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# DISPOSAL METHODS

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I am going to discuss a number of disposal options for space nuclear reactors and the associated risks, mostly in the long term, based on probabilities of Earth reentry.

The results are based on a five year study that was conducted between 1978 and 1983 on the space disposal of high level nuclear waste. It was a study actually begun at Lewis Research Center and later transferred to Marshall. The study provided assessment of disposal options, stability of disposal or storage orbits, and assessment of the long term risks of that bad stuff coming back to Earth.

Just recently, we completed an application study of nuclear thermal rockets to the lunar outpost scenario. I suppose most of the mission results that you have heard about have to do with Mars, but we have looked at it in terms of the moon and have examined, as part of that overall study, the case of the disposal options. Therefore, I will try to configure the presentations so that it will treat both the moon and Mars because many of the options are quite similar as I will show you.

Just to put it in perspective, for the lunar NTR study we looked at various combinations of NTR (see Figure 1) starting with one burn, that is just using it for the translunar injection (TLI) and then doing everything else chemical and aero. We end with a complete four burn, where the nuclear thermal rocket was the only propulsion system starting from LEO and going back into LEO.

The disposal options you have available that might work best depend very much on how the nuclear reactor is going to be used in the mission scenario. If it were only going to be used for TLI in this case, or transMars injection (TMI), then you would have a different kind of a disposal option, probably, than if it were going to be used and brought all the way back to Earth orbit, perhaps reused for several missions, but eventually disposed of in some way.

So what we mean by a spent reactor then is a device that has been operated and is radiologically active at end of life (see Figure 2). Normally the end of life would occur after normal operations and the number of reuses that it has been designed for. But, of course, end of life could also occur from a disabling accident, in which case a disposal option may be required too.

Then the question is what to do with that spent reactor to eliminate or minimize the subsequent hazard of the radioactive material coming back to Earth: being released in the biosphere.

I have listed some ten factors of consideration. If there is a need for disposal at the end-of-life, it's a fairly complex problem and needs to be considered in terms of trades (see Figure 2)

Let's look at some of the disposal options (see Figure 3 and 4).

They start with some moderate altitude Earth orbits that would be stable for some period of time, to a high earth orbit, which I called super GEO, somewhat above normal operations in GEO. If it were used for a lunar mission it could be a lunar surface delivery, including impact, which is probably not desirable, or an actual soft landing and storage on the moon.

The libration points of the Earth-moon and Earth-sun system are a possibility for disposal. If you are going to Mars you could leave it in Mars orbit. There are also libration points in the Mars system. Or we could put it into an Earth elliptical orbit, which does have a long-term risk of reentry, which I will describe. You could put it into a solar orbit that is stable for very long periods of time, which could apply either to the moon or Mars missions. Or, you could send it out of the solar system altogether, but the Delta V to escape the solar system is so high it would have a serious impact on mission performance.

To give a flavor of the kind of work that was done for the lunar application, we examined all of the cases shown in Figure 3 an 4. We looked at the situation of a disposal from a particular orbit state to another orbit state. We then calculated the disposal Delta V that would be required at the end-of-life. We found it varies quite a bit.

The lowest Delta V disposal was lunar gravity assist as applied to the NTR 1-burn case. You could deflect the trajectory to the trailing edge of the moon, take a lunar swing by and inject into a heliocentric orbit. A possible disposal solution for the NTR 4-burn case is a 1000 km circular orbit about Earth for a Delta V cost of about 300 meters per second.

The highlighted disposal options are the ones we actually examined in detail. We made comparisons against the nominal mission performance, and tried to determine what the disposal actually cost in terms of mass penalty.

In the case of the full NTR burn for lunar applications we examined two options. One was to put it into a heliocentric Earth-crossing orbit after coming back to LEO at end-of-life, or raise that orbit to a thousand kilometer altitude Earth orbit.

Now I am going to talk about reentry risk (see Figure 5). For example, a propulsion system failure might occur during injection prior to actually escaping the Earth. If we start in an orbit that has a high eccentricity with crossing of the lunar orbit distance, then you would have a mean reentry lifetime of 200 to 700 years. Lunar collision would occur with a much smaller lifetime, on the order of 50 years.

A VOICE: Are you talking about reentry into earth or an encounter with the moon?

