WS# 9b
N8510

AEROJET NUCLEAR SYSTEMS COMPANY
SACRAMENTO, CALIFORNIA

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TO: J. L. Watkins 7 June 1971
FROM: J. J. Williams JJW:jm:N8110:M1707
SUBJECT: Nozzle Performance Loss Analysis - Contour Imperfection
(W.O. 1190-14-109) Project 141

DISTRIBUTION: R. H. Coppo, O. J. Demuth, L. A. Shurley

REFERENCES: ✓(a) Memo N8110:M1683, J. J. Williams to J. L. Watkins,
Dated 28 April 1971, Subject: "Nozzle Performance
Loss Analysis - Contour Imperfection"

✓(b) Note from R. H. Coppo, Dated May 5, 1971, Subject:
"Nozzle Performance Loss Analysis - Contour Imperfection"

✓(c) Memo 7734:048, J. J. Williams to L. A. Shurley,
Dated 8 June 1970, Subject: "AGCarb Erosion/Corrosion
Scaling"

(d) Computing Sciences Report No. E-3, "Real Gas Supersonic
Flow", R. D. Glauz, J. D. Huang and C. H. Lundelius,
Dated 28 March 1968

ENCLOSURES: (1) Figure 1 - Flow Boundary With 1.5 Inch Deep Step

(2) Figure 2 - Calculated Performance Change With a
Circumferential Discontinuity at an Area
Ratio of 24:1

I. SUMMARY

The analysis reported in Reference (a) was to determine the effect on nozzle performance of a 0.10 inch deep circumferential discontinuity at an area ratio of 24:1. As requested in Reference (b), it was extended to include steps 0.30 and 0.50 inches deep. The present analysis indicated that calculated performance changes resulting from discontinuities as large as 0.50 inches are within the uncertainty of the analytical method (with the boundary point limitation of the existing computer code). For this reason several larger discontinuities (up to

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<i>OJ Demuth; Unclassified</i>	
CLASSIFYING OFFICER	6-8-71 DATE

MASTER

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four inches) were analyzed and the calculated performance changes plotted against step size. Based on an examination of this plot it is estimated that a 0.50 inch deep discontinuity will result in a specific impulse loss of approximately 0.25 seconds.

II. DISCUSSION

The engine operating conditions assumed for this analysis were the nominal conditions used in Reference (a) ($P_c = 450$ psia, $T_c = 4250^\circ\text{R}$). The nozzle had an expansion ratio of 100:1 and a throat radius of 5.605 inches.

The surface profile irregularities had the same general shapes as in Reference (a). A sudden increase in contour radius (from the nominal value) was assumed at an expansion ratio of 24:1 decreasing to zero increase in radius 23 inches downstream from the initial step. The use of 23 inches as the length of the affected zone rather than 11.887 inches as used in Reference (a) was to more closely reflect the extent of the zone as indicated by Figure 3 of Reference (c).

As in Reference (a) local flow separation was accounted for in the analysis by assuming a straight flow boundary consistent with the maximum flow turning angle and pressure rise that can be sustained by a turbulent boundary layer at the attachment location. The maximum turning angle for turbulent boundary layer attachment is approximately 14 degrees. A scale drawing of the flow boundary with a 1.5 inch deep step is shown in Figure 1.

Method-of-characteristics analyses (Reference (d)) were carried out for a 0.3 and a 0.5 inch step. The calculated performance changes (shown later) were inconsistent, and were attributed to uncertainty in the analysis method. It was judged that at least part of the difficulty in achieving more accurate values for performance change resulted from the necessity of using approximately 10 additional contour points to adequately describe the contour imperfections. For a fixed total number of allowable contour points this results in fewer number of points available for contour description in the critical throat region.

Modification of the computer code to treat additional boundary points or modify the spacing routines is beyond the scope of the present study. Consequently, the method used to estimate the effect of step size on performance

was to calculate performance for several large steps (0.7. 1.5 and 4.0 inches) so that actual trends would not be masked. The results are shown in Figure 2, which is a plot of calculated performance change versus step size. Based on this plot it is estimated that a 0.5 inch deep discontinuity will result in a specific impulse loss of approximately 0.25 seconds.

