BELLCOMM, INC.

SUBJECT: The Utilization of Lunar Refueling During Planetary Exploration Missions - Case 103-2

DATE: April 4, 1966

FROM: T. R. Kornreich

ABSTRACT

An evaluation of the potential of lunar refueling of planetary spacecraft is presented. While the nature and abundance of water deposits on the moon is highly controversial, it is hoped that several other lunar constituents will provide the hydrogen and oxygen needed for refueling. Possible chemical processes for manufacture of propellants from lunar resources are discussed.

Three modes of achieving a particular planetary mission are considered, i.e., direct flight from earth orbit, lunar orbit refueling (LOR), and lunar surface refueling (LSR). A lunar propellant production parameter (r) is introduced to provide a measure of determining the effectiveness of the manufacturing process. For specified mission ΔV, I_{sp}, and mass fraction, breakeven values of r are calculated for LOR and LSR compared to the direct mode. As the required mission velocity increases it is found that both LOR and LSR improve with respect to direct flight with the LSR approach making better progress. With a lunar based reusable tanker, LOR is better at all velocities; however, at higher velocities there is little difference between LOR and LSR.

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BELLCOMM, INC.

SUBJECT The Utilization of Lunar Refueling During Planetary Exploration Missions - Case 103-2

DATE April 6, 1966

FROM T. R. Kornreich

MEMORANDUM FOR FILE

Selenology and Lunar Propellant Manufacture

At present the nature and abundance of water deposits on the moon is highly controversial. If water is present in sufficient quantities, hydrogen and oxygen obtained via electrolytic processes can be used as chemical propellants or as reaction mass for nuclear rockets. In the absence of water, hydrogen and/or oxygen might be available from other minerals or volcanic gases.

Selenologists currently believe that there is a high probability that hydrated rock serpentine will be encountered on the moon. Water content of this rock is estimated to be 12 to 17 per cent by weight, thereby providing a good source of hydrogen and oxygen. Other deposits which conceivably will be encountered on the moon and which provide a source of hydrogen are metallic hydrides, hydroxides, hydrocarbons, and volcanic gases.

Even without water, oxygen could be readily available at almost any lunar base location by the employment of techniques such as the carbothermal process. The applicability of this process depends only on the presence of a large amount of silicate rock on the moon. Oxygen can be produced directly from this rock by the process outlined below.

Magnesium silicate is taken to typify lunar rock. The process can be described by the following set of chemical equations:

1. $MgSiO_3 + 2\,CH_4 \xrightarrow{1625^\circ} MgO + Si + 2\,CO + 4\,H_2$

2. $2\,CO + 6\,H_2 \xrightarrow{250^\circ C} 2\,CH_4 + 2\,H_2O$

3. $2\,H_2O \xrightarrow{75^\circ C} 2\,H_2 + O_2$

In the first step, the silicate is reduced to carbon monoxide, silicon, and slag by using methane as a reducing agent. In the second step, the carbon monoxide is reduced with hydrogen to form methane and water. The methane is recycled to step one and the water is electrolyzed in the final step, with oxygen being obtained as an end product and the hydrogen formed being recycled into the second step. Figure 1 represents a flow diagram of the process.

The only material consumed is the silicate rock. If water is present in any form in the raw material, it will also be obtained as a product.

Excellent product yields have been demonstrated on a laboratory scale. Research and development efforts are continuing on the use of lightweight cell materials in the electrolysis unit and operation of bench scale processing equipment for the carbothermal process. Reference 1 contains a more detailed description of the process.

Two types of water extraction processes have been discussed most frequently for use on the moon, i.e., processes using mined deposits and in situ processes. When large amounts of water are needed the latter type will be of prime importance since the water is extracted from the deposit in its original location thereby obviating the necessity for mining and/or transport of the deposit. (An example of an in situ process in terrestrial use is the Frasch process for the recovery of sulfur.)

It is anticipated that considerable study and analysis will be required before actual employment of an in situ process on the moon in order that technical problems involving drilling, emplacement of heat sources, sealing of formations to prevent undesirable fluid movement, possible formation capping to provide pressurization, etc., will be resolved. A detailed knowledge of the selenology is mandatory; therefore, a great deal of prospecting of the lunar surface will be necessary.

As formidable as these requirements appear, the utilization of surface processes would undoubtedly present more severe complications since extremely complex mining and transportation techniques would be needed.

Reference 2 presents a detailed description of the water extraction process, along with the broader aspects of water electrolysis equipment, hydrogen liquefaction, and long term storage of liquid hydrogen.

Selected Mission Modes for Achieving Planetary Missions

Three modes of achieving a particular planetary mission have been considered in the following analysis.

1. Direct Flight - The planetary spacecraft, including its entire propellant supply for maneuvers at the planet and the transplanetary propellant weight, is assembled in earth orbit and departs for the planet from that point.