MR. FRIEDLANDER: This combines both types of events. In other words, this was not a disposal orbit but an orbit that resulted from some kind of a failure that had a perigee close to Earth and crossed the lunar orbit. Subsequently, this "stay body" would either reenter Earth's atmosphere, collide with the Moon, or be ejected from the Earth-Moon system.

Now, what I want to talk about are some disposal options, including the stable solar orbit, the heliocentric planet-crossing orbit, and then the moderate-altitude Earth orbit.

Figure 6 is a plot of heliocentric planetary distances. It shows the maximum and minimum extent of Earth, Mars and Venus. It turns out there are two stable zones not too far from Earth. One of them is between Earth and Mars, 1.17 to 1.19 AU circular orbit. The other is between Earth and Venus. If you can get it into that circular orbit it's going to stay there for a very long period of time - at least a million years.

To give you an example of what happens to that orbit, Figure 7 is a time history over a million years of an orbit which was initially at 0.86 AU circular, between Earth and Venus. It doesn't stay circular at all because of the mutual perturbation of the planets and Earth. You can see the Venus aphelion and the Earth perihelion changing quite a bit with time.

But, though it doesn't stay circular, the disposal orbit is stable to at least a million years and probably much longer. That is to say, it does not become a planet-crossing orbit.

In fact, this was the nominal disposal destination selected for space nuclear waste after consideration of all the possibilities.

Now let's look at a situation of an Earth-crossing orbit where the orbit starts out initially with a perihelion of .85 AU and a aphelion at 1, so it left Earth on the way toward a stable circular orbit. But let's suppose that the circularization burn at .85 failed and we are left in an Earth-crossing orbit.

Figure 8 shows the results of the Monte Carlo statistical analysis. Initially the orbit only crosses the Earth orbit, but because of the gravitational effects over the long term, it actually begins to cross all the planets out to Jupiter and could be eliminated by collision in various ways or by solar system ejection caused by Jupiter gravity perturbations.

In 54 percent of the cases it will eventually come back to Earth reentry. However, the mean time for that to occur is 26 million years, which is a rather long time. There is also a substantial probability of Venus collision, and once the object begins to cross Jupiter, at least ten percent of the time it will be ejected from the solar system altogether.

But the dominant event is an Earth collision and what is shown here is probability as a function of time for the various collision events.

So, for example, even though the mean lifetime greater than over 20 million years, at one million years the probability of Earth collision is 17 percent.

Figure 9 shows those results along with the sensitivity to orbit perihelion distance and inclination. For each of these cases the mean time to reentry is quite long, but there is a finite and not insignificant probability of Earth reentry occurring over shorter time periods.

A VOICE: Right now we are looking at an Earth reentry time of a "nuclear safe orbit" of 300 years. You are several orders of magnitude beyond that even in your worst case.

MR. FRIEDLANDER: That's quite true. This would be a very favorable result unless some particular design and analysis of the fission products showed that you really needed to provide nuclear safety for many, many thousands of years.

A VOICE: That's going to be a function of the safety groups to determine what is the minimum time we can have for reentry of any nuclear system in Earth orbit.

What I am trying to show is that, in the long term, we are talking about probabilities which might be quite acceptable. In fact, from my point of view, an Earth-crossing orbit is a fairly acceptable disposal place.

MR. FRIEDLANDER: You can get about a three and a half fold reduction in collision if you went ten degrees out of the elliptic plane. However, it's very costly to get ten degrees out of the elliptic plane.

If you are talking about disposal, you really want to put is someplace and be done with it. You don't want to be monitoring it for thousands of years.

A VOICE: I might want to reuse the materials.

MR. FRIEDLANDER: You might. In fact that was one of the considerations when it came to looking at space disposal of high level nuclear waste. Some people said they might want to use it in ten thousand years, so some people wanted to put it into Earth orbit. But that high level waste is bad stuff compared to a reactor.

Let's talk about the disposal in a moderate altitude Earth orbit. Consider a lunar or

Mars application that has been used for four burns and comes back to LEO. At that point, the easiest thing to do is add a very small Delta V is raise it up in altitude. Figure 10 shows the orbit lifetime against atmospheric drag and reentry.

If you place it at a thousand kilometers this would give you a lifetime against Earth reentry of 24 hundred years.

So if the safety time requirements are on the order of a few thousand years, you could put it into a moderate altitude circular orbit about Earth.