J. J. Williams
Thermophysics
Engineering Staff Department

FIGURE 1

FLOW BOUNDARY WITH 1.5 INCH DEEP STEP

FIGURE 2 - CALCULATED PERFORMANCE CHANGE WITH A CIRCUMFERENTIAL DISCONTINUITY AT AN AREA RATIO OF 24:1

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CLASSIFICATION CATEGORY	
<i>Unclassified</i>	
<i>O.P. Demuth 4-28-71</i>	DATE
CLASSIFYING OFFICER	

Drink -
Do 2 more
points to obtain
I_s step size
curve
JW

TO: J. L. Watkins ✓
FROM: J. J. Williams
SUBJECT: Nozzle Performance Loss Analysis - Contour Imperfection
(W.O. 1190-14-109)

28 April 1971
JJW:jm:N8110:M1683

DISTRIBUTION: R. H. Coppo, O. J. Demuth, L. A. Shurley

- REFERENCES: *(a)* Memo N8500:M1265, J. L. Watkins to O. J. Demuth,
Dated 13 April 1971, Subject: "Nozzle Performance
Loss Analysis - Contour Imperfection"
- (b)* Memo N4330:055, M. J. Ditore to J. L. Watkins,
Dated 13 January 1971, Subject: "Nozzle Performance
Loss Analysis"
- (c)* Memo 7734:048, J. J. Williams to L. A. Shurley,
Dated 8 June 1970, Subject: "AGCarb Erosion/Corrosion
Scaling"
- (d) Computing Sciences Report No. E-3, "Real Gas Super-
sonic Flow", R. D. Glauz, J. D. Huang and C. H. Lundelius,
Dated 28 March 1968

I. SUMMARY

As you requested in Reference (a), the contour imperfection analysis of Reference (b) was extended to include a circumferential discontinuity at an area ratio of 24:1. The analysis was performed, and it indicated a performance loss of 0.04 percent. However, this magnitude of this loss is believed to be within the uncertainty of the analysis technique. Consequently, no significant performance loss can be predicted for the step size analyzed.

II. DISCUSSION

Performance losses can result from contour imperfections when the associated flow anomalies cause shocks that are strong enough to significantly

influence the nozzle wall pressure distribution. In the divergent portion of a nozzle (supersonic flow regime) the changes in wall pressure are felt only downstream of the irregularity* and consequently the performance change associated with a wall discontinuity depends both on its nature and location. For identical operating conditions the same contour imperfection will tend to cause less of a performance change as the area ratio at which it is located is increased.

The operating conditions selected were the nominal conditions described in Reference (b) ($P_c = 450$ psia, $T_c = 4250^\circ\text{R}$). The nozzle had an expansion ratio 100:1 and a throat radius of 5.605 inches.

The surface profile irregularity was assumed to be a sudden increase in radius (from the nominal value) at an expansion ratio of 24:1 decreasing to zero increase in radius 11.887 inches downstream from the initial step. This length is smaller than the affected zone indicated by Figure 3 of Reference (c). The reason for the use of a decreased length was so that a minimum number of contour points would have to be changed for the present calculation. This was done to maintain maximum similarity in the flow calculation nets between the unperturbed and perturbed solutions. In this way it was hoped that minimum error would result from numerical inconsistencies between the two solutions.

Small local separation may occur at the initial step. This was accounted for in the analysis by assuming a straight flow boundary consistent with the maximum flow turning angle and pressure rise that can be sustained by a turbulent boundary layer at the attachment location. The maximum turning angle for boundary layer attachment is approximately 14 degrees. The shape of analyzed imperfection is shown in the following sketch.

Sketch 1 - Imperfection Shape (Not to Scale)

*Some effect is felt upstream of the discontinuity because of pressure feedback through the subsonic portion of the boundary layer. However, the upstream distance over which this influence exists is usually small unless it results in gross separation of the mainstream flow. Because of the vacuum environment in which NERVA operates, this type of flow separation is not a consideration in the present analysis.

Method-of-characteristics analyses were carried out for the nominal contour and one for a contour with the discontinuity just described. The difference in calculated specific impulse was 0.33 seconds or approximately a 0.04 percent loss with the step. Both the length of the affected zone and the shape of the separated flow boundary were to have been refined if any significant performance loss could be calculated. However, these corrections would make only minor changes in the final results and were considered unwarranted in view of the small loss computed.

In order to estimate the magnitude of performance change that could be associated with numerical inconsistencies, the analysis of the nominal contour was repeated using two additional boundary points in the vicinity of expansion ratio 24:1. This analysis indicated an apparent 0.01 percent gain in performance for the nominal nozzle contour. A complete study of the effect of contour point spacing and numerical grid size would be necessary to quantitize the effect of these parameters on the computed specific impulse. This is beyond the scope of the present study, and is probably not warranted. However, based on this single comparison of the same contour using a different number of points to define the wall, it appears reasonable to attribute performance changes as high as the present 0.04 percent to uncertainty in the numerical method. For this reason it is concluded that no significant performance loss can be assigned to a 0.10 inch deep circumferential step in the NERVA nozzle at an expansion ratio of 24:1.