2. Lunar Surface Refueling (LSR) - The inert portion of the planetary spacecraft and sufficient propellant to effect a lunar landing are mated in earth orbit. After lunar landing, the spacecraft is provided with sufficient propellant to perform its planetary maneuvers and the transplanetary propellant requirement.

3. Lunar Orbit Refueling (LOR) - The inert portion of the planetary spacecraft and sufficient propellant to achieve lunar orbit are mated in earth orbit. Upon arrival of the spacecraft in lunar orbit, a ferry vehicle is launched from the moon in order to provide the spacecraft with sufficient propellant to complete its mission. In the following evaluation two separate conditions will be taken to apply to the lunar ferry: first, the ferry completes one mission and becomes then completely expendable and second, the ferry is reusable and carries sufficient propellant upon its departure from the moon for its own return to the moon after fueling the spacecraft.

Mission Parameters and Basis of Comparison

The basis for comparison for these mission modes is taken to be the equivalent number of Saturn V launches to earth orbit required. One Saturn V vehicle is assumed to be capable of placing 250,000 pounds into a low-earth orbit.

The incremental velocity requirements to orbit the moon and land on the moon were taken to be comparable to those of the Apollo spacecraft and are enumerated below:

From Earth Orbit to Just Prior to
Lunar Orbit Attainment 10,000 fps

Braking into Lunar Orbit 3,900 fps

Direct Descent to Lunar Surface 8,800 fps

Typical planetary mission velocity requirements were assumed; i.e., 12,000, 14,000, and 18,000 fps, respectively, out of low earth orbit. Both chemical and nuclear propulsion systems were chosen with the following characteristics:

	Chemical	Nuclear
Specific Impulse, Sec.	460	900
Mass Fraction	0.90	0.75

A round-trip 60,000 pound payload was assumed for the manned planetary mission. This command module contains life support systems, power supplies, crew cabin, etc. An excursion module of 70,000 pounds weight was also selected but will not be returned to Earth. The resulting transit vehicle weighed 500,000 pounds and 250,000 pounds for the chemical and nuclear cases, respectively.

In order to assess the effectiveness of the lunar propellant manufacturing process, the lunar propellant production parameter is introduced and defined as:

$$r = \frac{\text{mass of useful propellant manufactured on moon}}{\text{mass of material carried from Earth for the process}}$$

Included in the material carried from the Earth are all necessary requirements for the chemical plant including hardware, installation, maintenance, and manpower. Naturally, all of this is presumed to have been delivered to the lunar surface well in advance of the time when propellant production is required for spacecraft fueling.

Engineering estimates of a typical value for r vary quite widely. In order to avoid being tied too closely to any specific value of r, mission cost will be evaluated as a function of r. The mission cost for the lunar refueling modes is stated as the number of Saturn V boosters required to place round-trip payload, unfueled excursion module, structure, and fuel tanks in lunar orbit (or on the lunar surface) plus the prorated amount to cover the operation of the lunar propellant manufacturing plant.

Comparison of Results

Using the aforementioned assumptions and ground rules, plots of r versus equivalent earth orbital weight are presented for the direct, LSR, and LOR modes in Figures 2 through 7. Some of the more significant results are tabulated below. In addition, Figure 8 depicts the variation of the breakeven value of r as a function of the ΔV requirement out of earth orbit.

Manned Planetary Mission	No. of S-IV Launches Direct Flight	LOR r for breakeven Chem. Direct E*	LOR r for breakeven Chem. Direct R**	LOR r for breakeven Nuclear Direct E*	LOR r for breakeven Nuclear Direct R**	LSR r for breakeven Chem. Direct	LSR r for breakeven Nuclear Direct
ΔV = 12,000 fps							
Chemical	5.2	--	10.7	--	110	48	--
Nuclear	1.8	--	1.2	--	6.8	0.70	12.5
ΔV = 14,000 fps							
Chemical	6.2	--	7.8	--	78	18	--
Nuclear	2.0	--	1.0	--	5.0	0.48	7.5
ΔV = 18,000 fps							
Chemical	9.2	--	5.8	--	60	6.3	--
Nuclear	2.6	1.5	0.75	--	4.0	0.34	4.0

* Lunar ferry assumed to be expendable

** Lunar ferry assumed to be reusable

-- Indicates that direct approach is always more economical than the applicable refueling mode.

For Example: Chemical LOR with reusable lunar-orbital refueling vehicles requires an r of 110 to be equivalent to a direct Nuclear-vehicle mission.

Another important consideration in examining the feasibility of the lunar refueling process is the determination of how much equivalent earth orbital weight is saved when the lunar propellant manufacturing plant operates at very high values of r. Indicated in Figures 2 through 7 are asymptotic values of equivalent earth orbital weight, i.e., those corresponding to r approaching infinity, for the LOR and LSR modes. It is seen that from the low energy missions very little actual weight saving is effected. Only when the ΔV out of earth orbit approaches the 16,000 to 18,000 ft/sec range does a marked weight saving arise.

