COMPARISON
DIRECT THRUST NUCLEAR ENGINE, NUCLEAR ELECTRIC ENGINE,
AND A CHEMICAL ENGINE FOR FUTURE SPACE MISSIONS

INTRODUCTION

The need for an advanced direct thrust nuclear rocket propulsion engine has
been identified in Project Forecast 2, the Air Force Systems Command report
which looks into future Air Force needs. The Air Force Astronautical
Laboratory (AFAL) has been assigned responsibility for developing the
nuclear engine and they in turn have requested support from teams of
contractors who have the full capability to assist in the development of
the nuclear engine. The Idaho National Engineering Laboratory (INEL) has
formed a team of experts with Martin Marietta for mission analysis, Science
Applications International (SAIC) for flight safety analysis, Westinghouse
for the nuclear subsystem, and Rocketdyne for the engine system. INEL is
the overall program manager and manager for test facility design,
construction and operation.

The INEL team has produced program plans for both the engine system and the
ground test facility. AFAL has funded the INEL team to perform mission
analyses to evaluate the cost, performance and operational advantages for a
nuclear rocket engine in performing Air Force Space Missions. For those
studies, the Advanced Nuclear Rocket Engine (ANRE), a scaled down NERVA
derivative, was used as the baseline nuclear engine to compare against
chemical engines and nuclear electric engines for performance of orbital
transfer and maneuvering missions.

Table 1 provides some general operational characteristics for the three
engine technologies (chemical, nuclear, electric) that were compared.

SUMMARY

A general life cycle cost (LCC) comparison of the three types of propulsion
systems for performing orbital transfer and maneuvering missions at various
levels of mission activity is shown on Table 2. The bottom three sets of
costs in the table correspond to an intermediate level of mission activity
from the Space Transportation Architecture Studies (STAS).

Comparing LCCs for the direct thrust nuclear and nuclear electric
propulsion stages (first and last columns) there is not any significant
cost advantage for electric over nuclear propulsion. Considering that the
long transfer time of the nuclear electric stage would obviate its use for
some, if not many, missions, if a single stage is to be developed, the
choice is reduced to a competition between the nuclear and chemical

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**TABLE 1. OPERATIONAL CHARACTERISTICS OF THREE ENGINE TECHNOLOGIES**

**CHEMICAL**

- Low Specific Impulse
- High Thrust to Weight
- Bi Propellant
- Lunar Based Oxygen Generation Alternative
- Compatible With Aerobrakes
- Impulsive Transfers
- Flight Times
  - LEO-GEO <1 day
  - LEO-Lunar Base ~3 days
  - LEO-Mars Base ~200 days

**DIRECT THRUST NUCLEAR**

- Medium Specific Impulse
- Medium Thrust To Weight
- Mono Propellant
- Earth Based Propellant (LH2)
- Compatible With Aerobrakes (Controversial)
- Impulsive Transfers
- Flight Times
  - LEO-GEO <1 day
  - LEO-Lunar Base ~3 days
  - LEO-Mars Base ~200 Days

**NUCLEAR ELECTRIC**

- High Specific Impulse
- Low Thrust To Weight
- Mono Propellant
- Earth Based Propellant (Ar)
- No Aerobrake
- Spiral Transfers
- Flight Times
  - LEO-GEO >50 days
  - LEO-Lunar Base >300 days
  - LEO-Mars Base ~2 years

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TABLE 2. LIFE CYCLE COST COMPARISONS

<table>
<thead>
<tr>
<th>Number of Missions</th>
<th>Direct Thrust Nuclear</th>
<th>Chemical</th>
<th>Nuclear Electric</th>
</tr>
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<tbody>
<tr>
<td>20</td>
<td>2.72</td>
<td>1.98</td>
<td>2.85</td>
</tr>
<tr>
<td>100</td>
<td>4.97</td>
<td>5.36</td>
<td>5.04</td>
</tr>
<tr>
<td>500</td>
<td>15.9</td>
<td>22.0</td>
<td>15.7</td>
</tr>
<tr>
<td>1000</td>
<td>29.4</td>
<td>42.6</td>
<td>28.8</td>
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<td>1542</td>
<td>43.8</td>
<td>64.8</td>
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</tr>
<tr>
<td>2972</td>
<td>81.8</td>
<td>123.2</td>
<td>79.8</td>
</tr>
<tr>
<td>3669</td>
<td>100.2</td>
<td>151.6</td>
<td>97.7</td>
</tr>
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</table>

engines. If the number of missions is small, e.g. less than 70, the chemical engine LCC is less than that of the nuclear engine and, barring any operational demands for which the nuclear engine is uniquely qualified, there is no incentive for undertaking development of a nuclear engine and stage. The situation changes as the number of missions increases and for the numbers of missions represented by the intermediate level of activity from the STAS studies. The potential savings indicated for the nuclear stage are very large, up to 50 billion dollars. These savings accumulate from both DOD and NASA missions and emphasize the need to consider all space activity in developing the most cost effective space transportation system.

