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T1D/SNA--1625

NUCLEAR HEATING EFFECTS IN
PROPELLANT IN CLUSTERED
PAIRS OF NUCLEAR STAGES

Prepared under Contract NAS 3-9500

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X-5784 (4014)

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FOREWORD

The studies reported herein were prepared by Lockheed Missiles & Space Company for the George C. Marshall Space Flight Center, Huntsville, Alabama under Task 5.2, Contract NAS 8-9500. This volume contains data on nuclear heating effects in the propellant in clustered pairs of nuclear stages.

SUMMARY

Preliminary analyses have been performed to determine the effect of nuclear heating in the LH_2 propellant on boil-off weight and resulting payload decrement; and propellant temperature rise in pairs of clustered nuclear stages. Two nuclear stage configurations were studied; propellant tank capacities of 180,000 pounds and 340,000 with 2000 and 5000 mw engines, respectively.

The study showed that differences in nuclear heating of the propellant between single and clustered stages does not impose large payload decrements for either size engine. Payload differences of 1000 lb and 1600 lb were found for the 2000 mw and 5000 mw engines, respectively.

Recommended future work includes extending this preliminary study to permit proper recognition of the thermal behavior of the propellant during the boost and early orbit phases of flight; conducting more thorough studies of clusters of three, four, and five stages for a wider range of engine power levels and shield weights; modification of the LMSC Propellant Flow Model to accommodate the anisotropic nuclear heat generation characteristics of clustered stages; and conduct of simple tests to confirm the predicted behavior of liquids when heated in an anisotropic thermal environment.

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I INTRODUCTION

The purpose of these analyses was to make a preliminary determination of the effect of nuclear heating on the LH_2 propellant temperature and boiloff for selected pairs of clustered nuclear stages. The study was initiated as an addition to LMSC Contract NAS 8-9500, Task 5.2 in response to direction received from MSFC in June 1964. It is part of a combined effort by MSFC and LMSC to identify technological problems associated with the clustering of nuclear stages for advanced space missions.

The major elements of nuclear stage inert weight are the engine, propellant tank insulation, and propellant tank structure. In this study engine weight and insulation weight were taken as fixed for each set of reactor configurations. During the design studies on the RIFT vehicle it was found that minimum stage inert weight was obtained when the propellant tank structure weight was lowest. This led to tank design conditions dictated by both the flight bending loads and by pressure head loads encountered during the boost phase of flight. The same criteria were applied in the present study to define the weight of the propellant tank structure. Since the propellant tank design conditions are governed by the boost phase environment, the tank must be vented during the orbital coast phase of flight to insure that ullage pressures do not exceed design allowables. Propellant boiloff results. A thorough discussion of the relationships between each major weight element and stage inert weight and the basis for the tank design criteria appear in Ref. 1.

In the present study the QAD code was applied to define energy deposition in the propellant and the LMSC Stratified Propellant Flow Model was applied to predict resulting propellant temperature rise. The flow model is based upon isotropic heating sources within the propellant such as encountered using a single nuclear engine. Since the anistoropic heating is experienced where clustered configurations are used, the Model was applied so as to bracket a maximum and a minimum temperature rise.

II ANALYSIS

A. Programs Description

The principal computer programs utilized to determine the nuclear radiation heating in the propellant of clustered nuclear rocket stages were the "QAD-NM" code developed by the Los Alamos Scientific Laboratory, an LMSC data conversion program, and the LMSC "Stratified Propellant Flow Model."

The QAD-NM is a general purpose shielding code of the point kernel type, that can be directly applied to almost any combination of source and attenuation-region geometries. The code calculates neutron and gamma flux or dose rates at each "receiver point" in the system being analyzed. The program input includes spatial distribution of the neutron moments method used to approximate the change in neutron spectrum as a function of shield penetration distance.

The basic procedure followed in the code is to mock up the entire region of interest into zones, or volumes, whose boundaries are planes or conic sections having appropriate equations in the coordinate system used. The equation identifies the shape of the boundary and its location relative to the origin of the coordinate system. The program permits the source geometry to be expressed in cartesian, cylindrical, or spherical coordinates.

At each (input) receiver point, the program sums the dose contributions from all source volumes. Each point source value is attenuated along a straight-line path from the source-coordinate point to receiver. The straight-line attenuation is corrected to account for scattering. All material zones along the path are accounted for, and checks are provided in the attenuation calculations to detect errors in the geometry specification.