Of course, all of these results presuppose a raw material supply on the moon for the manufacture of an unlimited quantity of hydrogen and oxygen. As an example of the supplies of raw material required for a single mission, about 220,000 pounds of hydrogen and 1,700,000 pounds of oxygen would be needed. Any circumstance which forces departure from this presumption will, of course, tend to portray LOR and LSR in a more unfavorable light than is shown here.

Conclusions

Providing that sufficient raw material is available on the lunar surface and that lunar propellant manufacturing processes are feasible, then:

1. Over the entire ΔV range considered, refueling in lunar orbit with a reusable ferry is superior to lunar surface refueling.

2. As the ΔV requirement increases, both lunar orbit refueling and lunar surface refueling significantly improve their standing with relatively greater improvement being shown by LSR. In fact, at ΔV = 18,000 fps, LSR and LOR are seen to be practically equal from an economy standpoint.

3. For a given ΔV requirement, the breakeven value of r is lower for nuclear rather than chemical, propulsion systems.

4. The use of a reusable ferry for the LOR mode (instead of an expendable one) is essential for economy of this mode. The expendable ferry is worse than direct flight with no lunar refueling.

TR Kornreich

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B. Campbell - NASA/MTL
P. E. Culbertson - NASA/MTL
F. P. Dixon - NASA/MTY
E. Z. Gray - NASA/MT
R. W. Gillespie - NASA/MTY
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2. Glaser, P. E., Wechsler, A. E., George, A. H. B., "Feasibility of Liquid Hydrogen Production on the Lunar Surface," Arthur D. Little, Inc.