It is recommended that any future analyses be conducted only for significantly larger steps (on the order of 0.5 inches or more) in order to prevent uncertainty in the analytical method from masking actual trends.

J. J. Williams, Sr. Engr. Spec.
Thermophysics
Engineering Staff Department

AEROJET NUCLEAR SYSTEMS COMPANY
SACRAMENTO, CALIFORNIA

TO: O J Demuth DATE: 13 April 1971
JLW:lm:N8500:M1265
FROM: J L Watkins
SUBJECT: Nozzle Performance Loss Analysis - Contour Imperfection
DISTRIBUTION: W E Campbell, R H Coppo, L A Shurley, J J Williams
REFERENCE: (a) Memo N4330:055, M J Ditore to J L Watkins, dtd 13 January 1971
Subj: "Nozzle Performance Loss Analysis"

It is requested to extend the Contour Imperfection Analysis as described in Reference (a) to include a circumferential contour discontinuity at an area ratio of $\epsilon = 24:1$. This discontinuity (a possible result of graphite erosion) shall be axisymmetric and .100 inch deep. A total of 60 salary hours, 6 hourly hours, and \$125 computer time is allotted for this analysis. The undersigned shall be notified immediately if any overexpenditure is anticipated. The work order charge number for this analysis is 1190-14-109. The required completion date is 30 April 1971. Additional analyses may be required based on the results of this initial analysis.

For any further information, contact R. H. Coppo, Ext. 3567.

J. L. Watkins
J. L. Watkins, Supervisor
Nozzle, Pressure Vessel
and Skirt Department *JLW*

CLASSIFICATION CATEGORY	
UNCLASSIFIED	
<i>J. L. Watkins</i>	<i>4-13-71</i>
CLASSIFYING OFFICER	DATE

9b Back up

AEROJET NUCLEAR SYSTEMS COMPANY
SACRAMENTO, CALIFORNIA

TO: G. F. Mader 8 February 1971
FROM: I. L. Odgers RHC:nla N4220:M1213
SUBJECT: Project No. 141 Work Statement Items, No. 7a, b and c
DISTRIBUTION: R. H. Coppo, L. A. Shurley, P. P. Ventura, J. L. Watkins
Enclosure: (1) Memorandum N4330:055 dated 13 January 1971, M. J. Ditore
to J. L. Watkins, subj: Nozzle Performance Loss Analysis

Enclosure (1) is forwarded in fulfillment of the requirements of Project 141 Work Statement No. 7a (Performance Loss due to Vibration), 7b (Performance Loss due to Divergent Section Contour Variations) and 7c (Document Results of 7a and 7b).

I. L. Odgers
I. L. Odgers, Manager
Engineering Department
Aerojet Nuclear Systems Company

CLASSIFICATION CATEGORY	
UNCLASSIFIED	
<i>J. L. Watkins</i>	2-8-71
CLASSIFYING OFFICER	DATE

AEROJET NUCLEAR SYSTEMS COMPANY
SACRAMENTO, CALIFORNIA

TO: J. L. Watkins 13 January 1971
MJD:res 4330:055
FROM: M. J. Ditore
SUBJECT: Nozzle Performance Loss Analysis
COPIES: R. H. Coppo, O. J. Demuth, L. A. Shurley, File

REFERENCES: (a) Memorandum 7734:099 to J. L. Watkins from M. J. Ditore,
Same subject, dated 2 October 1970.
(b) Memorandum 7734:090 to J. L. Watkins from M. J. Ditore,
Subject: "Derating Factors for the NERVA Nozzle",
dated 21 September 1970.
(c) Memorandum 7734:077 to C. K. Leeper from O. J. Demuth,
Subject: "Performance Prediction Variability for NERVA",
dated 3 September 1970.
(d) "A Second-Order Numerical Method of Characteristics
for Three-Dimensional Supersonic Flow", V. H. Ransom,
et al, Technical Report AFAPL-TR-69-98, Volume I and II,
October 1969.
(e) Computing Sciences Report No. E-3, "Real Gas Supersonic
Flow", R. D. Glauz, J. D. Hwang, and C. H. Lundelius,
dated 28 March 1968.