Figure 11 shows results from a recent paper by Chobotov and Wolfe in the Journal of Astronomical Sciences, January- March of this year. It's probably the latest update of a summary of the meteoroid and debris flux impact per year per square meter as a function of particle diameter.

This is the natural or man-made environment that an object put into a moderate altitude disposal orbit would face.

If you have a collision with a meteorite it's at about 20 kilometers per second impact speed. A collision with space debris tends to be around ten kilometer per second impact speed.

Even though the debris flux is low, it's getting worse and worse, and some people talk about trying to sweep some of that debris out. But, there is debris out there which could certainly do damage.

In future work, I would think that we might want to do a preliminary trade study of the disposal options for Mars applications to get a handle on what the impact on the nominal mission performance would be.

There are also short-time reentry risks. These would come about as a result of failure or accident environments. In this case, quantitative information about risk could not come out of the long-term statistical analysis that I have described. A different type of analysis would have to be performed.

Both short-term and long-term risks were examined in the previous studies of space disposal of nuclear waste. We looked at the reentry probability and the radioactive element inventory as a function of time. This was quite important for nuclear waste. I am not sure how important it is for the reactor operation but it is something that might need to be done. Eventually one would want to do an overall risk benefit assessment of disposal options.

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## NTR CONCEPT OPTIONS

SPECIFIC APPLICATION OF NTR CONTROLS THE TRADE SPACE: 4 CASES

| | Propulsion Application | | | | | |
|---|---|---|---|---|---|---|
| "Handle" | Trans Lunar Inject | Lunar Orbit Capture | Trans Earth Inject | Earth Return Capture | LTV/NTR Separation | Application |
| 1-BURN | NTR | CHEM | (CHEM) | (AERO) | After TLI | · NTR to CHEM Transition<br>· Easy disposal |
| 2-BURN | NTR | NTR | (CHEM) | (AERO) | Post-Capture at Moon | · Expendable LTV<br>· One-way Cargo<br>· Low-Risk NTR Use |
| 3-BURN | NTR | NTR | NTR | AERO | After TEI | · Reduce Risk to Crew on Return |
| 4-BURN | NTR | NTR | NTR | NTR | After Earth Orbit Capture | · All-Nuclear LTV |

( ) = ONLY IF THE MISSION IS A ROUND TRIP

NOTE: "Handle" refers only to number of major LTV burns this mission

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Figure 1

END-OF-LIFE DISPOSAL OF SPACE NUCLEAR REACTORS

- DEFINITION OF SPENT REACTOR

  DEVICE HAS BEEN OPERATED AND IS RADIOLOGICALLY ACTIVE AT END-OF-LIFE WHICH OCCURS EITHER AT TERMINATION OF NORMAL OPERATION OR AS A RESULT OF A DISABLING ACCIDENT EVENT

- QUESTION OF FOCUS

  WHAT TO DO WITH SPENT REACTOR TO ELIMINATE OR MINIMIZE SUBSEQUENT HAZARD OF RADIOACTIVE MATERIAL RELEASE TO BIOSPHERE?

- FACTORS OF CONSIDERATION

  1. DISPOSAL DESTINATION
  2. PROPULSION SYSTEM REQUIREMENTS AND COST
  3. OPERATIONAL COMPLEXITY, RELIABILITY AND COST
  4. FAILURE MODES AND ACCIDENT ENVIRONMENTS
  5. PAYLOAD RESPONSE TO ENVIRONMENT
  6. ORBIT EVOLUTION CONSEQUENCES OF FAILED ORBITS
  7. PAYLOAD MONITORING
  8. RETRIEVABILITY/RESCUE MISSION CAPABILITY
  9. REENTRY PROBABILITY - SHORT VS LONG TERM
  10. RADIOACTIVE RELEASE RISK TO BIOSPHERE



