant—Pusher Interaction

The manner in which the detonated nuclear pulse system expands and the resultant interaction with a massive target plate (the pusher) are completely independent of the character of the engine structure beyond the target plate. If the target plate is insulated from the high-temperature stagnating propellant, its mechanical response is limited to the fluid dynamic pressure pulse of the interaction. The pulse system appears to be fully developable as a component completely independent of the engine considerations. However, the pulse system must operate within a series of constraints which are set by over-all system operation and engine structural limitations.

2.3.3. Ablation

The pusher surface facing the detonated pulse system intercepts a portion of the pulse-system mass (the inert propellant), and in the process the propellant stagnates, developing an elevated pressure and temperature. The pusher structure must be insulated from this adjacent high-temperature plasma layer to minimize the heat-transfer rate. It has been calculated and experimentally demonstrated[14] that a relatively thin layer of hydrogeneous material (e.g., oil) is sufficient to keep the pusher temperature rise within a very small fraction of a degree per pulse; any ablation is limited to the layer of oil and thus no structural material is ablated. This antiablation oil is capable of efficient transmission of the fluid dynamic pressure to the pusher structure. It is anticipated that a new layer of oil will be applied after each pulse, or group of pulses, to make the pusher surface be the same for any specific pulse. In this way the ablating conditions would be the same for all pulses.

2.3.4. Mechanical Response of Vehicle

Effects other than the pressure pulse which emanates from the detonation of any given pulse system are expected to be insignificant.[14] The repeated pressure-pulse effects on the mechanical response of the engine are a very involved problem because of the interdependencies of the response of the engine's many components. Ground-testing with repeated nuclear pulse systems is believed to be economically infeasible because simulation requires vacuum between the detonating point and the vehicle. Single-pulse tests in vacuum, however, appear to be possible, but it is not clear that they are required. It has been demonstrated with sheet high-explosive (HE) separated from the target plate by inert pressure-attenuating material that pulse shapes can be made which closely approximate those calculated for the interaction of the pulse-system propellant on the pusher (see Section 2.4.1.). Repetitive delivery of such pulse systems appears feasible (see Section 2.7.5.). Therefore, by simulating the nuclear pulse with a chemical energy pulse, repeated pulsing of a test engine can be accomplished, with each pressure pulse being of the proper shape and duration and repetitively delivered at the design operational frequency of the nuclear-pulsed system.

By the exploitation of the natural independence of various operating conditions, a ground test program utilizing underground nuclear tests and chemical high explosives can advance the development of this system to a preliminary flight rating.

2.4. EXISTING TEST DATA PERTINENT TO ORION DEVELOPMENT

As discussed in Section 1.3, several technical milestones of importance to the development of ORION have been reached.

2.4.1. Pulse Simulation with HE

Pulse units of sheet HE and pressure-attenuator have produced pressure-time pulses in the range of interest to ORION. Pulse-shaping can be accomplished by varying such parameters as the mass of HE; the mass, density, and thickness of the attenuator; and the material from which the attenuator is made. Three typical pressure pulses as measured by piezoelectric sensors and taken from oscilloscope traces are presented in Fig. 4. For these curves the value of P_{max} is 100,000 psi, which is

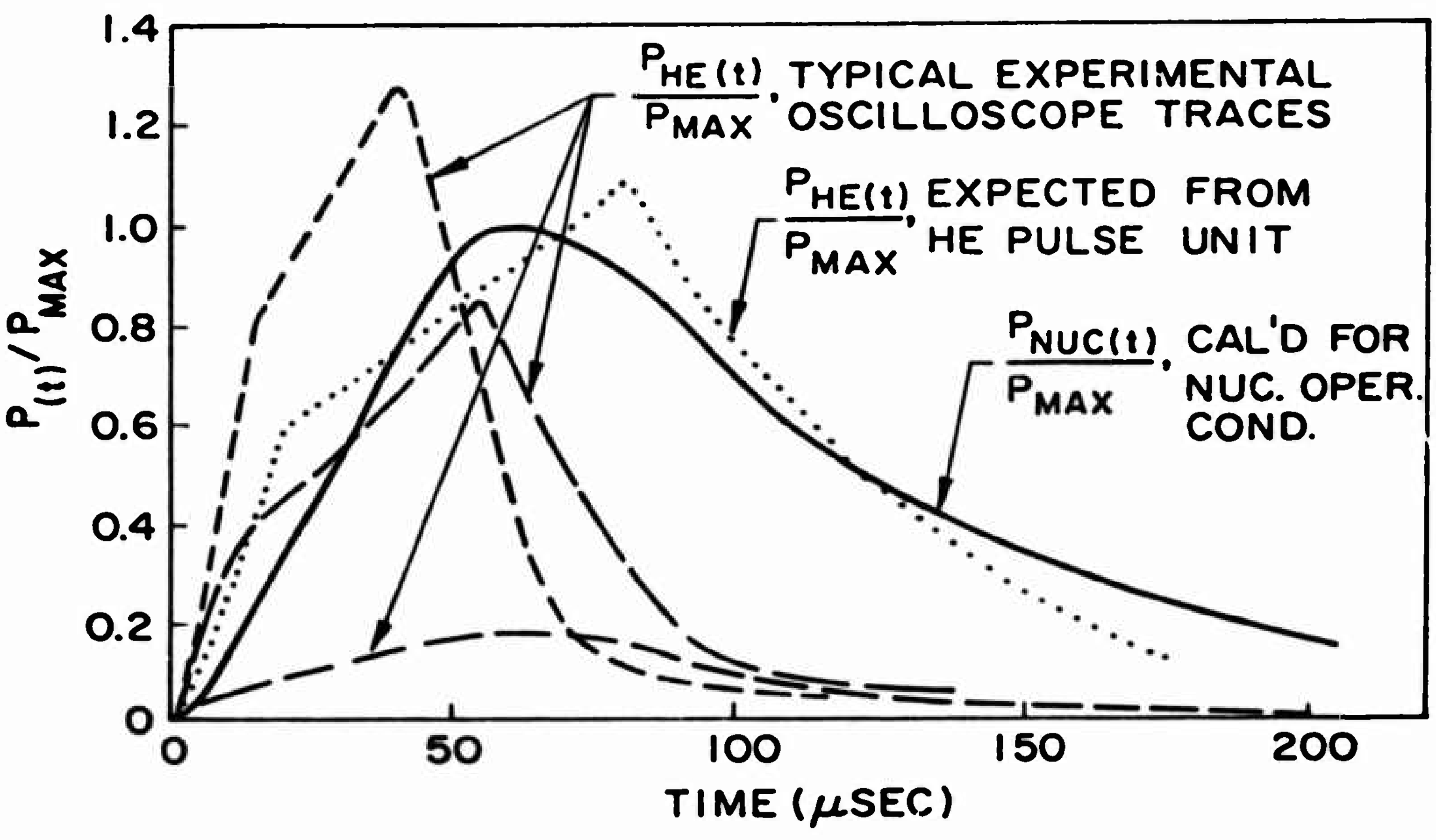

Fig. 4--Pulse shapes for normalized pressure vs time as predicted for nuclear operating conditions and HE test conditions

the proposed design peak pressure at the center of the pusher. It is anticipated that this pulse shape can be altered to approach that shown by the "expected HE pulse" curve. The solid curve is the calculated pressure pulse on the pusher plate. If this pressure is taken at the center of the pusher, P_{max} is equal to 100,000 psi; at the positions radially outward from the center, P_{max} becomes progressively less.