I. SUMMARY

Performance losses due to nozzle vibration and geometry imperfections were estimated for the NERVA ($\epsilon = 100:1$) nozzle operating at the nominal chamber conditions of $P_c = 450$ psia and $T_c = 4250^\circ\text{R}$. The results were used to upgrade the estimated derating factors presented in References (a) and (b). The derating factor due to nozzle vibration was estimated to be 0.05 percent. The maximum performance loss of geometric variations in the radial dimensions of +0.02 and -0.040 inches was computed to be 0.12 percent.

A revised summary of performance losses and uncertainties for the 100:1 expansion ratio nozzle operating at nominal chamber conditions is given below:

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<i>O. J. Demuth</i>	1-15-71
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Estimated uncertainty in one-dimensional equilibrium performance (3σ)		± 0.14
Divergence Loss	0.47	± 0.17
Heat Transfer and Friction Loss	1.62	± 0.50
Kinetic Loss	0.13	± 0.10
Contour Imperfection	0.12	± 0.05
Vibration	0.05	± 0.05
*Velocity and Temperature Maldistribution	<u>0.10</u>	<u>± 0.05</u>
	2.49%	± 0.56

Based on the revised derating factor, the nominal attainable specific impulse is 825.3 lbf-sec/lbm. The present estimate of the 3σ range (Reference (c)) in delivered specific impulse is between 820.6 and 830.1 lbf-sec/lbm due to the uncertainty of the analysis. 820.68
829.92

II. INTRODUCTION

This memorandum briefly describes the method of approach used to compute performance derating factors due to nozzle vibration and geometry imperfections. The results were used to upgrade the derating factors presented in Reference (a). A revised table of derating factors and corresponding specific impulse for selected chamber operating conditions is presented in Table I. It should be noted, however, that performance losses due to vibration and contour imperfections were computed for the 100:1 expansion ratio nozzle operating at nominal operating conditions. In revising the table for other operating conditions, it was tacitly assumed that the influences of chamber pressure and temperature on these losses are negligible. This assumption, however, will need to be verified particularly at the lower temperature and pressure conditions.

III. CALCULATION PROCEDURE

A. NOZZLE VIBRATION

Vibration of a nozzle produces a deformation of the circular cross section as a result of meridional, hoop, and torsional stresses and moments. The magnitude of the deformation and the geometric modes are determined from dynamic analyses which depend upon (1) the magnitude

* Estimate based on preliminary analysis of the effects of peripheral cooling.

and the characteristics of the forcing function, and (2) the system stiffness, mass, and geometric properties. The performance loss, therefore, is a consequence of the non-optimum flow expansion imposed by the distorted physical boundaries.

Determination of performance loss due to nozzle vibration is accomplished using the three-dimensional method of characteristic solution of the flow equations described in Reference (d). The numerical method was devised to determine the flow characteristics and subsequent performance of three dimensional nozzle geometries. It may be used to determine the flow conditions in the supersonic region of the nozzle. Initial flow conditions, required for the propagation type solution, is determined along a plane perpendicular to the flow center line. Several options, such as source flow, input data table, etc. are available to define the initial conditions in the throat region.

The computer program is limited to nozzle geometries which vary parabolically along longitudinal planes and which intersect the centerline. Further, the throat cross-section must be circular, however, the location of initial deviation from a circular geometry may be located downstream of the throat. The cross-sectional geometry in the noncircular region is defined by the geometric expression

$$\left(\frac{y}{a}\right)^c + \left(\frac{z}{b}\right)^d = 1 \quad (1)$$

The values of a and b are the radial dimensions of the intersection of the contour with the y and z axes.

It may be noted that if c and d are selected equal to 2 then $a = b$ in the above equation defines a circular cross-section, and for $a \neq b$ defines an elliptical shape. Further if $a = b$ and $c = d \gg 2$ is used in the expression, a square-like configuration is prescribed and for $a \neq b$ will define a rectangular-like shape. Thus, it is seen that the program is capable of evaluating the performance of a wide variety of nozzle configurations. The program evaluates the flow conditions between geometric symmetry planes in a single quadrant, and consequently selection of a number of symmetry planes greater than two affords additional geometries, such as triangular or scalloped shapes, to be evaluated by appropriate selection of a, b, c and d values.