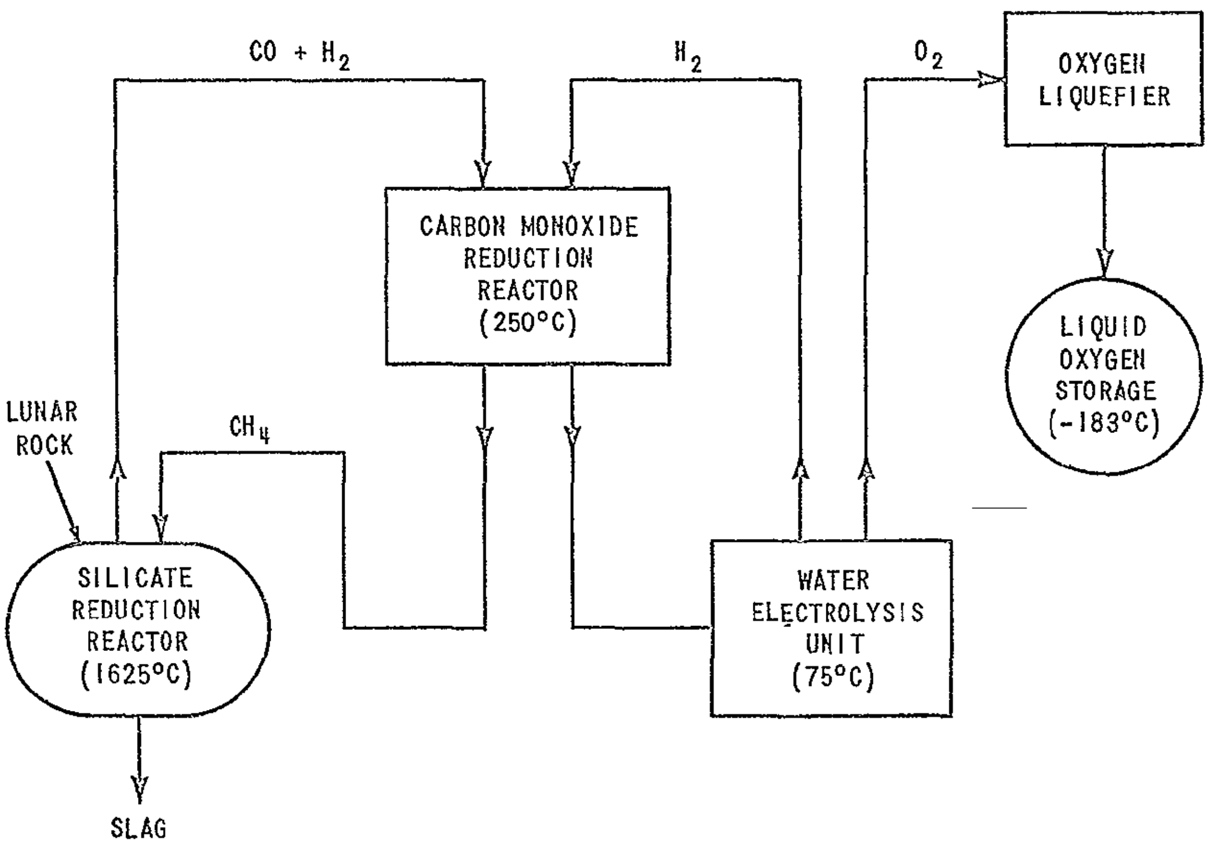

FIGURE I - FLOW DIAGRAM OF CARBOTHERMAL PROCESS

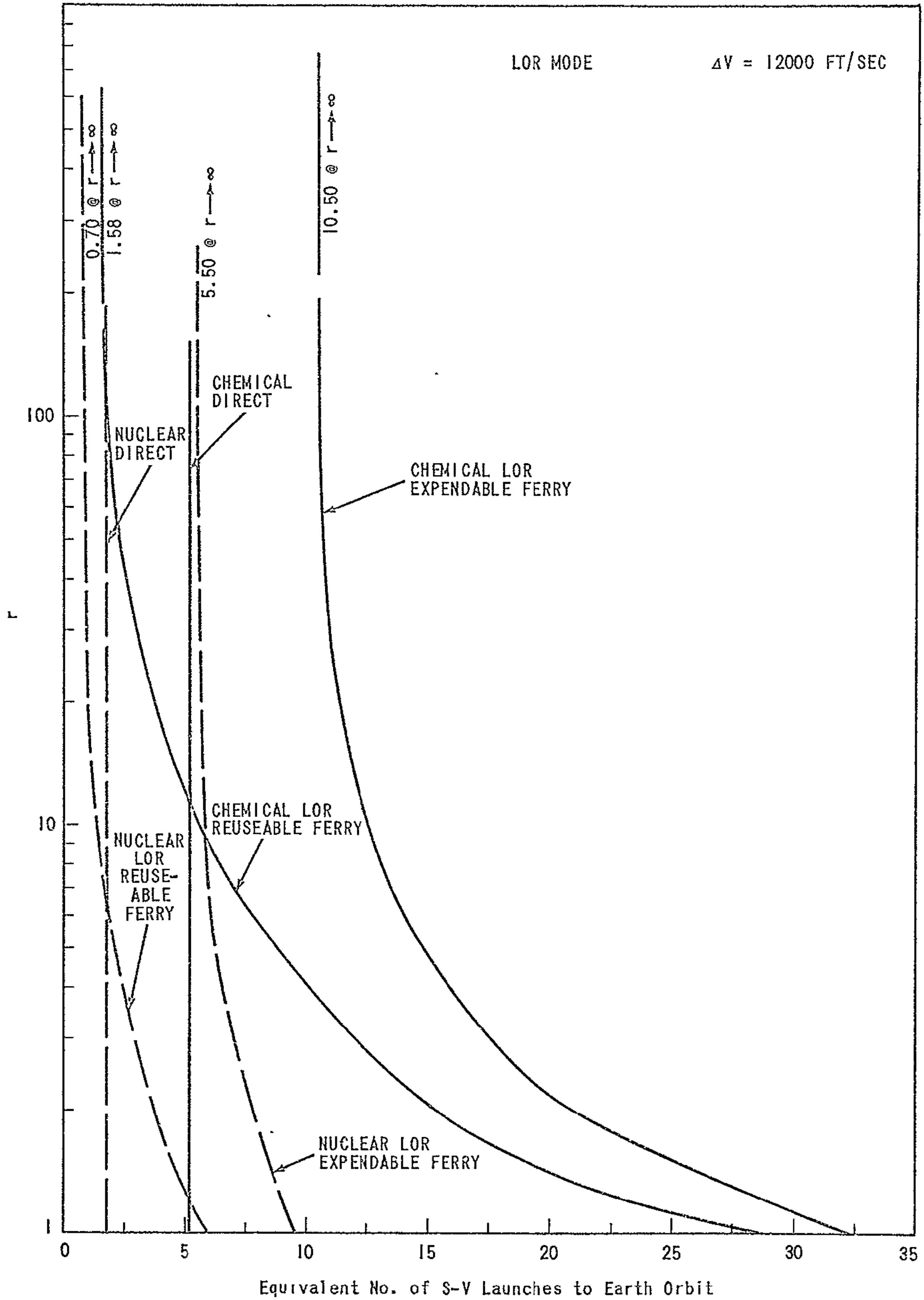