A preliminary design study has indicated the feasibility of delivering and detonating many HE pulse units at a frequency as fast as one per second. This is discussed in more detail in Section 2.7.5.

The basic technology for simulation of the nuclear pulse with HE is now well developed. Detailed fitting of the HE pulse to the nuclear pulse will require a moderate experimental effort.

In parallel with pulse development work, dynamic tests have been made on pusher-plate sections, some with shock-absorber attachments, and on shock-absorber structures. No advancement in current material technology has been considered. Results of these tests have indicated the limits for peak pulse pressures (P_{max}) and practical structural designs for the pulse-loaded pusher and shock-absorber structures.

2.4.2. Confirmation of Ablation Theory by Tests

During the past several years theoretical and analytical studies have been made of the thermal effects (especially ablation) at the pusher surface caused by the stagnation of the high-energy propellant. The theory has been used to predict the ablation caused by HE-driven plasma stagnating against a target plate. Good correlation exists between the calculated and observed results.[14]

The HE plasma is of lower incident velocity and higher density than that calculated from a typical nuclear pulse system. However, the resulting pressures and temperatures are in the regions of interest for nuclear operation. Therefore, the theory is believed to be of good accuracy for the prediction of ablation from a nuclear-driven plasma.

2.4.3. Pulse-system Expansion Theory

Theory of the pulse-system expansion has also been developed over the past several years. The expansion of the mass of a pulse system is calculated with MOTET.[7, 14] The general correctness of this calculational technique has been demonstrated by good correlation between the calculated and observed results of the Starfish event and by the fact that nuclear weapons behave as predicted by similar calculations.

2.5. DEVELOPMENT WITH GROUND TEST FACILITIES

It now appears that the major development problems can be attacked independently with test facilities on the ground to obtain results that will be representative of flight conditions. It is unlikely that any major cross-coupling or interdependencies will produce unpredictable results

Nuclear testing can be limited to underground experiments for the development of the pulse system and for studying the interaction process. The employment of the LENS system (discussed in Section 2.7.6.) will minimize the size and expense of the interaction studies and will particularly enhance the recovery possibilities. There is no predictable need for multiple nuclear tests prior to the free-flight tests above the earth's atmosphere.

The major hardware development of the engine can be carried out on the ground by HE techniques which permit repetitive testing under proper pressure-time and pressure-radius conditions at the right scale and with the right frequency.

2.6. TECHNOLOGY DEVELOPMENT APPROACH

A possible phased development plan (which does not include time and cost considerations) with well-defined milestones which have been generated with careful consideration of the background of problems, existing knowledge, and practical methods of attacking the problems is presented here. The objective of the plan is the orderly development of a nuclear-pulse engine to a point of initial operational capability (IOC). (See Ref. 5 for a more detailed treatment.)

A step-by-step program progressing from basic technology to the development of components to preliminary flight rating and qualification can be carried out in fairly well defined research and developmental phases. Each phase culminates in a series of technology milestones that provide the necessary information and confidence to justify starting the succeeding phase. Figure 5 shows schematically the relation between the major development areas and the development phases.

Phase I may be described as "research to project definition." This phase includes all work that has been accomplished up to the present time and additional work required to provide the necessary technical information for a project-definition-phase (PDP) study. Early underground nuclear interaction experiments and scaled mechanical testing with HE would occur in this phase. Phase II is the prototype development phase; it is a period during which the research of Phase I is extended to the ground-based development of all the full-scale components of a prototype engine. Components and