Figure 2

## NTR DISPOSAL OPTIONS

| DISPOSAL FROM | DISPOSAL TO | ΔV (m/s) | COMMENTS |
|---|---|---|---|
| Post-TLI Separation Trajectory (1 Burn) | Lunar Gravity Assist (LGA) to Heliocentric Earth-crossing orbit | 30 | · C3 = 2 [illegible]<br>· Mean lifetime to reentry [illegible] dependent on [illegible] |
| " | LGA to E-M L1 Halo | 580 | · Must control for long-term orbit stability |
| " | LGA to E-M L2 Halo | 330 | " |
| " | LGAs to E-Sun L1 Halo | 54 | " |
| Post-TLI (1 Burn) or Post-TEI (3 Burn) trajectory | Perigee kick to final heliocentric orbit | 194 | · Orbit at 1x1.15 or 0.88x1 AU<br>· Reentry risk = f(rp,a) I=2 deg |
| " | Capture to h=1,000 km (1 Burn - free return) | 2955<br>155 | · Capture incl. 20 m/s nav.<br>· Circularize at h = 1,000 km |
| " | Raise orbit altitude to "Super-GEO" | 710<br>1456 | · Capture incl. 20 m/s nav.<br>· Circularize at h = 36,287 km |
| " | Solar circular orbit at .85 or 1.19 AU, I=2 deg | 200<br>1250 | · Orbit stability > 1,000,000 yrs<br>[illegible] |
| " | Solar system escape | 5678 | · $C_3$ = 152 |

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Figure 3

## NTR DISPOSAL OPTIONS (CONTINUED)

| DISPOSAL FROM | DISPOSAL TO | ΔV (m/s) | COMMENTS |
|---|---|---|---|
| 300 km circular lunar orbit (2 Burn) | Lunar surface delivery | 2000 | · 2-burn program for controlled landing on lunar surface |
| " | E-M L1 halo orbit<br>E-M L2 halo orbit<br>E-Sun L1 halo | 1150<br>775<br>850 | · 2-burn sequences |
| Full NTR Propulsion (4 Burn) | Heliocentric Earth-crossing orbit | 3287 | · Orbit is 1x1.15 or 0.88x1 AU<br>I = 2 deg; 3200 m/s w/LGA |
| " | Solar circular orbit at .85 or 1.19 AU; I=2 deg | 3300<br>1250 | · 2 burns to circularize |
| " | Capture to h=1,000 km | 313 | · Earth orbit |
| " | Raise orbit altitude to "Super-GEO" | 3859 | · 2 burns and 20 m/s nav.<br>h = 36,287 km |
| " | Solar system escape | 8751 | · C3 = 152 |
| " | Refurbish for Use on Robotic Mission | varies | · SEI Mars Robot Explorer<br>· Outer Solar System Mission |