FIGURE 2 - r VS EQUIVALENT NO. OF SATURN V LAUNCHES TO EARTH ORBIT

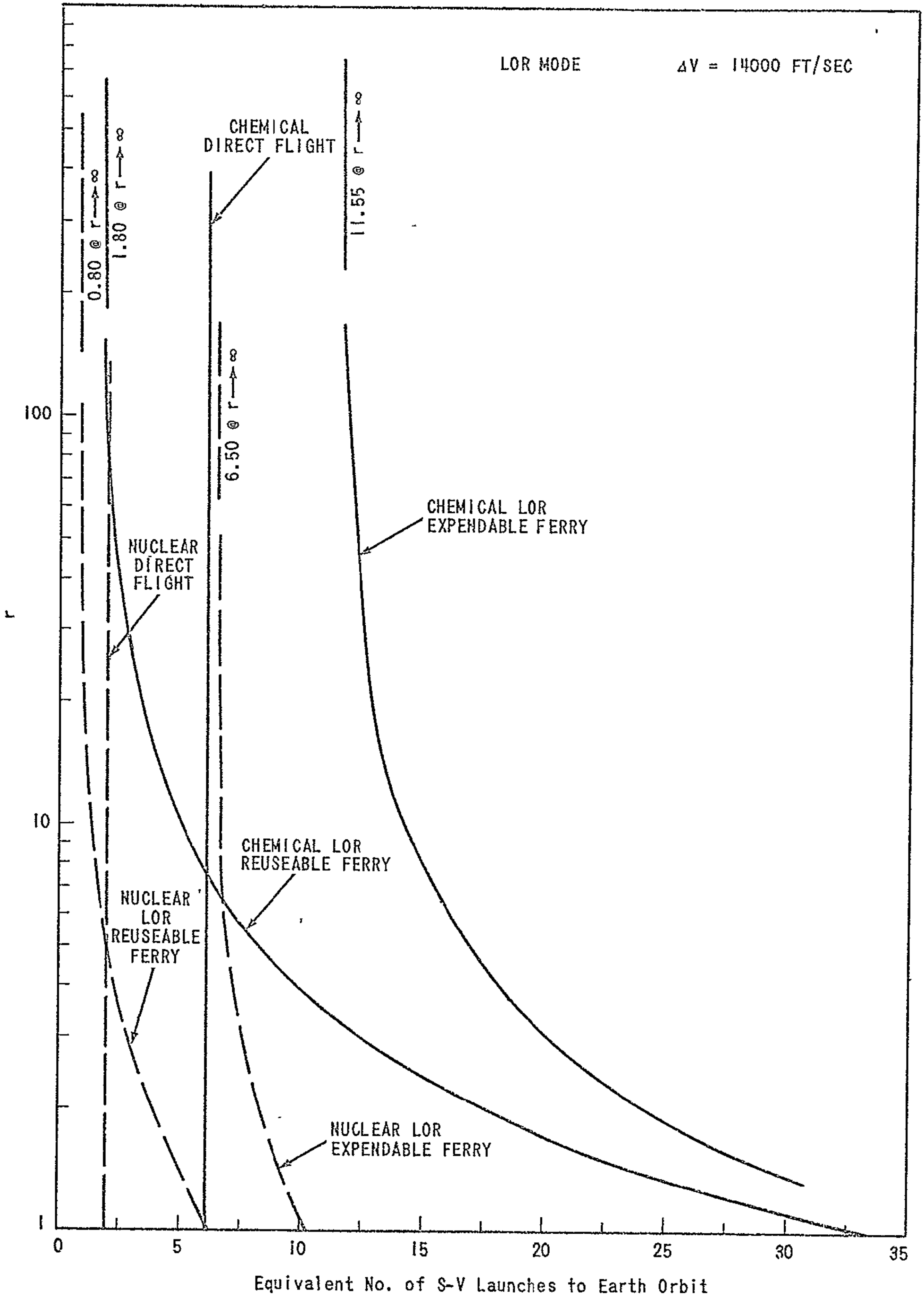

FIGURE 3 - r VS EQUIVALENT NO. OF SATURN V LAUNCHES TO EARTH ORBIT