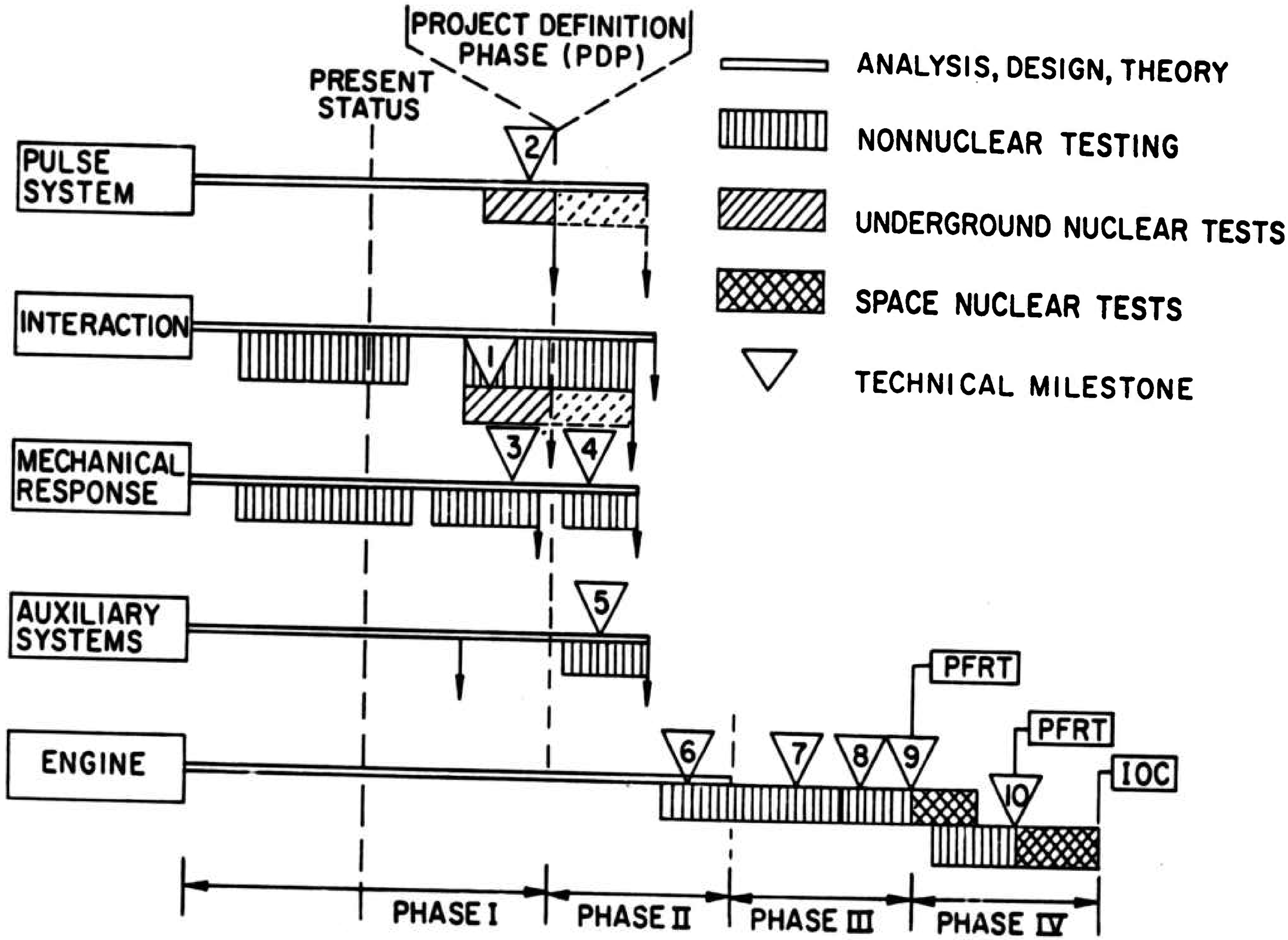

Fig. 5--Abbreviated phased development chart

subsystems would be designed and tested independently as much as possible. Several full-scale underground nuclear experiments would be performed to prove the design of the pulse system. The assembled prototype engine would be developed with repetitive HE testing at a ground test facility. Phase III consists in "flight prototype ground qualification"; this would include the complete systems operation of a flight prototype engine subjected to impulsive life-testing on the repetitive-HE test facility, and preliminary flight-rating testing (PFRT) of ballistic test engines would be made on the same or a similar facility. Finally, Phase IV, the ballistic and orbital testing phase, represents the first requirement for nuclear testing in space. Initially, a series of unmanned ballistic tests would bring together all real space conditions for the flight prototype. Then, from a parking orbit, manned prototypes would be put through a series of shakedown and mission qualification tests to bring the engine design to a condition of intial operational capability (IOC).

The basic development philosophy is that each element, system, and total assembly of systems which make up the engine shall be tested and proved under practical and realistic conditions at full scale. Different specific experimental techniques can be applied to each problem area with redundant results. The known basic problem areas and the experimental techniques which may be applied to study or prove each component are shown in Fig. 6.

DEVELOPMENT AREAS	EXPERIMENTAL TECHNIQUES								
	HE PLASMA	EM PLASMA	COMPONENT TESTS (VACUUM)	HE PULSE	HE REPETITIVE PULSES	UNDERGROUND NUCLEAR		SPACE NUCLEAR	
						PULSE SYSTEM	ABLATION	BALLISTIC	ORBITAL
PULSE SYSTEM						●		●	●
INTERACTION	●	●			●	●	●	●	●
PUSHER					●		●	●	●
SHOCK ABSORBER			●		●		●	●	●
AUXILIARIES			●		●	●		●	●
ENGINE QUALIFICATION					●			●	●

Fig. 6--Abbreviated development approach

2.7. DEVELOPMENT TECHNIQUES

2.7.1. Ablation Experiments with High-explosive Plasma Generator

A high-velocity, high-density plasma generator has been developed to confirm propellant-pusher interaction theories under interaction conditions similar to those of the nuclear-pulse propulsion system. The plasma generator is shown in Fig. 7. Plasma is produced by an HE cylindrical implosion of a thin-walled metal (usually lead) tube. Stagnation of the high-velocity plasma against a target produces hydrodynamic impulses (pressure as a function of time) and stagnation temperatures similar to those expected from a nuclear pulse system. The velocity of the plasma is lower than that of the nuclear pulse system, but the temperature of the stagnated plasma is high enough (150,000°F, or 7 to 8 ev) that radiation is the dominant mode of energy transfer from the plasma to the target, as it is for the propellant-pusher interaction conditions, and thus the same calculational techniques apply equally well to both.

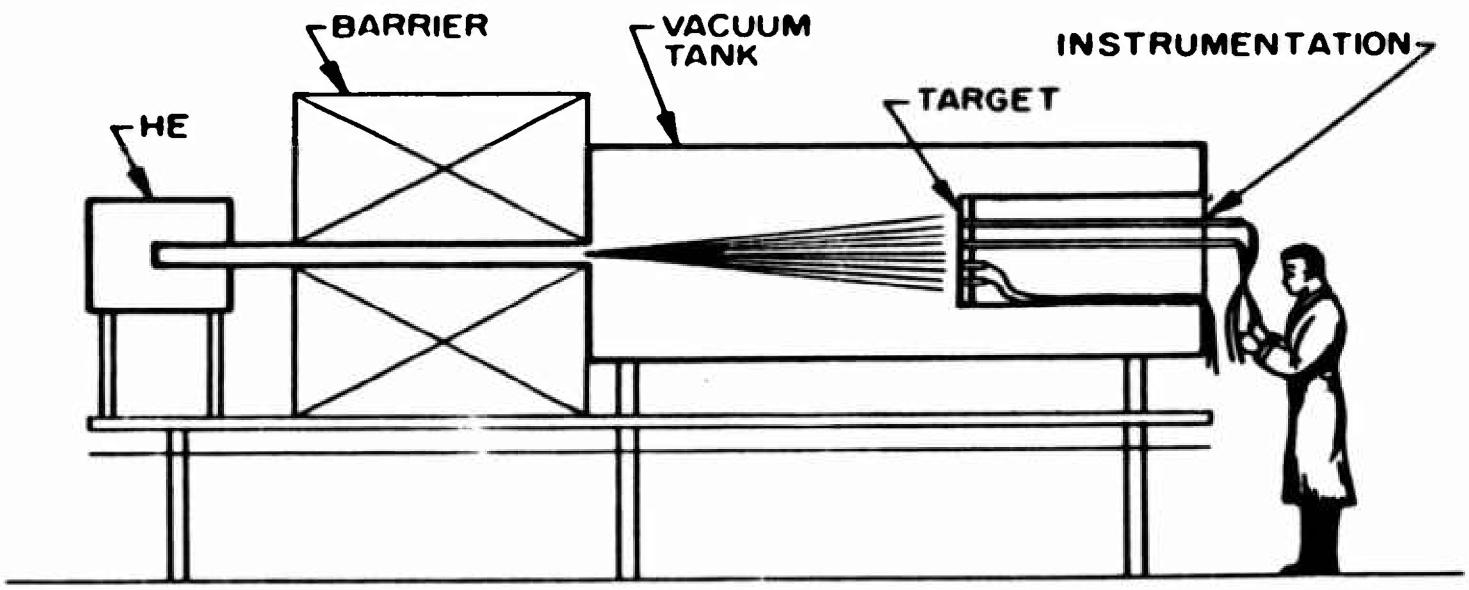

Fig. 7--HE plasma generator

The main objectives of these experiments are (1) to check theoretical calculations of the ablation process, (2) to study effects (such as radial flow and convective instability) that may not be amenable to calculation, and (3) to develop techniques and instrumention with the HE plasma generator for use in nuclear tests. Results to date have largely confirmed the validity of the theoretical treatments in the regimes achievable and have led to diagnostic techniques and test hardware applicable to nuclear experiments.[14, 15]

2.7.2. Pulsed High-energy Electromagnetic Plasma Accelerator

A proposed advanced plasma-acceleration system which should accurately simulate in one dimension all propellant-pusher interaction environments could be used to test target plates up to 6 in. in diameter. The basic acceleration mechanism is magnetohydrodynamic in nature. Explosive-electric generators (IBEX) would be used to obtain the required high, total, plasma kinetic energy. These generators, which are currently being designed and developed for other applications, will provide high electrical energy which will then be converted into plasma kinetic energy by a multiple-rail-gun system. The necessary high-current switching system has already been developed. The plasma densities within the separate coaxial rail guns should be comparable to those which are presently being achieved in operative rail-gun systems. By focusing the plasmoids generated by the separate rail guns, the plasma densities required for the interaction tests may be obtained; the energy losses upon convergence are not predicted to be large. The basic techniques have been experimentally established and an advanced IBEX system conceived specifically to achieve nuclear-pulse environments is expected to present no major development obstacles.