For these analyses, the QAD output provides heating rates in the propellant of a given stage at specified detector point in BTU/SEC-FT³. These points must first be separated into bulk heating and boundary layer heating data points, and the heating values from the nuclear sources of each of two adjacent stages added to obtain the total heating at the detector points in the stage of interest. Three cases were considered; propellant tank of interest with its axial source below, right side (far side) of propellant tank with source on the adjacent stage axis, and left side (near side) of propellant tank with source on the adjacent stage (see fig. 1).

The bulk heating (q_b) data was radially area averaged for each horizontal plane considered in the stratification code according to the relationship:

$$q_b = \int_0^{A_{\max}} \frac{(q_n + q_p + q_c) dA}{A_{\max}}$$

Additionally, the decay factor (b) in the equation:

$$q_{BL} = q_o e^{-by}$$

Where

- q_n = primary neutron heating (BTU/ft³ sec)
- q_p = primary gamma heating (BTU/ft³ sec)
- q_c = capture gamma heating (BTU/ft³ sec)
- q_{BL} = boundary layer heating (BTU/ft³ sec)
- q_o = boundary layer heating at tank wall (BTU/ft³ sec)
- b = decay factor determined from boundary layer heating data.

The necessary conversion of the preceding data for use in the stratified propellant flow model was performed by a new auxiliary program

established specifically for this study. (This program will be further refined in order to be integrated into the QAD-NM to facilitate data handling time and effort. This will provide a unique capability of providing, directly as an output, the nuclear heating data input cards to the stratified propellant flow model.)

The "Stratified Propellant Flow Model" is a mathematical model depicting the complex fluid-dynamic and thermodynamic behavior of a heated liquid in a tank that is subjected to transient heating and dynamic forces. A turbulent natural-convection boundary-layer flows upward along the inside of the heated vessel walls, and this layer transports additional liquid to the free surface. At the liquid-ullage interface, both mass transfer and energy transfer can take place. Additionally, liquid draining from the tank can be represented, while the liquid is subjected to either (or both) side wall or nuclear heating. If nuclear heating leads to a density inversion in the liquid, the flow model resolves this unstable state by the mechanism of turbulent mixing of the affected bulk liquid. Discrete geometric volumes and time-steps are taken and mass/energy balances are performed along with mass transfer and heat transfer calculations. The region where the natural convection boundary layer starts is determined at each time-step in the program. In addition, integration of the differential equations describing boundary-layer development is performed over the wetted portion of the tank for each time step. Finally, the program prints out the temperature, mass, and position of each layer, thus providing tabular data for the mapping of the propellant temperature history.

B. Cluster of Two 2000 MW Stages

1. Configuration Description

A sketch of the general configuration that was studied is shown in figure 1. The propellant tank capacity at start of nuclear burn was 180,000 lb for each stage. The nuclear rocket engines were of a nominal

2000 MW size based on an uprated NERVA I, with a pump inlet flow rate of 125 lb/sec for each engine.

2. Nuclear Energy Deposition Rates

Heating rates in $\text{BTU}/\text{Ft}^3 \text{ sec}$ were calculated with the QAD code utilizing source terms from report AGC 2492. (Ref. 2). The contributions considered were from primary neutrons, primary gammas, and secondary gammas generated by capture in the core upper support plate and the lower section of the shield. Curves of "area averaged" bulk heating and boundary layer heating at the tank wall are shown in figures 2 and 3 respectively. It should be noted that the crossover of the bulk heating curves for the two clustered cases is due to the shadowing effect of the adjacent tank. This would also be true for the boundary layer curves if the heating was calculated higher in the tank (see fig. 8, 5000 MW case).

3. Propellant Heating

The nuclear heat generation data cited above was applied to the Flow Model as input in conjunction with the effective steady-state heat flux value of $0.01 \text{ BTU}/\text{hr ft}^2$ due to space heating in orbit. As a result the temperature data presented herein incorporates the influences of both space and nuclear heating.

Previous propellant heating studies (Ref. 1) conducted by Lockheed for the RIFT vehicle indicated that space heating influenced the propellant temperature rise more than either the "direct" nuclear heating within the propellant or the "indirect" nuclear heating due to gamma absorption within the propellant tank structure. This conclusion was in part based upon the use of state-of-the-art insulation namely, a foam insulation affixed internal to the propellant tank wall. In the present study an external multilayer insulation one-inch thick was taken as the thermal protection system for each propellant tank. This type of insulation will probably be available for use on operational space vehicles by the early

1970's. The change in type and placement of the insulation affected the relative influence of space and nuclear heating on temperature rise.