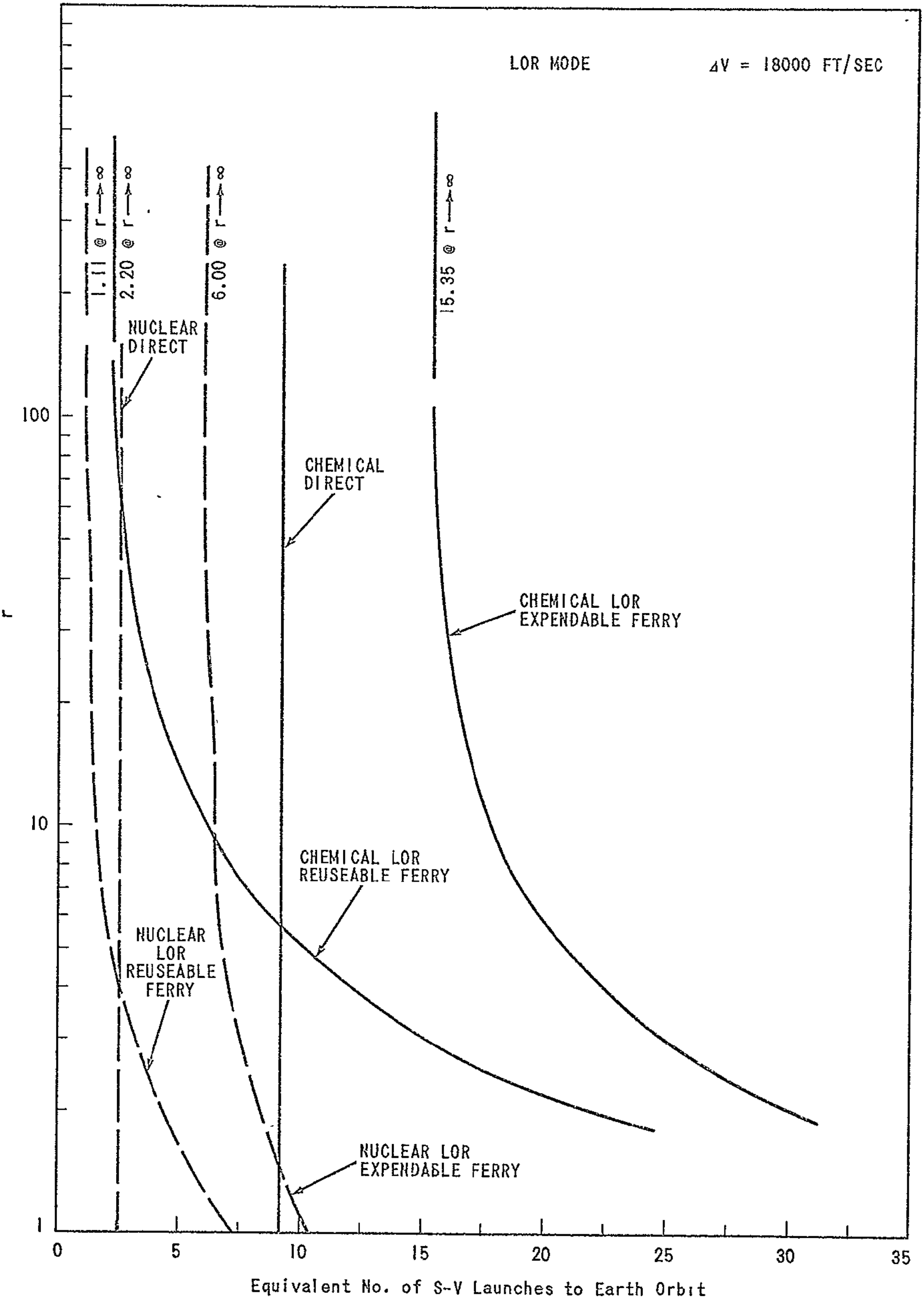

FIGURE 4 - r VS EQUIVALENT NO. OF SATURN V LAUNCHES TO EARTH ORBIT

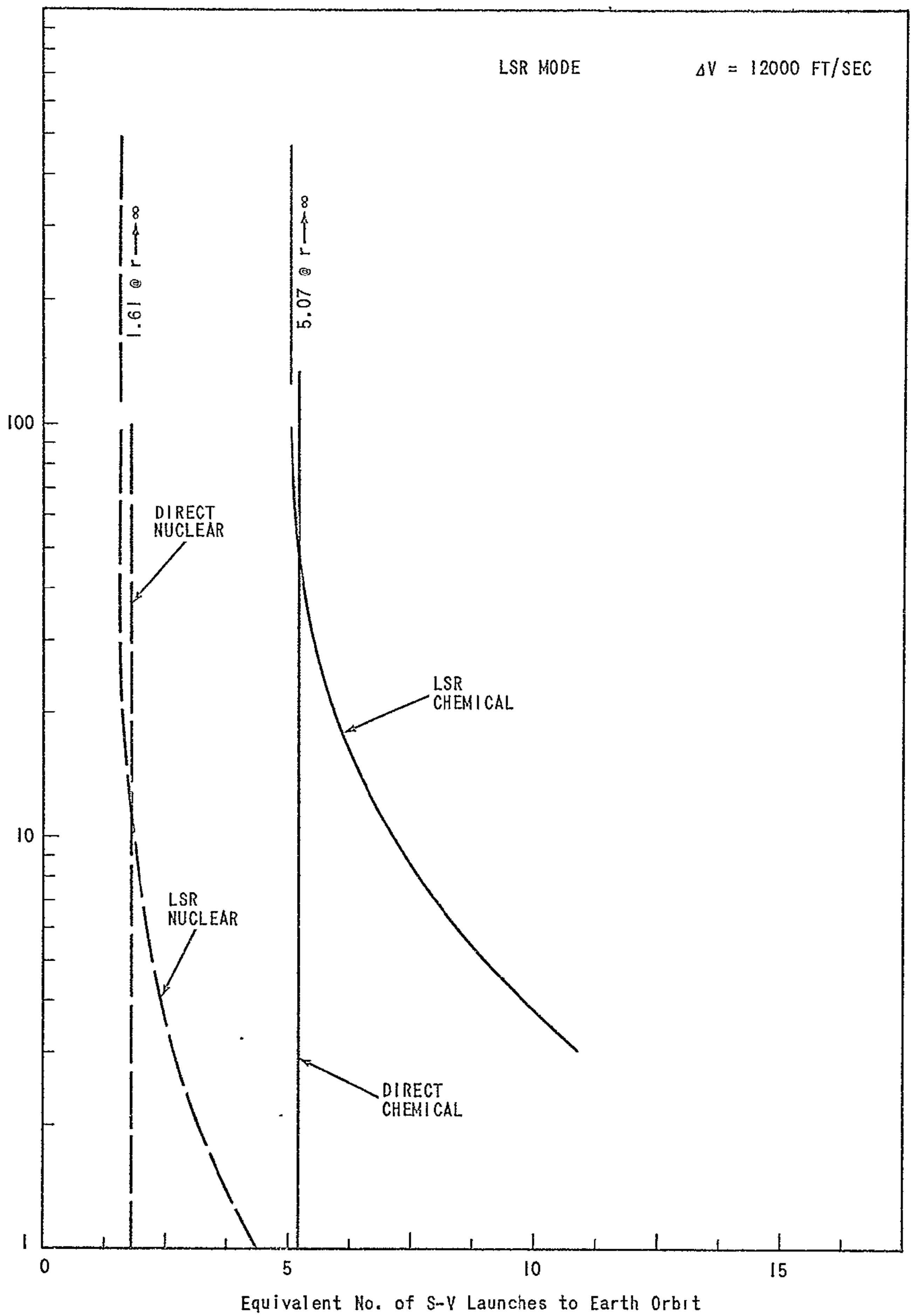