To determine the performance loss for the NERVA nozzle, the three configurations shown in Figure 1 were initially considered to be the significant modes of vibration. In each case, care was exercised to insure that the perimeter of the nozzle exit plane was equal to the circumference of the original circular geometry. For the elliptical nozzle this was accomplished by direct computation, however, for the triangular and square nozzle configurations, the required perimeter was determined by a graphical iteration technique. Nozzle deflections and computed performance losses for the three configurations shown in Figure 1 are tabulated in Table 2.

Subsequent to the above analyses, preliminary dynamic analyses were completed and indicated (per R. C. Rosser) that (1) the elliptical geometry is the principal mode of vibration and having a maximum deflection at the exit plane of 2.59 inches, (2) the second significant mode of vibration was the three-lobe (triangular) geometry with considerably smaller amplitude and (3) the four-lobe or square mode would be essentially non-existent during nozzle vibration. The influence of meridional and bending stresses resulted in a coordinate deformation which could be closely approximated by an elliptical flow cross-section. It should be noted that these stresses do not produce any displacement (or bending) of the axis. The influence of torsional loads modified the geometry in such a way as to change the orientation of the major (and minor) axis from the throat to the exit. That is, the elliptical cross-section rotates with axial position producing a swirling of the flow. The three-dimensional method of characteristics program is incapable of accounting for swirl flow, and thus this effect was ignored. It is believed, however, that the performance loss as a result of swirl will be small because of the small deflection magnitude which is considered to influence the peripheral regions of the flow.

Based on these results, the performance loss was determined for the elliptical nozzle configuration as a function of nozzle deflection; the orientation of the axis was assumed fixed. These latter results, presented in Figure 2, show the expected trend in performance loss with nozzle deflection. For the anticipated 2.59 inch nozzle deflection anticipated, the computed performance loss for the elliptical mode is approximately 0.02 percent. It should be noted, however, that the values presented in Figure 2 are applicable to nozzle configurations having smooth (parabolic) transition from a circular geometry in the throat region to the elliptical configuration at the exit plane. Thus, these results do not include possible distortion in coordinates expected at the interface between the cooled and uncooled portions of the nozzle exit cone or the effect of swirl created the rotating orientation of the axes of the elliptical cross-section due to torsional modes. Further, it must be realized that the elliptical geometry considered is but an approximation of the actual two lobe vibrational mode. For these reasons, therefore, it was assumed that a more reasonable estimate of vibrational performance loss was 0.05 percent so as to account for minor inaccuracies in the definition of the nozzle geometry. A major revision to the existing computer program would be necessary to evaluate the flow characteristics for arbitrary nozzle coordinates. Because of the small loss magnitudes computed, this effort was considered unwarranted at this time.

B. GEOMETRY IMPERFECTION

Nozzle contour imperfections may result from a buildup in manufacturing tolerances or component distortion caused by nonuniform thermal expansion. These deviations will contribute to flow anomalies within the nozzle and if they are of sufficient magnitude will create

strong shocks thus degrading the specific impulse. The magnitude of performance loss will depend on the location of the flow disturbances. Larger performance losses may be expected for disturbances located in the throat (or high pressure) region of the nozzle. This results from flow anomalies being propagated throughout the supersonic flow regime as compared with a disturbance in the exit region influencing only a small portion of the flow. Further the coordinate deviations, considered in this analysis, are small compared with the overall dimensions at any cross-section. The consequent result is that contour deviations in the exit region are an order of magnitude smaller than the boundary layer displacement thickness and thus the effects on the potential flow field will be small. Therefore, only contour imperfections in the throat region, are considered significant. Contour deviations were provided by the project based on a dimensional analysis of the design, and including the effects of expected component thermal growth.

The numerical method of analysis used to evaluate the performance of arbitrary nozzle configurations is described in Reference (e) and is the same computer program used to compute divergence loss discussed in Reference (a) (i.e., E21222). Because of the sensitivity of the numerical calculations to the flow angle at each coordinate location, a contour integration scheme was devised to insure a smooth transition in flow angle in the region of the coordinate deviation and to provide consistency between the x , R and θ_w such that the appropriate expansion ratio is obtained by integration of the axial coordinate. The procedure includes selection of the coordinates of the perturbed geometry in a small region to conform to the expected tolerance buildup; the remaining portion of the nozzle was assumed to conform to the optimum configuration. The wall angle in the perturbed region is determined by graphical means and the integration program is used to insure dimensional consistency. The wall angles are modified and the integration repeated if necessary, before submitting the coordinates for evaluation of performance.