The high thermal resistance to heat flow across the multilayer insulation reduces space heating by a factor of about 1000 as compared with the presently available foams. With external insulation, however, nuclear heat generated in the tank structure can be transferred directly to the propellant with essentially no losses. It was found that the general level of heat flow to the propellant from the wall is similar regardless of the insulation type, but the source of the energy differs. Essentially all of the heat transferred from the wall to the propellant during nuclear engine operation is due to nuclear heating when the multilayer insulation is applied.

Figure 4 presents the predicted propellant temperature rise at locations close to the free surface as a function of engine operating time. The temperature at the free surface of the propellant is taken as being equivalent to the saturated temperature corresponding to the imposed ullage pressure (assumed fixed during engine operation). The anisotropy of the nuclear heat generation experienced by the clustered tanks required two computer runs using the Flow Model to bound the resulting temperature rise. The "near side" curve represents a worst case or upper bound on temperature rise since the highest nuclear heat generation rates in the boundary layer and in bulk liquid were used. The "far side" curve provides the lower bound. The lower curve labeled "direct only" applies to the case of a single tank with a single engine placed below. Taking the arithmetic mean temperature rise of the upper and lower bounds, a 3.2°R rise is obtained for the cluster. This compares with a 2.6°R rise predicted for the single stage configuration. A 20% increase is indicated for the cluster of two stages.

Figure 5 shows the vapor pressure versus engine operating time for the upper bound condition. The curves shown represent propellant vapor pressures at the engine pump inlet and near the free surface. Note that the pump inlet curve is consistently higher. This condition is encountered when nuclear heating in the tank bottom region predominates over heating

through the tank walls (due either to space or nuclear sources). Side-wall heating promotes stratification and nuclear heating in the tank bottom promotes mixing of the bulk liquid.

Propellant Boiloff

As cited earlier in this report the propellant tank must be vented while in orbit to insure that the maximum tank design pressures are not exceeded. The method applied to determine the amount of boiloff is one which requires the pressure loads on the base of the tank cylindrical section during nuclear engine operation be equivalent to those encountered during the boost phase of flight. Since the maximum ullage pressure, vent pressure and boiloff are related, the maximum ullage pressure is found first. Then the vent pressure in orbit is selected and the boiloff determined by appropriate energy balance. In general, the following equation defines the vent pressure:

$$P_{\text{VENT}} = P_{\text{MAX ULLAGE}} - \Delta P_{\text{NPSP}} - \Delta P_{\text{VAPOR DURING ENGINE OPERATION}}$$

It was found that in order to provide equivalent pressure loadings on the tank bottom and on the cylinder during both the boost phase and during the nuclear engine operating conditions the maximum ullage pressure should not exceed 26 psia during the latter time period. The NPSP of the engine pump was taken as 4 psia. The maximum vapor pressure of the propellant entering the pump therefore is 22 psia. Using these criteria as the basic input the boiloff was computed for a range of temperature rises typical of those encountered during nuclear engine operation.

The boiloff weight vs. temperature rise is plotted in Fig. 6. Since nuclear heat is the only source contributing to the temperature rise, the boiloff weight shown can be considered as the weight penalty charged to nuclear engine operation.* In deriving the curve of Fig. 6 it was

* The complete description of boiloff requires detailed investigation of the ascent phase thermal environment. In the present brief study the effect of this variable has not been investigated.

tacitly assumed that space heating was sufficiently high during the boost and early orbital phases of flight to insure that the vapor pressure of the bulk propellant exceeded 22 psia ($t_{\text{sat}} = 37^{\circ}\text{R}$). The curve shows that the difference in boiloff weight between the cluster and the single engine is approximately 1700 lb. Note that this is not payload decrement. The effective inert weight or payload decrement for a pound of propellant vented in orbit is about 0.6 lb. This means that for every pound vented in orbit only 0.6 lb is payload. Hence, the payload decrement in this case is 1000 lb. If venting is accomplished earlier in the flight, such as during the S-II firing, a 0.4 factor is valid. This would make the payload decrement due to nuclear heating attributable to the clustered configuration using a 2000 MW engine approximately 700 lb.