FIGURE 5 - r VS EQUIVALENT NO. OF SATURN V LAUNCHES TO EARTH ORBIT

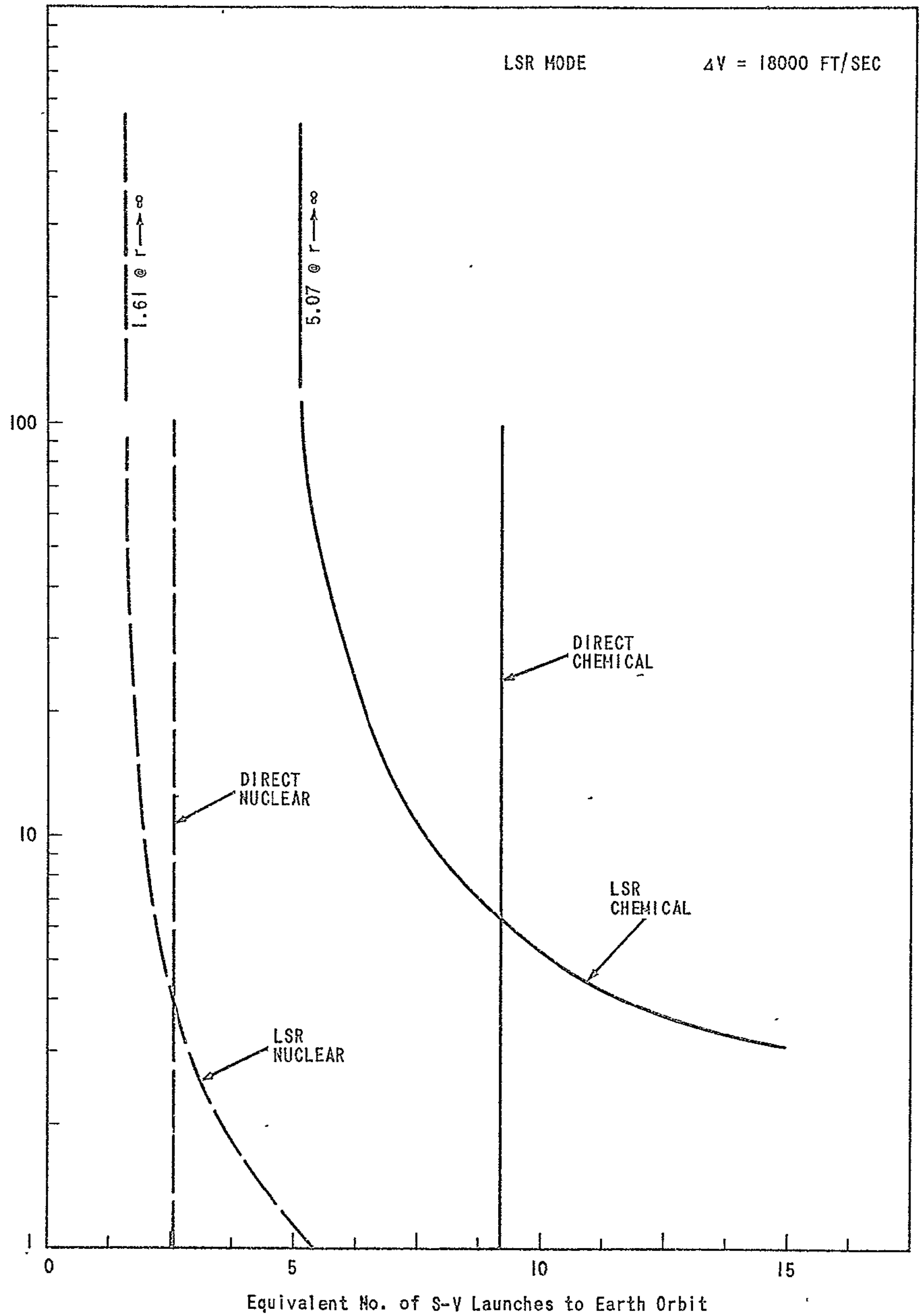

FIGURE 7 - r VS EQUIVALENT NO. OF SATURN