Because the scope of the performance evaluation task was reduced, only contour perturbations at one location in the nozzle was evaluated. The imperfection was assumed to occur at a location of 1.3 inches downstream of the throat. The tolerance buildup at this location was found to be +0.02 and -0.04 inches. A schematic of the nozzle imperfections, considered in this analysis, are depicted in Figure 3. Although other geometric variations are equally probable, time permitted evaluation of only one pair of typical imperfections. The aforementioned procedure was used to evaluate the performance loss for the two selected contour imperfections. The performance losses computed are 0.12 and 0.10 percent for the +0.02 and -0.04 inch contour variations, respectively. These results should be considered preliminary since the performance loss at other locations in the nozzle were not computed. It is believed, however, that the results presented are of reasonable magnitudes for the degree of variance of the contour coordinates.

M. J. Ditore
M. J. DITORE, Engr. Supv.
Aerophysics Section

APPROVED:

O. J. Demuth
O. J. DEMUTH, Manager
Aerophysics Section
Scientific Staff Department

TABLE I - NERVA NOZZLE DERATING FACTORS (Revised 1-8-71)

Expansion Ratio	100						
Temperature Pressure	4250 450	4250 360	4250 270	3600 360	2800 360	2800 270	2800 164
Theor. Performance, Sec.	846.4	846.7	847.3	768.9	670.1	670.1	670.1
Divergence Loss, %	0.47	0.46	0.51	0.47	0.48	0.51	0.54
*Boundary Layer Loss, %	1.62/1.59	1.72/1.70	1.89/1.85	1.58/1.56	1.45/1.43	1.44/1.43	1.71/1.70
Kinetic Loss, %	0.13	0.21	0.24	--	--	--	--
Contour Imperfection, %	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Vibration, %	0.05	0.05	0.05	0.05	0.05	0.05	0.05
**Maldistribution, %	0.10	0.10	0.10	0.10	0.10	0.10	0.10
*Total Loss (Derating Factor), %	2.49/2.46	2.66/2.64	2.89/2.87	2.32/2.30	2.20/2.18	2.22/2.21	2.52/2.51
*Attainable (nom.) Performance, Sec.	825.3/825.6	824.2/824.3	822.8/823.0	751.1/751.2	655.4/655.5	655.2/655.3	653.2/653.3

* Legend - Start-of-Life/End-of-Life

** Estimated values, actual losses yet to be determined

TABLE II

<u>Geometric Shape</u>	<u>Nozzle Deflection (inches)</u>	<u>Performance Loss (Percent)</u>
Two-lobe (ellipitical)	3.0	0.03
Three-lobe (triangular)	3.0	0.08
Four-lobe (square)	3.0	0.06

TYPICAL COMPUTER SIMULATION OF NOZZLE VIBRATORY MODES

Elliptical
(2-lobe simulation)

Square
(4-lobe simulation)

Triangular
(3-lobe simulation)

NOZZLE VIBRATION PERFORMANCE LOSS AS A FUNCTION OF NOZZLE DEFLECTION
(ELLIPTICAL MODE)

Figure 2

NOZZLE GEOMETRY IMPERFECTIONS CONSIDERED IN THE ANALYSES

M E M O R A N D U M

TO: L. A. Shurley 8 June 1970
JJW:res 7734:048

FROM: J. J. Williams Ext. 2400:Blgd. 2015

SUBJECT: AGCarb Erosion/Corrosion Scaling (W.O. 1188-26-524)

COPIES: R. L. Brown, H. J. Bronner, L. B. Claassen, H. O. Davis,
O. J. Demuth, M. J. Ditore, C. W. Funk, H. H. Inouye,
C. M. Kawashige, I. M. Rehn, J. O. Sane, K. Sato,
A. J. Stosick, L. Shenfil, P. P. Ventura, File

REFERENCES:

- a. GWA 246691, AGCarb Erosion/Corrosion Scaling, dated 9 April 1970.
- b. Memorandum 9648:537, to L. A. Shurley from C. M. Gracey, "AGCarb 101 Erosion Data Obtained from High Temperature Hydrogen HES Flow Tests", dated 25 March 1970.
- c. Memorandum 7734:007, to L. A. Shurley from O. J. Demuth, "Analysis of AGCarb Regression Data", dated 24 March 1970.
- d. Memorandum 7734:01, from M. J. Ditore/R. L. Knapp to C. M. Kawashige, "NASS Primary Diffuser AGCarb Erosion Study", dated 3 March 1970.
- e. Memorandum 9615:2932, from O. J. Demuth to H. J. Bronner, "AGCarb Regression Analysis Transmittal" dated 21 July 1969.
- f. Unreleased Memorandum 7731:M1464 from R. L. Brown to L. B. Claassen, "HES AGCarb-101 Erosion Test Heat Transfer Analysis"
- g. Memorandum 7731:M1446, to O. J. Demuth from J. O. Sane, "NERVA Nozzle Extension Profiles for AGCarb 101 Erosion Analysis", dated 27 April 1970.
- h. NASS Primary Ejector Collar Design for the NERVA Engine-Interim Report, Report ICER 9641-362, Liquid Rocket Division, August 1969.
- i. Bird, R. B., Stewart, W. E. and Lightfoot, E. N., "Transport Phenomena", Wiley 1960.
- j. Memorandum from A. J. Stosick to Distribution, "Chemical Erosion of Graphite or Carbon by Reactive Gases", dated 13 May 1969.
- k. Memorandum 7734:004, from J. J. Williams to C. M. Kawashige, "Preliminary Test Results from NASS AGCarb Erosion Tests", dated 6 March 1970.

ENCLOSURES:

- (1) Listing of Computer Code Used for Data Reduction (3 pages)
- (2) Tabulation of Reduced Data
- (3) Figure 1 - AGCarb Erosion Correlation for a Kinetic Limited Process
- (4) Figure 2 - AGCarb Erosion Correlation for a Diffusion Controlled Process
- (5) Figure 3 - Predicted Erosion for the Fullscale NERVA Nozzle

CLASSIFICATION CATEGORY	
UNCLASSIFIED	
<i>William H.</i>	6-1-77
CLASSIFYING OFFICER	DATE

I. INTRODUCTION

In response to the request of Reference (a) a study was conducted to evaluate the erosion data obtained in the AGCarb test series described in Reference (b). A primary objective of the test series was to determine the applicability of AGCarb as a liner material for the full scale NERVA nozzle.

In order to interpret measured regression data in terms of predicted erosion for the NERVA nozzle it was necessary to first determine how the various test parameters controlled regression. Consequently, this task consisted of the following phases*:

A. reduce and attempt to correlate the data as if the erosion process were kinetically limited;

B. reduce and attempt to correlate the data as if the erosion process were diffusion limited;

C. determine the range of surface temperatures for which each model best fits the data, and thus define applicable scaling laws for the NERVA application;

D. predict full scale corrosion rates as a function of expansion ratio for the NERVA nozzle.

II. SUMMARY

All phases of the study were completed and the following are the principal results.

A. At surface temperatures above approximately 2500°R the chemical erosion of AGCarb-101 from hydrogen is a boundary-layer diffusion limited process.

B. At surface temperatures below approximately 2500°R the chemical erosion of AGCarb-101 from hydrogen is controlled by chemical kinetics, surface absorption or some other process which does not depend primarily on local mass transfer coefficient.

C. At a chamber pressure of 450 psia and a stagnation temperature of 4250°R, the extrapolated erosion rate of an AGCarb skirt extension for the NERVA full scale nozzle is 5.85 mils/hour at an expansion ratio of 24:1 and 1.38 mils/hour at an expansion ratio of 50:1.

* The initially proposed task is described in detail in Reference c.

II. DISCUSSION

A. GENERAL

A complete description of the analytical considerations used to establish the necessary correlating parameters is contained in Appendix A of Reference (d) and Appendix A of Reference (e). Erosion, surface pressure and other test data were obtained from Reference (c). Detailed surface temperatures and heat transfer coefficient were obtained from Reference (f) and full scale nozzle conditions are those reported in Reference (g).

B. CORRELATION WITH KINETIC REGRESSION MODEL

The first phases of this analysis was an attempt to correlate the measured erosion by the use of models that were based on both kinetically limited processes and diffusion limited processes. It was indicated in Reference (h) that the chemical regression of AGCarb-101 is proportional to free stream hydrogen pressure to the first power*. Consequently, the kinetic model selected for use in an attempt to correlate the measured data was based on the following relationship:

$$\dot{r} = k P_{H_2} \exp (-E_A/RT) \quad (1)$$

where E_A = activation energy factor

k = constant which depends on material and experiment

P_{H_2} = the pressure of hydrogen gas

R = gas constant

$\dot{r}$ = surface regression rate

T = temperature

If Equation (1) describes the regression mechanism, a plot of the ratio of regression rate to pressure versus the reciprocal of surface temperature will yield a straight line on semi-log graph paper. This parameter was computed for each of the measurements reported in Reference (b) using the computer code listed as Enclosure (1), and results of the calculations are tabulated in Enclosure (2). Each of the quantities listed in Enclosure 2 along with the source is described in the following table:

* In addition, if the concentration of hydrogen at the surface is taken as proportional to the free stream hydrogen pressure, this is equivalent to postulating a simple, first order reaction. This type of model is often suitable for engineering calculations over limited ranges of parameters even when conformity with all analytical requirements is not rigorously met.