Additional studies were conducted to compare the three types of propulsion systems in general categories of mission. The results are shown on Table 3. For the LEO-GEO transfer the nuclear electric system has a clear advantage in propellant consumption and a clear disadvantage in the time required to perform the orbit transfer. The direct thrust nuclear engine consumes about half the propellant of a chemical engine and accomplishes the mission in about the same time. For this application the chemical engine is the least desirable option and the selection between direct thrust nuclear and nuclear electric depends on the value of time. There are some missions which require a fast transit time and if only one system is to be developed, direct thrust nuclear is the best choice.

The propellant requirements for the three options for lunar base support indicate that both the direct thrust nuclear and nuclear electric vehicles would have a large operational cost advantage over a chemical stage because of the latter's large propellant requirements. The long transfer time of the electric OTV provides no incentive to select it and thus the direct thrust nuclear OTV/lunar descent/ascent vehicle combination is the preferred choice.

For the Mars base support there are more options to consider, but the direct thrust nuclear engine is again indicated as the preferred choice. Considering the large propellant requirements of the chemical taxi and the long transfer time of the nuclear electric propulsion vehicle, they do not provide reasonable choices over the direct thrust nuclear engine.
CONCLUSIONS

At a low level of space activity, <70 missions, chemical engines are the most cost effective means to perform necessary orbit transfer and maneuvering missions. These consume more propellant, but they require the least costly development to meet mission requirements. As the level of space activity increases, the direct thrust nuclear engine and the nuclear electric engines become more cost effective, their lower level of propellant consumption overriding the higher development costs. As the level of activity increases to that defined at the intermediate level in the STAS studies, the LCC for the direct thrust nuclear and nuclear electric engines remains fairly close.

The nuclear electric propulsion system has a much higher specific impulse than the direct thrust nuclear system, but in low earth orbit it has a high propellant consumption because it uses a circular orbit which has high gravity losses. When used in missions which require a landing in a high gravity environment the electric engine cannot perform the mission and it must carry an auxiliary propulsion system for the descent and ascent.

For the mix of missions defined in the STAS studies, these factors tend to offset each other, resulting in life cycle costs which are fairly close between the two types of nuclear propulsion systems. The direct thrust nuclear system always has a time advantage over nuclear electric and it can perform all missions, whereas the nuclear electric is not a "stand alone" system; it must have support in some missions.

A major development program is not required to produce an operational direct thrust nuclear rocket system. The following summarizes the reasons for this conclusion:

- Development work for the NERVA type engine was completed in the sixties.
- Documentation has been retained by Westinghouse and capabilities exist to rapidly begin fabrication and testing of engine components.
- No major breakthroughs are required for design or fabrication of the engine system.
- Facilities exist for verification of fuel technology but a new facility will be required for engine system testing.
- The NERVA engine has demonstrated a wide range operating capability which will permit it to perform all missions initiating from low earth orbits.
- Design of the flight qualification engine had initiated when the program was cancelled.

It is concluded the direct thrust nuclear rocket engine should be the priority Air Force development system for orbital maneuvering and transfer missions.
<table>
<thead>
<tr>
<th>Mission/Stages</th>
<th>One-Way Transfer Time (Days)</th>
<th>Propellant Required (lbs.)</th>
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<tbody>
<tr>
<td><strong>LEO-GEO</strong></td>
<td></td>
<td></td>
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<tr>
<td>Direct Thrust Nuclear</td>
<td>1</td>
<td>25,394</td>
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<tr>
<td>Chemical</td>
<td>1</td>
<td>53,000</td>
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<tr>
<td>Nuclear Electric</td>
<td>58</td>
<td>3,310</td>
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<td><strong>LUNAR BASE SUPPORT</strong></td>
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<tr>
<td>Direct Thrust Nuclear OTV (w/o aerobrake)/Nuclear LDAV</td>
<td>3</td>
<td>92,670</td>
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<tr>
<td>Chemical OTV (w/o aerobrake)/Chemical LDAV</td>
<td>3</td>
<td>243,800</td>
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<td>Nuclear Electric OTV (w/o aerobrake)/Chemical LDAV</td>
<td>&gt;300</td>
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<td><strong>MARS BASE SUPPORT</strong></td>
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<tr>
<td>Direct Thrust Nuclear Taxi (w aerobrake)/Nuclear MDAV</td>
<td>200</td>
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<td>Nuclear Electric Taxi (w/o aerobrake)/Chemical MDAV</td>
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<td><strong>CASTLE/Cycling Orbits</strong></td>
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<td>428,000</td>
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<tr>
<td>Direct Thrust Nuclear Taxi (w aerobrake)/Chemical MDAV</td>
<td>&lt;200?</td>
<td>619,000</td>
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