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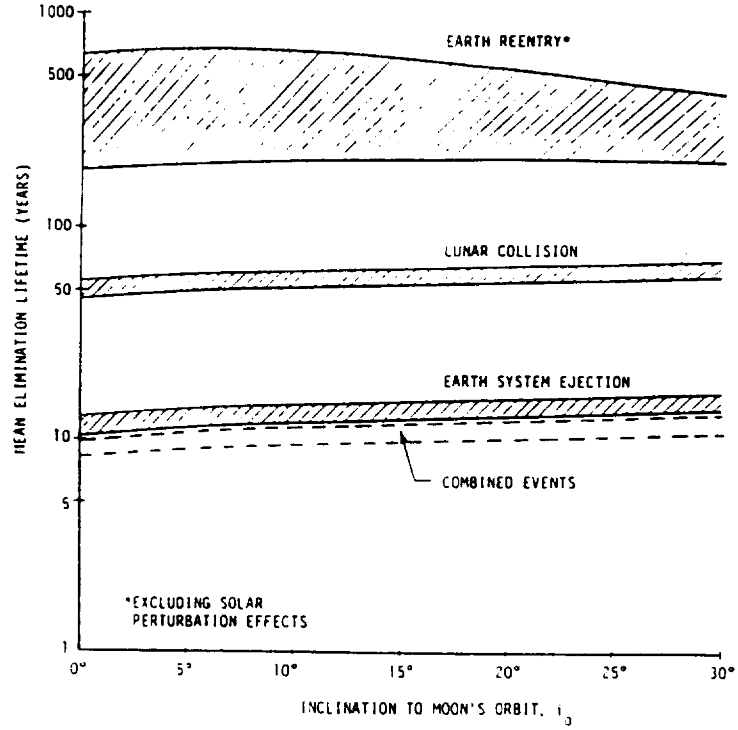
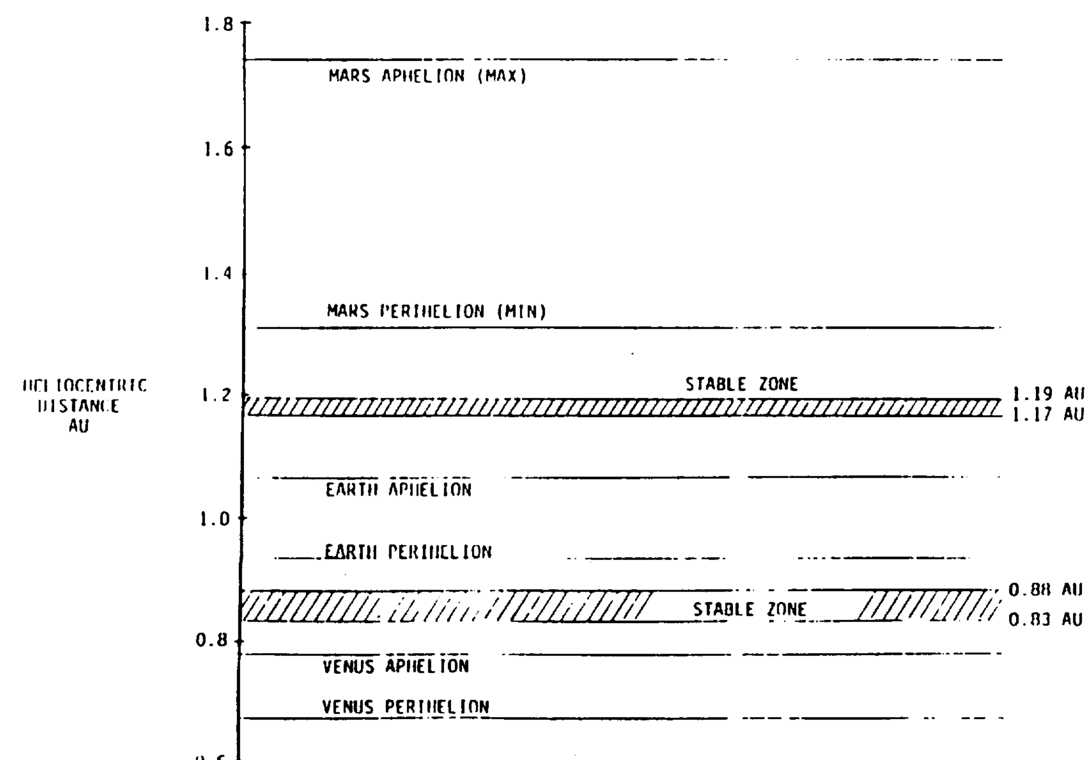
Figure 4




PROBABILISTIC EFFECT OF LUNAR ENCOUNTERS ON ELIMINATION
OF STRAY BODY IN LUNAR CROSSING ORBIT (OPIK'S THEORY)