C. Cluster of Two 5000 MW Stages

1. Configuration

The general configuration is similar to the 2000 MW case, and is shown in Fig. 1. The propellant tank capacity at start of nuclear burn was 340,000 lb for each stage. The nuclear rocket engines were of a nominal 5000 MW size based on AGC preliminary NERVA II design, with a pump inlet flow rate of 288 lb/sec per engine.

2. Nuclear Energy Deposition Rates

Heating rates in $\text{BTU/ft}^3 \text{ sec}$ were calculated with the QAD code utilizing source terms based on AGC preliminary data. The contributions considered were from primary neutrons and from primary and some engine secondary gammas. The secondary gammas generated by capture in the core upper support plate and the lower section of the shield were not available. Curves of "area averaged" bulk heating and boundary layer heating at the tank wall are shown in Figs. 7 and 8, respectively. The cross over noted in Section II. B. 2 is more prominent for this case.

An additional QAD run was performed for this case to determine the nuclear tank sidewall heating.

3. Propellant Heating

Similar thermal analyses to those described in preceding paragraphs were performed for the 5000 MW engine. The results are described below.

Fig. 9 presents the predicted temperature rise in the liquid hydrogen propellant at locations close to the free surface as a function of engine operating time. It is noted that the temperature rise at the end of 5000 MW engine operation is lower than for the 2000 MW engine. This is due to the larger liquid volume and higher outflow rates. An increase in the liquid volume permits more propellant to absorb the incident energy. The higher outflow rate resulted in shorter engine operating time; consequently, the total energy input to the propellant was comparable for both engine sizes. The overall effect of more propellant and shorter engine operating time over-compensated for the increased rate of heat generation due to higher power level reactor. The temperature rise curves of Fig. 9 indicates an arithmetic mean rise of about 2°R for the cluster as compared to 0.4°R for the single stage, or about a 500% increase. The effects cited appear to make the total temperature rise small although all secondary gamma radiation sources were not considered. Larger differences in temperature rise between single and cluster stages are evident for the 5000 MW engine as compared with the 2000 MW engine (500% vs 20%), but it is not obvious why this difference exists. Further study is required.

The vapor pressure for the upper bound condition is shown in Fig. 10 as a function of engine operating time. Note that the vent pressure is 13.5 psia (time equals zero). The boiloff weight is shown in Fig. 11 as a function of propellant temperature rise during nuclear operation. In deriving this curve it was assumed that 140,000 lb of LH_2 were transported through the boost phase of flight and that 200,000 lb were added in earth orbit. At the end of the boost phase the tank would be vented

* This insures compatibility of total nuclear stage weight with the payload capability of the Saturn V launch vehicle.

to the desired pressure and the boiloff accepted. Since less propellant exists in the tank at the start of the vent process (as compared with the 2000 MW case), there is less boiloff for the same temperature rise. The difference in payload due to nuclear heating in the cluster as compared to a single stage is found to be about 1600 lb if venting is initiated while in orbit, and 1000 lb if venting is initiated during the S-II firing.

FIG. 1

CONFIGURATION OF CLUSTERED PAIRS OF NUCLEAR STAGES FOR PROPELLANT HEATING STUDY

TANK 1

TANK 2

NEAR SIDE

FAR SIDE

TYPICAL DEFECTOR POINTS

Adjacent

Direct

Direct

Adjacent

Top

FIG. 2

PROFILIANT BULK HEATING

CONDITIONS:

2000 MW ENGINE

SOURCE TEMPERATURE

400 °C

DIRECT & ADJACENT
 (NEAR SIDE)

DIRECT & ADJACENT
 (FAR SIDE)

DIRECT
 ONLY

Ex. 2, 1960, 2/1

Ex. 2, 1960, 2/1

FIG. 3

BOUNDARY LAYER HEATING AT TANK WALL

CONDITIONS:

2000 KW ENGINE

COOLANT TEMPERATURE

100 DEG

DOWNSTREAM (WIND SIDE)

UPSTREAM (WIND SIDE)

DOWNSTREAM

BOUNDARY LAYER HEATING AT TANK WALL

FIG. 4

PROPELLANT TEMPERATURE RISE FOR CLUSTERED NUCLEAR STAGE PAIR

CONDITIONS:

2000 MW PER ENGINE

TOTAL PROPELLANT = 180,000 LB

$Q_{WALL} = 0.02 \text{ BTU/FT}^2/\text{SEC}$

INCLUDES NUCLEAR BOUNDARY-LAYER HEATING

INCLUDES NUCLEAR BULK HEATING

PROPELLANT TEMPERATURE RISE
OF TOP LAYER - °R

100

400

500

600

700

800

900

1000

1100

1200

1300

1400

1500

TIME - SEC

DIRECT & ADJACENT
(NEAR SIDE)

DIRECT & ADJACENT
(FAR SIDE)

DIRECT ONLY

FIG. 5

FIG. 6

PROPELLANT BULLOFF DUE TO NUCLEAR HEATING ALONE

CONDITIONS:

2000 MW PER ENGINE

$M_{TOTAL} = 180,000 \text{ LB}$

12,000

10,000

8,000

6,000

4,000

2,000

BULLOFF - LB.

0

1

2

3

4

$\Delta T_{EMP} \text{ } ^\circ R$

FIG. 7

PROPELLANT BULK HEATING

CONDITIONS:

5000 PSI BURNING
 FOURTH PERIOD
 AGC PROGRAM, DATA

DIRECT + ADJACENT (HEAD END)

ADJACENT + ADJACENT (TAIL END)

DIRECT ONLY

AVG. BULK HEATING $\dot{Q}_b$ (°F/SEC)

SEMI-LOGARITHMIC 359-91
 KEUFFEL & ESSER CO. WACING, U.S.A.
 5 CYCLES X 70 DIVISIONS

PROPELLANT WEIGHT - LBS

10⁰

FIG. 8

BOUNDARY LAYER HEATING AT WAKE WALL

CONDITIONS:

5000 REYNOLDS

BOUNDARY LAYER

100 PERCENT DATA

DIRECT MEASUREMENT
 (FAR SIDE)

DIRECT MEASUREMENT
 (NEAR SIDE)

THEORY - CALCULATION

BOUNDARY LAYER HEATING q_w (W) (W/M²) SEC

FIG. 9

PROPELLANT TEMPERATURE RISE FOR CLUSTERED NUCLEAR STAGE PAIR

CONDITIONS:

5000 MW PER ENGINE

TOTAL PROPELLANT - 240,000 LB

INCLUDES NUCLEAR BOUNDARY LAYER HEATING

INCLUDES NUCLEAR BULK HEATING

INCLUDES NUCLEAR WALL HEATING

PROPELLANT TEMPERATURE RISE OF TOP LAYER - °R

DIRECT & ADJACENT
(NEAR SIDE)

DIRECT & ADJACENT
(FAR SIDE)

DIRECT ONLY

TIME - SECONDS

FIG. 10

PROPELLANT HEATING: DERIVED VAPOR PRESSURE VS. OPERATING TIME

CONDITIONS:

5000 MW PER ENGINE

W TOTAL = 340,000 LB

WITH NUCLEAR BOUNDARY LAYER HEATING

WITH NUCLEAR BULK HEATING

WITH NUCLEAR WALL HEATING

DIRECT & NEAR-SIDE ONLY

FIG. 11

PROPELLANT BOLLOFF DUE TO NUCLEAR HEATING ALONE

CONDITIONS:

5000 MW PER ENGINE

$M_{TOTAL} = 140,000 \text{ LB}$

BOLLOFF, LB

$\Delta \text{TEMP. } ^\circ\text{R}$

REFERENCES

1. NSP-63-96, LMSC, "RIFT Systems Analysis, Thermodynamics," Vol. 7, May 1964 (U)
2. AGC 2492, "Standard NERVA Engine Analytical Model for Radiation Analysis," February 1963 (CRD)
3. NSP-64-02, LMSC, "Stratified Propellant Flow Model," April 1964 (U) ✓

III. CONCLUSIONS

The following conclusions are based on trends that appeared in this preliminary study between selected pairs of clustered 2000 MW and 5000 MW stages and single stage configurations. It is to be noted that the shadow shields are different, and it must be presently assumed that the conclusions are valid only for the shields used.

1. For pairs of clustered superinsulated stages mixed flow exists. This is primarily because the bulk heating in the tank bottom is dominant over boundary layer heating for these engine power levels.
2. The decrements in payload due to nuclear heating of two clustered stages vs. single stages for the two engine/stage cases studied are relatively small with 1000 lb and 1600 lb cited as decrements for the 2000 MW and 5000 MW engines, respectively.
3. Clusters of two 5000 MW stages do not present severe propellant heating problems requiring additional engine side shielding from the propellant tank design standpoint.