2.7.3. Space-simulated Component Tests

The development of the nuclear-pulse propulsion engine will require a broad range of tests of materials, elements, components, and systems, some in simulated atmospheres, prior to specific tests for the pulse system, pusher ablation, and propulsion-engine mechanical response. Most of the tests envisioned can be made with standard techniques in existing laboratory facilities. Strength tests of tensile, compression, and torsion specimens under one-time, fatigue, and nuclear-radiation conditions, tests of sliding surfaces for friction and radiation conditions, and tests of subsystem operation under simulated space conditions can be accomplished using standard techniques.

Some tests of certain major engine subsystems will require installations in large vacuum vessels. Examples of such tests are (1) shock-absorber seals for friction and fatigue, (2) antiablation-fluid distribution, and (3) pulse-system transfer from storage to delivery tube, firing from delivery tube, trajectory accuracy, and detonation timing accuracy. Existing space-simulation chambers with special modifications should fulfill the facility requirements for these tests.

2.7.4. Single-HE-pulse Tests

The internal arrangement of the ORION pulse system for the nuclear-pulse propulsion system is such that the inert propellant effectively shields the vehicle from the nuclear radiation and essentially all of the fission products created by the nuclear explosion move away from the vehicle. Most of the inert propellant is subsequently intercepted by the pusher, and the momentum of the propellant is transferred to the pusher when the propellant stagnates against the pusher. The duration of the propellant-pusher interaction is on the order of 100 μsec, during which time the propellant temperature rises to $\sim$200,000°F or 120,000°K, and then rapidly cools. The structural material of the pusher (a medium-strength steel) is insulated from this short burst of temperature by a layer of oil. Calculations and tests[14] show that a few thousandths of an inch of oil will keep the metal of the pusher at temperatures below 250°F even after a long powered flight of a thousand pulses. The mechanical subsystems of the engine, being isolated from the nuclear and thermal effects of the energy source, respond to the impulse in a purely mechanical way.

A simulation of this mechanical response is necessary for the development of the pusher and shock-absorber designs and for the eventual fatigue tests of the assembled engine. A technique for simulating the nuclear-driven propellant impulse has been developed. The technique will simulate, for example, a pressure distribution that is approximately 100,000 psi maximum at the center of the pusher and radially diminishes to the edge of the pusher in a manner similar to the actual impulse distribution. The pressure-pulse simulation technique employs sheet HE separated from the pusher by a layer of pressure-attenuating material of the required thickness and density. The range of pressure pulses obtained and required was shown in Fig. 4. The HE-pulse test units can be assembled on the pusher of an inverted engine or portion(s) thereof and subsequently detonated by an electric blasting cap to produce a single-impulse load.

2.7.4.1. Test at Existing Facilities. Many tests have been made on both small-scale and small-diameter plates and shock-absorber structures. Results from these tests indicate that there are practical solutions to the many unique problems connected with the pusher—shock-absorber mechanism proposed for nuclear-pulse propulsion systems.[8, 9] Several proposed specific designs[5] have been scale- or full-size-tested with HE.[9]

The experimental study of full-thickness portions of some parts of the pusher plate and scaled plates weighing up to 400 lb can be undertaken with existing facilities. These tests are necessary and adequate to prove the structural integrity of materials and shapes, especially of attachments, to the extent that a sound decision can be made for the construction of large-scale test pusher plates.

2.7.4.2. Four-meter Test Stand. The second-stage shock-absorber system for the 10-m engine consists of a circular array of six identical, rigid-walled, double-acting shock absorbers. It appears both feasible and economically most desirable to perform dynamic testing initially on a single full-scale secondary shock-absorber unit. This can be accomplished by equipping the full-scale unit with a suitable first-stage shock absorber, pusher, and the other necessary hardware and then subjecting the assembly to full-scale high-explosive impulses. A pusher diameter of approximately 4 m would be compatible with the energy-storage capability of a full-size second-stage shock absorber. A test stand suitable for shock-absorber development would be similar to an existing 1-m test stand. A sketch of such a test setup drawn approximately to scale is shown in Fig. 8. In addition to testing a single full-scale second-stage shock absorber, this 4-m setup would be used to test the center section of a full-size first-stage shock absorber. It is also possible to scale or section the pusher plate in various ways so that valuable information on pusher design may be gathered concurrently with the shock-absorber data.