$e_0 = 0.965$; $1.02 \leq Q_0 \leq 1.10$ LUNAR DISTANCE

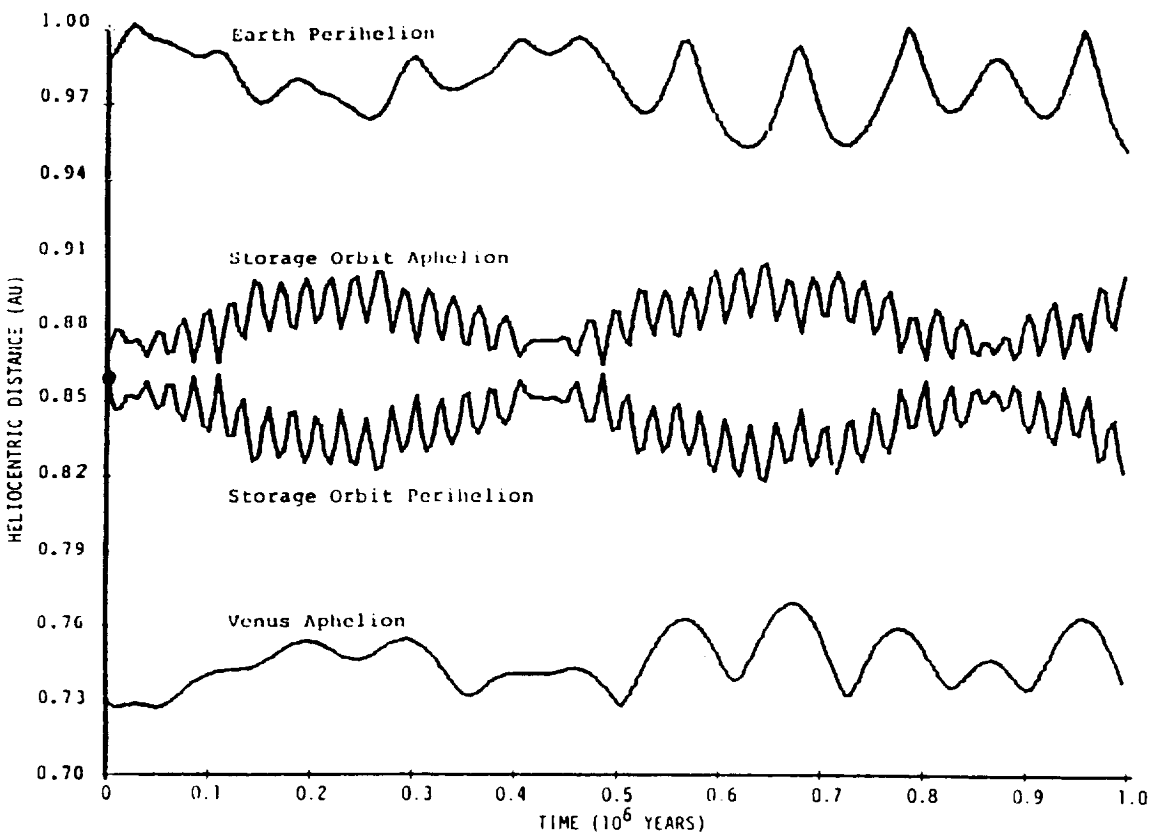
**Figure 5**






STABILITY BOUNDS OF INITIALLY CIRCULAR ORBITS BETWEEN THE PLANETS

**Figure 6**




ORBITAL VARIATIONS OF AN INITIALLY CIRCULAR ORBIT AT a = 0.86 AU

**Figure 7**

## PLANETARY ENCOUNTER PROBABILITY ANALYSIS – COMPUTER PRINTOUT

MONTE-CARLO STATISTICAL SUMMARY

NUMBER OF CASES = 500
MEAN LIFETIME = .438E+08 YEARS

| EVENT | | NUMBER | FREQUENCY | MEAN TIME | MEAN U |
|---|---|---|---|---|---|
| COLLISION WITH PLANET | | | | | |
| | MERCUR | 9 | 0.0180 | .536E+08 | 0.507 |
| | VENUS | 162 | 0.3240 | .310E+08 | 0.264 |
| | EARTH | 270 | 0.5400 | .263E+08 | 0.189 ($V_e$ = 12.6 km/sec) |
| | MARS | 8 | 0.0160 | .578E+09 | 0.325 |
| | JUPITE | 1 | 0.0020 | .524E+08 | 0.619 |
| | SATURN | 0 | 0.0000 | .000E+00 | 0.647 |
| | URANUS | 0 | 0.0000 | .000E+00 | 0.000 |
| | NEPTUN | 0 | 0.0000 | .000E+00 | 0.000 |
| | PLUTO | 0 | 0.0000 | .000E+00 | 0.000 |
| 0 SOLAR IMPACT | | 0 | 0.0000 | .000E+00 | |
| SOLAR SYSTEM EJECTION | | 50 | 0.1000 | .925E+08 | |