V LAUNCHES TO EARTH ORBIT

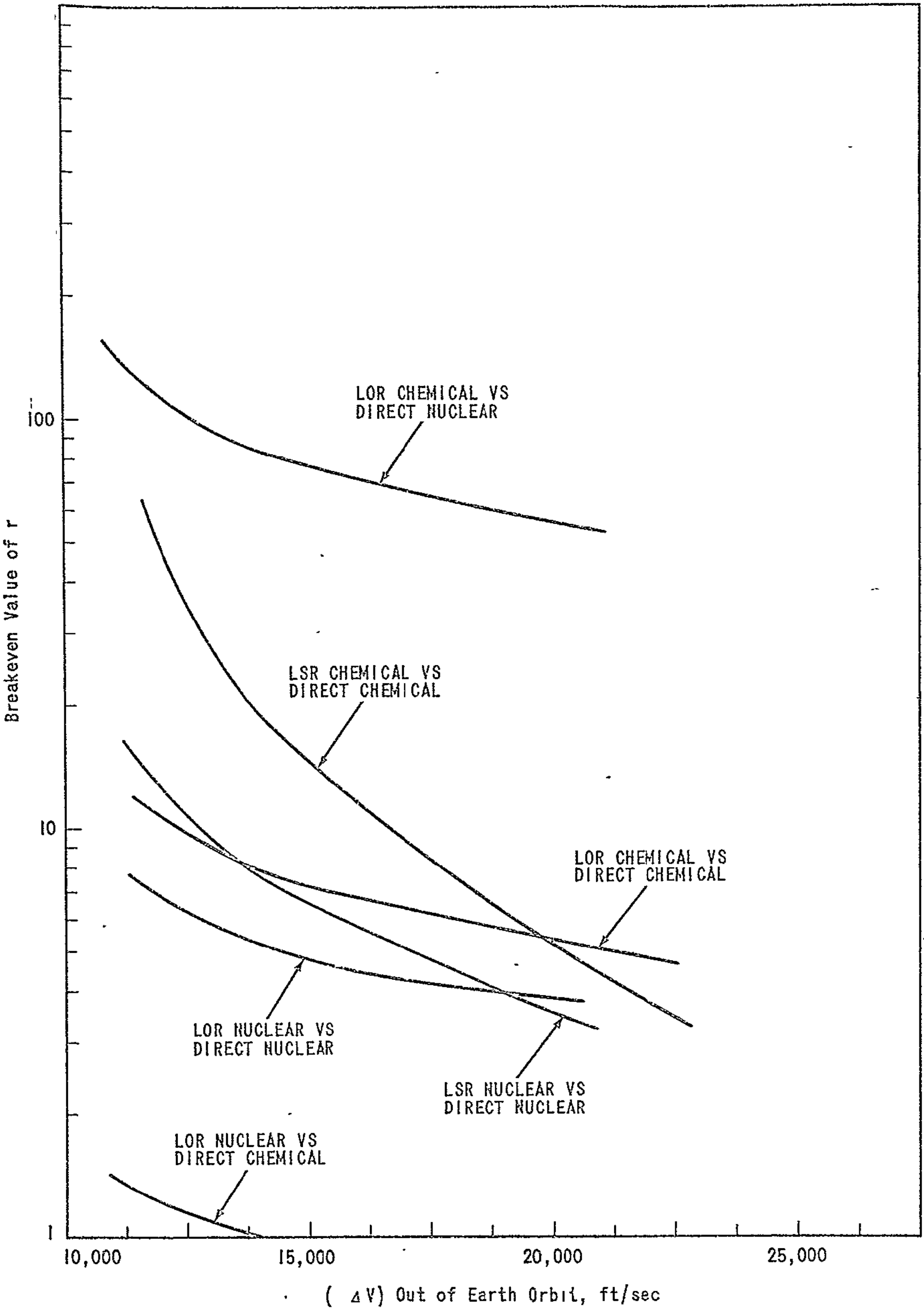

FIGURE 8 - BREAKEVEN VALUE OF r VS. (ΔV) OUT OF EARTH ORBIT FOR THE VARIOUS MODES