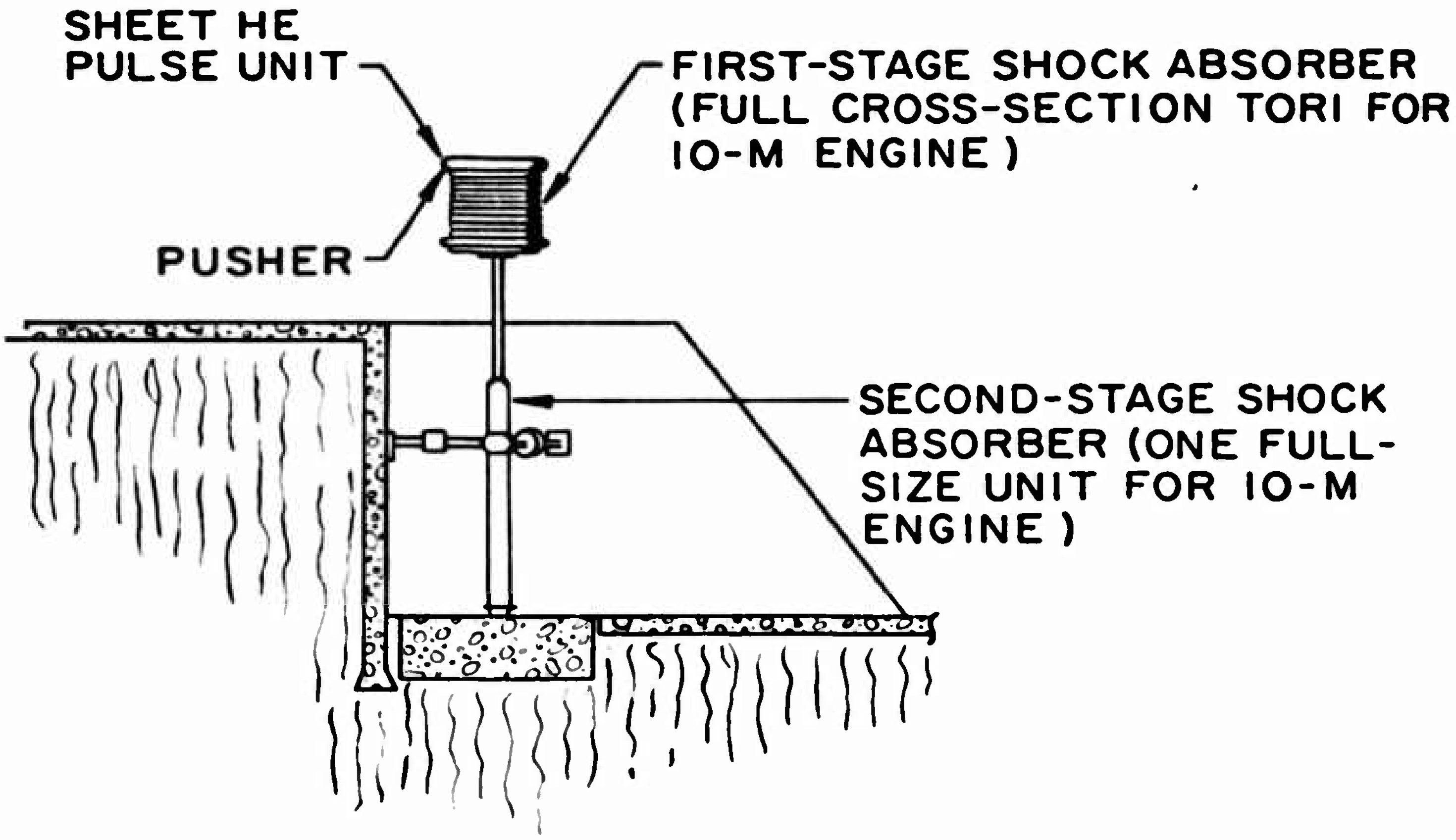

Fig. 8--4-m-diam single-HE-pulse test facility

2.7.4.3. Ten-meter Test Stand. More than one test setup would be required to obtain the data necessary to prove the design and fabrication of the two shock-absorber systems and the pusher. The 4-m test-stand arrangement would be especially useful for shock-absorber development. The pusher, on the other hand, should be proven in full size before subjecting the very costly shock-absorber assembly to full dynamic tests. The pusher should therefore be well developed and proven on a special test setup before the integrated testing of pusher and shock absorber. Furthermore, the development problems of the two systems are to a certain extent separate. The development of the pusher would be carried out on a 10-m-diam test setup for which a special dissipative shock-absorbing system would be designed to simplify the test setup and the test shock absorber. The general arrangement for these tests would be similar to that shown in Fig. 8.

After the pusher and shock absorber have been separately tested extensively with single pulses, a complete full-scale assembly of shock absorbers and pusher would be tested, first with single pulses and then with repetitive pulses on a 10-m test stand as described below.

2.7.5. Repetitive-HE-pulse Tests

Results from tests indicate that the impulse expected from the nuclear pulse system can be reproduced with HE on a full-size engine prototype at the design operating frequency while the vehicle is secured to a test stand. The importance of this technique, which can play a strong role in proving the design in preliminary flight-rating tests and in preflight ground qualification, cannot be overemphasized. A preliminary design study indicates that a facility of this type can be built and that 100 or more HE pulse units can be delivered at a rate of one per second to an inverted 10-m engine.[(10)] Sufficient HE pulse units (approximately 100) could be stored in a magazine-silo for test runs of sufficient duration to ensure that the engine will reach its operating temperature equilibrium. By reloading the magazine-silo and repeating such bursts, the engine prototype can be effectively life-tested or an operational engine can be ground-qualified before delivery to orbit. This repetitive-HE-pulse test installation would be invaluable for component life-testing, engine fatigue testing, and vehicle preliminary flight rating and ground qualification.

The test facility is illustrated in Fig. 9. The vehicle would be tested in an inverted position for two basic reasons: vehicle support is simplified and, more importantly, the arrangement provides free expansion of the pulse-system explosion products and strong shock waves.

Both a 4-m and a 10-m repetitive HE-pulse test facility are planned for the development phase. The 4-m facility could be developed economically and would be useful for inexpensive development work on individual full-size shock absorbers.

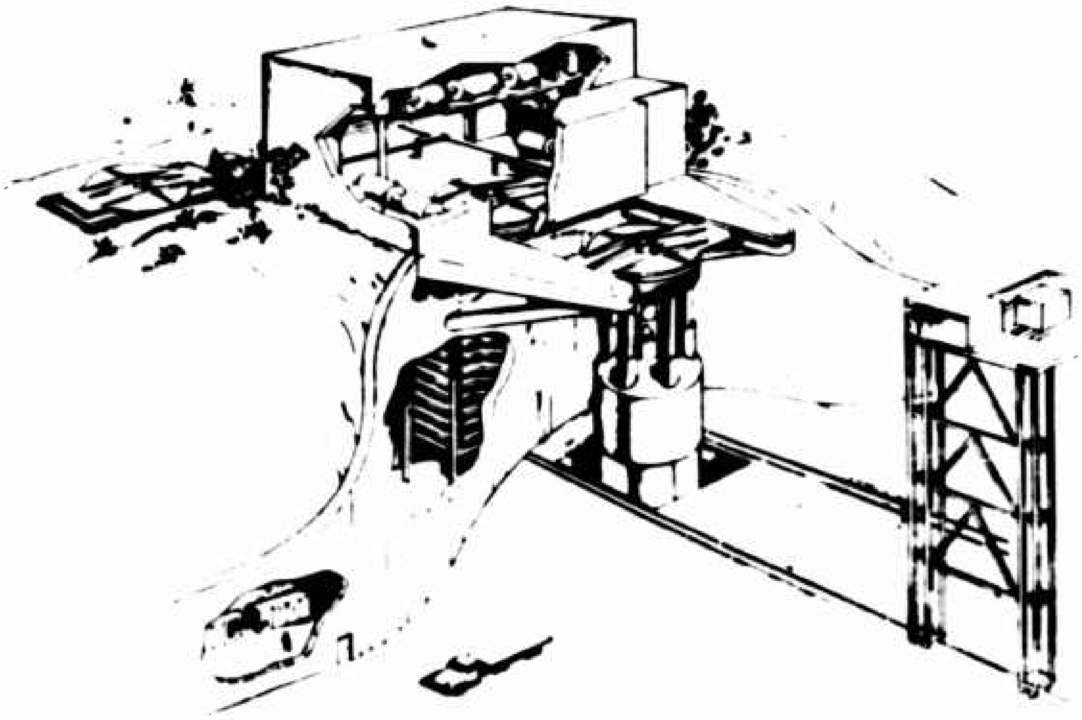

Fig. 9--Propulsion module test facility (repetitive pulse simulation—HE)

The size of vehicles for which this technique becomes impractical is not established. Certainly such modifications as dual storage and dual transfer of half-sectioned HE pulse units for testing a 20-m-diam engine at approximately the same frequency as that of the 10-m vehicle could be made. Experience gained from the 4-m and 10-m installations should provide the necessary test data to allow more accurate determination of size limits.