0 MEAN ELEMENTS AT ELIMINATION
A= 2.041 E= 0.279 I= 7.65

0

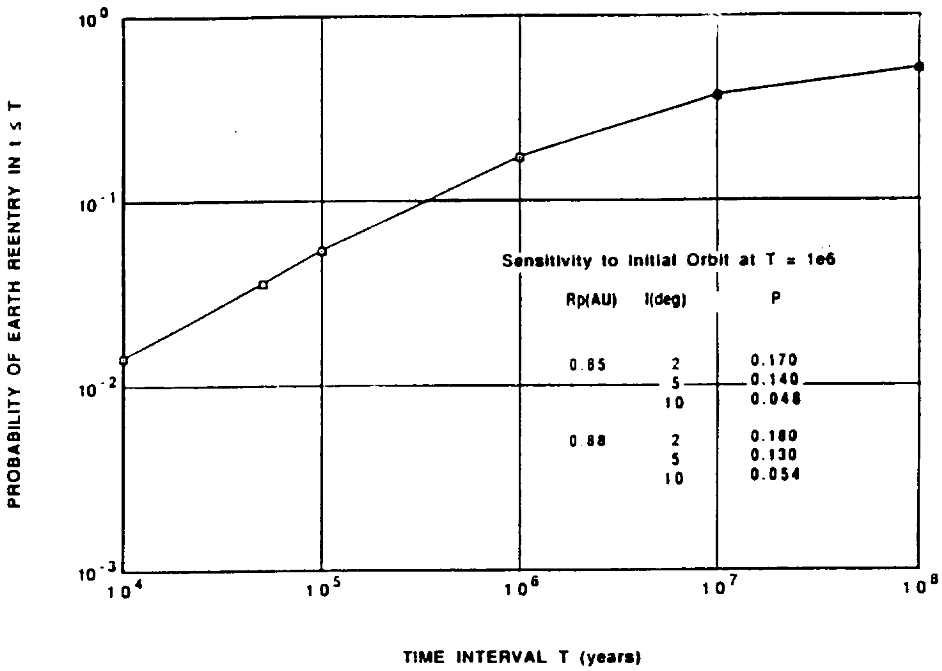
INITIAL ORBIT CONDITIONS TIME= 0.00
PERIHELION(AU) = 0.850 APHELION(AU) = 1.000
INCLINATION(DEG) = 2.000 PERIOD(YRS) = 0.890

OEVENT PROBABILITIES

| OFOR TIME INTERVAL = | 0.10E+05 | 0.50E+05 | 0.10E+06 | 0.10E+07 | 0.10E+08 | 0.10E+09 |
|---|---|---|---|---|---|---|
| COLLISION WITH PLANET | | | | | | |
| MERCUR | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.20E-02 | 0.16E-01 |
| VENUS | 0.00E+00 | 0.20E-02 | 0.20E-02 | 0.30E-01 | 0.17E+00 | 0.31E+00 |
| EARTH | 0.14E-01 | 0.36E-01 | 0.54E-01 | 0.17E+00 | 0.37E+00 | 0.31E+00 |
| MARS | 0.00E+00 | 0.0 | .00E+00 | 0.00E+00 | 0.20E-02 | 0.40E-02 |
| JUPITE | 0.00E+00 | 0 | .00E+00 | 0.00E+00 | 0.00E+00 | 0.20E-02 |