2.7.6. Underground Nuclear Tests

Nuclear tests prior to flight tests of preliminary-flight-rated engine prototypes are limited to support and confirmation of theoretical and analytical studies of the propellant-pusher interaction process and pulse-system design. These tests require a vacuum environment and are suitable for underground test setups.

2.7.6.1. Interaction Studies. Underground experimental studies could be made of the interaction of the propellant and the pusher, particularly the ablation processes. The test plate sizes could range from a few feet in diameter to the full engine size. The propellant source considered for these tests is a special nuclear source--the LENS system--which is a very low-yield "gun-type" assembly.[16] The advantages of a low-energy nuclear source for underground tests are that (1) less burial depth is required, (2) there is less over-all energy to contain, which makes recovery of test specimens more promising, and (3) the source can be scaled down, thus making tests on less than full-scale pusher specimens practical. The operational pulse system is far less amenable to down-scaling, so that scaled nuclear tests with such a device are impracticable. A test facility for interaction experiments with a test plate one-fourth the diameter of the 10-m pusher is illustrated in Fig. 10.

2.7.6.2. Pulse-system Development. A substantial portion of the past research program has been directed toward understanding the behavior of the nuclear pulse system. Theoretical and analytical studies using and expanding the calculational techniques developed for weapon design have provided an understanding of the characteristics of various designs of nuclear-energy-driven "propellants." There is considerable promise that the pulse system can be constructed in a desirable form with a minimum number of iterations. The current plan calls for early tests of full-scale pulse systems in Phase I. Additional tests are scheduled in Phase II. The anticipated configuration of the pulse-system test facility is similar to the interaction test setup of Fig. 10. Essentially all of the energy yield of the nuclear device would expand into the air-filled cavity; the energy density in the cavity must be low enough to prevent reradiated energy from perturbing the state of the inert propellant on its flight to the target plate. This would be an instrumented test where there would be no target recovery.

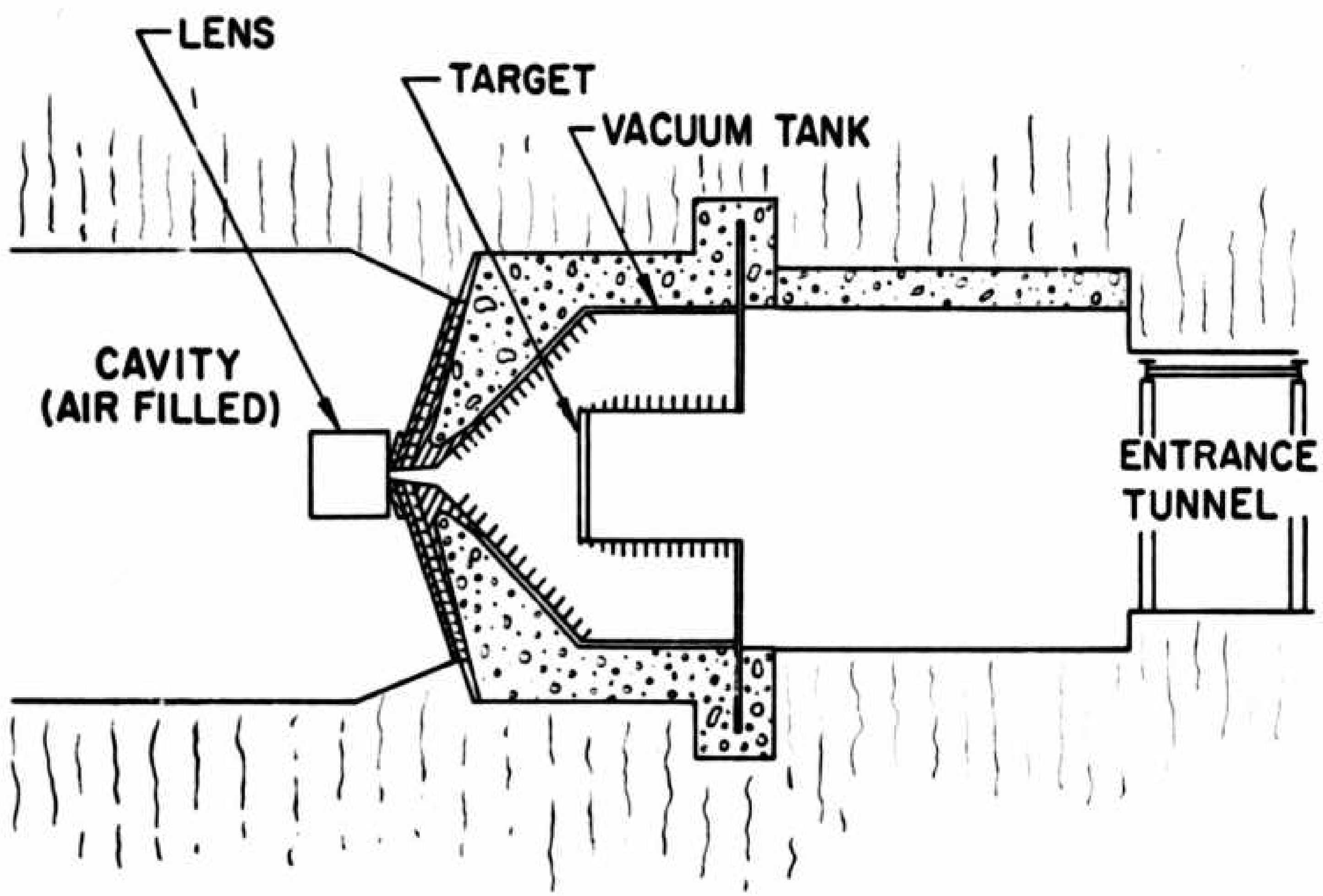

Fig. 10--Underground nuclear test arrangement for propellent-pusher interaction studies

After the pulse-system expansion tests have been satisfactorily completed and the design established, tolerance of device yield must be established. To accomplish this, a series of approximately 100 underground yield tests on production units is planned. Minimum complications are anticipated for these tests, the units would be fired in shaft-type well holes on a production-like schedule. These yield tolerance tests are scheduled for Phase II.

2.7.7. Nuclear Ballistic Tests

The first space tests are scheduled after the engine has been thoroughly tested and qualified for space operation in the HE ground test facilities. Space tests would be made to obtain operational data with operational nuclear pulse systems in actual space conditions. The first space tests are planned as a series of ballistic tests in which the engine would be lofted by a chemically fueled stage to such an altitude that the engine can be subjected to a series of nuclear pulses and recovered after the tests. To minimize or to avoid contamination of the atmosphere, the tests would be performed at altitudes in excess of 120 km (approximately 400,000 ft) and conducted in such a way that the fission products created by the nuclear pulse systems expand away from the earth's surface. This implies that the engine would be lofted to an apogee well above 120 km, which is determined by the distance the engine would travel back toward the earth during operation.

A typical trajectory of the ballistic tests is shown in Fig. 11. After lofter burnout, the lofter and test engine would coast up to apogee as a unit. At apogee this unit would be rotated so that the front end of the engine is pointing toward the earth, at which point the lofter and engine would be separated by a retrorocket on the lofter. After separation to a distance greater than 80 ft (the approximate standoff distance of the pulse system from the pusher), the pulse systems required for this test would be sequentially ejected and fired. The recovery system controlling the attitude and the sink speed of the engine would then be activated. Flotation gear would be employed to recover the engine from the water for subsequent detailed inspection.

With regard to the radioactivity of the nuclear-pulse engine after the test, preliminary studies indicate that the amount of radiation due to activation of the engine will be very low (approximately 20 mr/hr after 50 pulses) and that almost unlimited personnel access to the engine would be permitted immediately after recovery. Therefore, the recovery from the water appears to be straightforward mechanical operation. A surface vessel equipped with a crane with a lift capacity of 100 tons at a 20-ft radius and with the required deck cargo capacity or towed barge could handle the pickup and return of the engine.

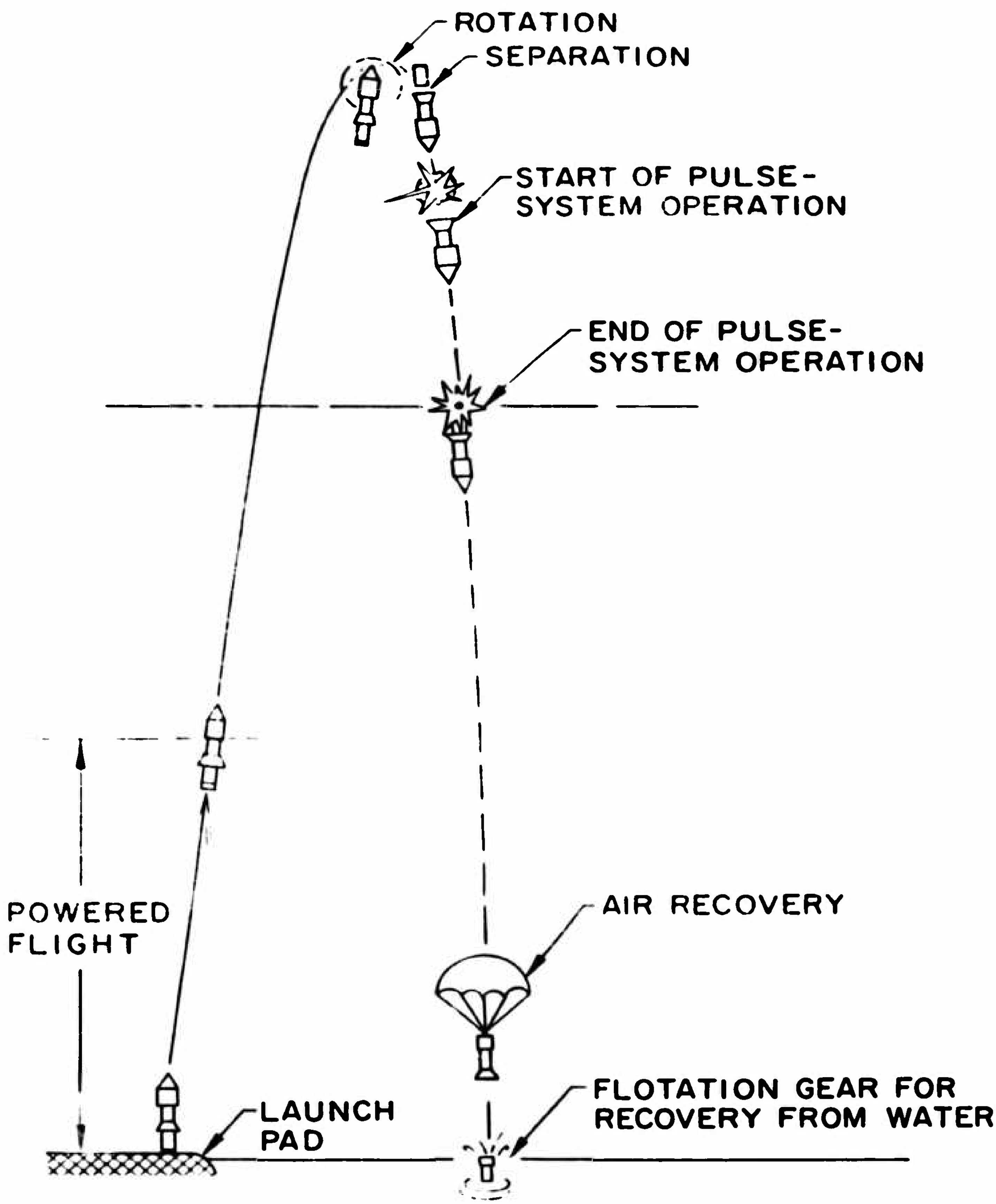

Fig. 11--Trajectory for nuclear ballistic tests

2.7.8. Orbital Tests

The final qualification to obtain initial operational capability (IOC) would be achieved by a series of orbital tests. Two basic assumptions have been made for the orbital test program: (1) orbital rendezvous and assembly in orbit are routine operations and (2) space survival and operation by man is well established.

The first obvious objective of the orbital tests, therefore, is to manifest the proper functioning of the entire engine under prolonged operational conditions. A second objective is to gain a maximum of operational experience with the engine involving repetitive orbital start-ups, shutdowns, maneuvers in orbit, and in-flight maintenance. Concurrently, a series of measurements much like those made for the ballistic tests would be made to record temperature, pressure, and radiation profiles during operational cycles.

Each propulsion test engine would be put into a low earth orbit by a two-stage Saturn V launch vehicle. The objectives of the orbital test program require a test crew sufficient to conduct the tests and to monitor all other experiments scheduled for the test runs. Hence, a capsule for the test crew, including shielding and a complete life-support system, would have to be provided. Test personnel, test equipment, crew module, and the nuclear pulse systems would be launched separately and assembled in orbit (see Fig. 12).