**Figure 8**




Long-Term Probability of Earth Reentry
Initial Orbit: 0.85 x 1.0 AU, I = 2 deg

Figure 9

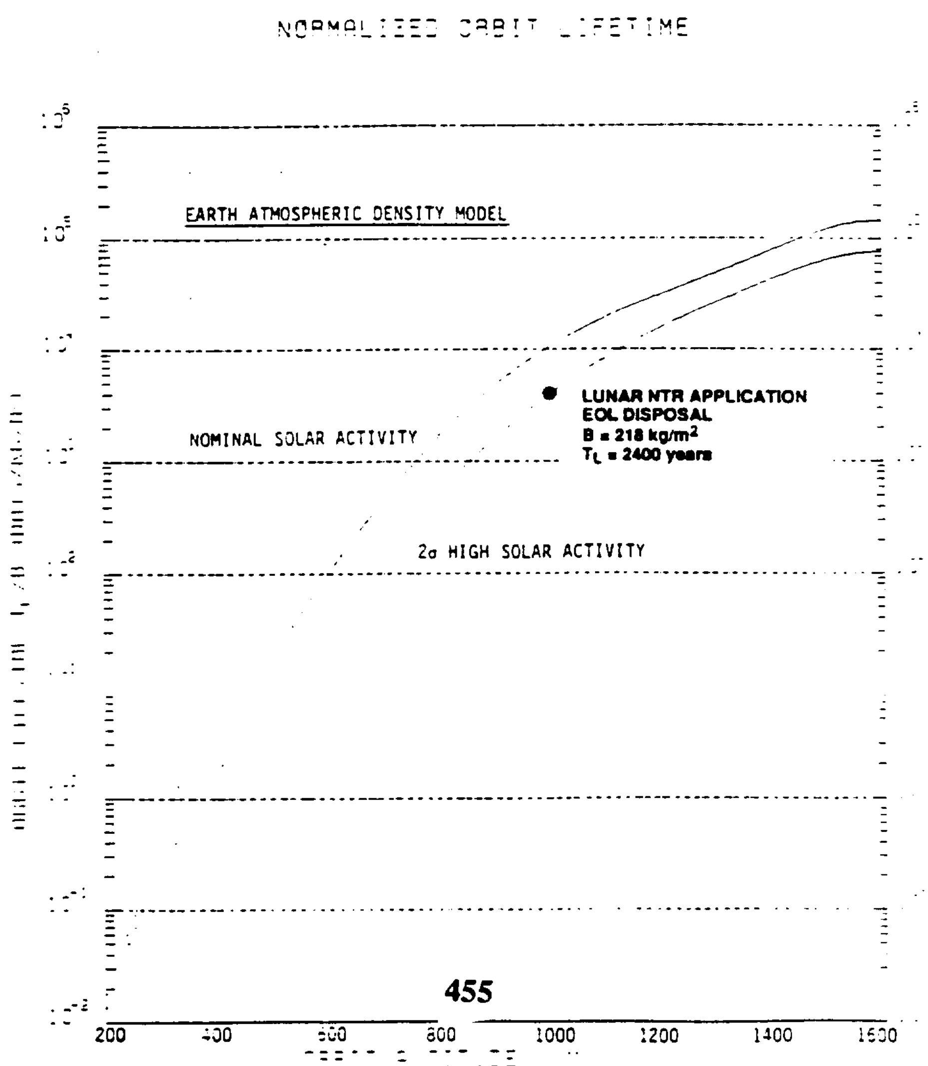



Figure 10

fragmentation events is the migration of the fragments as a function of time, resulting in a larger volume of debris through which threatened satellites may have to pass. For instance, the fragmentation of an object in a 60 deg inclination orbit produces a torus of orbits at 60 deg inclination. With time, the orbits of the fragments remain at 60 deg inclination but cross the equator at random points. The fragmentation cloud effects are therefore expected to be of great significance to the permanent manned occupation of low Earth orbit as well as to the safe use of the remainder of near-Earth space.

The total mass of man-made debris in orbit is currently on the order of three million kilograms at altitudes below 2000 km. This compares with about 200 kg of meteoroid mass in particles of about 0.1 mm diameter. Man-made debris is much larger, however, ranging from millimeters to meters. Also, the relative velocity at encounter is on the order of 10 km/s for space debris, compared to 20 km/s for meteoroids. Primary sources of man-made debris were more than 100 United States and Soviet spacecraft explosions in orbit, possible collisions among debris objects, and the erosion of spacecraft surfaces due to oxygen, ultraviolet, and thermal radiation effects. Solid rocket motor firing also contributes to particles in the 0.0001-to-0.01-mm range [3].

In addition to the above sources of man-made debris, there have been numerous intentional breakups of spacecraft in orbit. Among these were a number of Soviet antisatellite tests at low altitudes, and United States intercepts of spacecraft in orbit, such as the breakup of the Solar Wind satellite in 1985 and a Delta-180 stage in 1986.

On November 13, 1986, an Ariane third stage exploded into more than 460 trackable objects 10 cm in diameter and larger. This suggests the presence of several thousand or more small particles that cannot be tracked by ground-based radars. Recent orbital debris measurements are summarized in Fig. 3 [3].

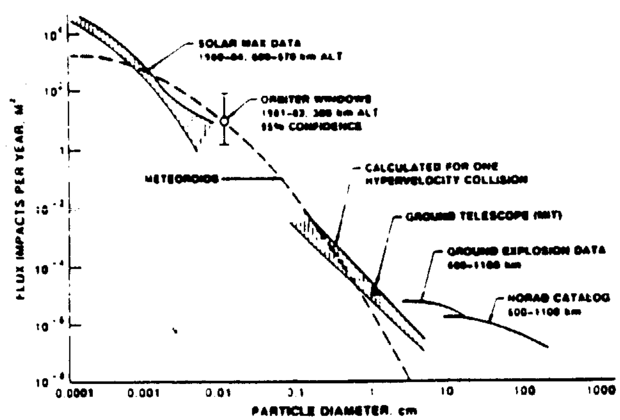



FIG. 3. Recent Orbital Debris Measurements Compared to Meteoroid Flux

Figure 11