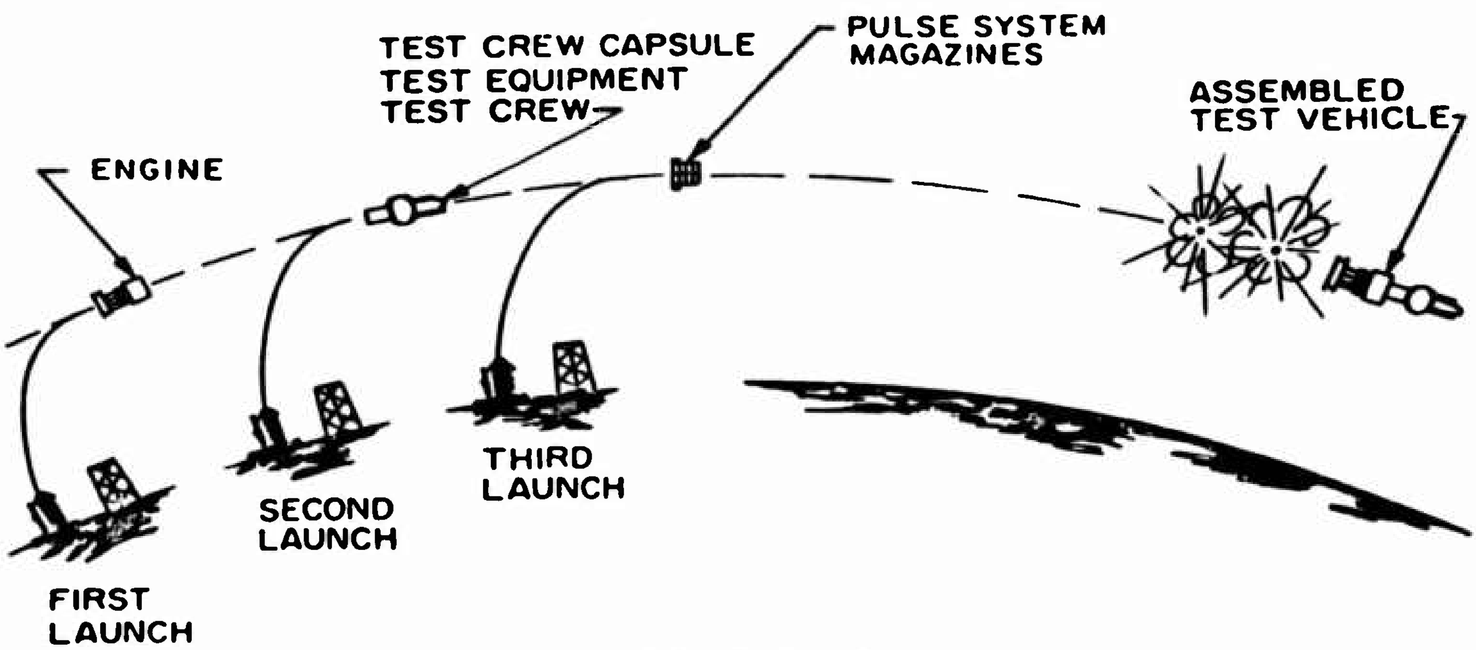

Fig. 12--Orbital tests

The launch schedule for this operation, as given in Table 1, is based on the following considerations: With a reliability factor of 0.75 for Saturn V orbital launches, four test vehicles (test engines plus a test crew module for each) would be required for a successful launch of three test vehicles; three of the vehicles would be launched into orbit and one would be kept as a spare. Nine Saturn V's would be required for the launch-to-orbit operation. Each test engine would be equipped in orbit with 800 nuclear pulse systems (this quantity should be sufficient to conduct orbital tests

Table 1

SATURN V LAUNCH VEHICLE FOR CONDUCTING IOC TESTS

Launch No.	Item to be Launched
1	Propulsion Module No. 9
2	Test-crew Module, Personnel, Test Equipment
3	Nuclear Pulse Systems (800)
4	Propulsion Module No. 10
5	Test-crew Module, Personnel, Test Equipment
6	Nuclear Pulse Systems (800)
7	Propulsion Module No. 11
8	Test-crew Module, Personnel, Test Equipment
9	Nuclear Pulse Systems (800)
10 - 14	Nuclear Pulse Systems (4,000)
	Propulsion Modules No. 12, 13
	Test-crew Module

involving a few to a few hundred pulses). To loft these would require three Saturn V's. In order to perform the final IOC tests, where a few thousand nuclear pulse systems would be necessary, five additional Saturn V launches would be required. These additional Saturn V's could carry a total of 4,000 nuclear pulse systems. In the event of a launch failure, any of the remaining Saturn V's could be used as a spare, still leaving sufficient pulse systems for the IOC tests by orbital transfer of pulse systems to the vehicle selected for the IOC tests. Therefore, a total of fourteen Saturn V's would be required to set up and equip the orbital test program. However, depending on the allowed stay time of the test personnel in orbit, additional launches may be required for personnel exchanges at certain defined time intervals.

2.8. DEVELOPMENT MILESTONES

The development program is highlighted by several important events which are referred to as milestones. These milestones were indicated in Fig. 5. Three major milestones fall within Phase I, which spans the research up to the project definition phase (PDP):

Phase I

Milestone 1 is the initial test of a nuclear-driven propellant-pusher interaction and ablation.

Milestone 2 is the initial test of a nuclear pulse system.

Milestone 3 consists of two parts: (1) the initiation of full-scale shock-absorber tests (4-m tests) and (2) the initiation of full-scale pusher tests (10-m tests).

At the completion of Milestones 1, 2, and 3, the theories and analyses applied to the basic questions of system feasibility should be confirmed to the extent that sound technical decisions can be made concerning these areas in a PDP.

Phase II

Milestone 4 is the beginning of the 4-m repetitive pulse tests.

Milestone 5 is the start of the first 10-m integrated pusher—shock-absorber assemblies tests.

Milestone 6 is the start of the repetitive tests of a 10-m engine; this engine is complete with all auxiliary systems.

Phase III

Milestone 7 is the completion of the HE ground tests of the 10-m engine.

Milestone 8 is the start of ground qualification on the repetitive test facility of the ballistic flight engines.

Phase IV

Milestone 9 is the initiation of the ballistic flight tests.

Milestone 10 is the beginning of the orbital tests.

At the completion of the orbital tests, the engine design will have been proven and will have attained a state of initial operational capability (IOC).

CONCLUSIONS

Theoretical and experimental efforts over the past several years have produced practical modes of nuclear pulse operation whereby ORION vehicles can perform manned interplanetary missions. The same efforts have developed self-consistent engine designs which are technically feasible and appear economically practicable. In spite of the violent energy release of the fuel, the environments in which the engine components operate are mild in comparison with more conventional systems. For instance, (1) the operating temperature range of all parts of the engine structure is from zero to a few hundred degrees Fahrenheit and thus no cryogenic or high-temperature super-alloys are required; (2) the induced radiation levels are low enough that personnel can directly inspect test parts and engine operating structures; and (3) the mechanical loading can be controlled to the extent that currently available materials can be used.

The problems identified for solution in a development program appear sufficiently independent that a development plan using nonnuclear techniques on the ground for all but the last phase appears technically feasible. The final phase of the development plan utilizes space nuclear tests on ground-qualified engines. Manned engines operating from parking orbits can be tested much in the same fashion as ocean-going vessels, i.e., short runs (one or more nuclear explosions) to long complicated maneuvers can "shake down" the engines and train crews. The crews for such tests have the option of shut-down and direct inspection of all exposed engine parts.

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