1. TEST	Test number from Reference (b).
2. SPECIMEN TYPE	Specimen description from Reference (b).
3. DURATION	Test duration from Reference (b).
4. TC	Stagnation temperature from Reference (b).
5. PC	Stagnation pressure from Reference (b).
6. SPECIFIC HEAT	Hydrogen specific heat from Reference (f).
7. BACK SIDE TEMP	Specimen measured temperature from Reference (b).
8. PR/SC	Ratio of Prandtl to Schmidt numbers from Ref. (e).
9. DENSITY	AGCarb-101 density from Reference (e).
10. LOCATION	Measurement location as described in Reference (b).
11. PRESS	Local pressure from Reference (b).
12. EROSION	Measured erosion from Reference (b).
13. TW	Local wall temperature from Reference (f).
14. H	Local heat transfer coefficient from Reference (f).
15. HD/M	Ratio of mass flux based on measured surface regression to theoretical mass transfer coefficient.
16. R/P	Ratio of measured regression rate to local static pressure, mils/hr/psia
17. DIFFUSION RATIO	Ratio of actual to theoretical regression rates with calculated values based on a diffusion limited regression model.

To test the applicability of Equation (1) the quantity R/P was plotted versus $1/T_{wall}$ and the results are shown on Figure 1 (Enclosure 3). It is clear from the scatter of data on this plot that one could not select a straight line curve to correlate all the points. Since it is recognized that experimental error may mask some actual trends, it was decided that no final conclusions should be drawn from this figure. It was thought significant, however, that much of the data fell well below the band shown on Figure 15 of Reference (h); thus making the use of the data shown on Figure 15 questionable for the present application.

C. CORRELATION WITH A DIFFUSION LIMITED REGRESSION MODEL

The second model evaluated was based on diffusion through the concentration boundary layer as the limiting step in the regression process. Again, the details of this model are discussed in detail in Appendix A of Reference (e). The significant difference between this erosion mechanism and a kinetically limited model is that surface regression depends not only on pressure (hydrogen concentration) and temperature but also on the local mass transfer coefficient which is determined by the boundary layer characteristics.

For a diffusion controlled reaction, the material removal rate may be described by a relationship of the following form:

$$\dot{m}_c'' = h_D (K_{c,w} - K_{c,e}) \quad (2)$$

where h_D = mass transfer coefficient

$K_{c,e}$ = weight fraction of carbon in the free stream

$K_{c,w}$ = weight fraction of carbon at the boundary layer,
wall interface

$\dot{m}_c''$ = mass flux of carbon through the boundary layer.

For the present system $K_{c,e}$ may be taken as negligible in comparison to $K_{c,w}$ and the carbon removal rate becomes:

$$\frac{\dot{m}_c''}{h_D} = K_{c,w} \quad (3)$$

The value of $K_{c,w}$ for a carbon-hydrogen system is a function of pressure and temperature. These values are computed from equilibrium chemistry considerations and are shown for a range of pressures and temperatures in Appendix A of Reference (d).

It should be noted that when there is a small variation in mass transfer coefficient (h_D) for a number of erosion tests it is difficult to determine the actual controlling mechanism because, over some temperature ranges, both temperature and pressure have the same qualitative influence on regression.

The mass transfer coefficient, h_D , may be evaluated from*:

$$h_D = (\rho u)_e \text{St}(\text{Pr}/\text{Sc})^{2/3} \quad (4)$$

where: $(\rho u)_e$ = mass flux at the boundary layer edge

St = Stanton number

Pr = Prandtl number

Sc = Schmidt number

and as in Reference (e) the utilized Schmidt and Prandtl numbers were 1.08 and 0.701, respectively.

By using the relationship between Stanton number and heat transfer coefficient, Equation 4 may be expressed as:

$$h_D = h/C_p (\text{Pr}/\text{Sc})^{2/3} \quad (5)$$

where C_p = effective specific heat at constant pressure

The actual data correlation for a diffusion limited system was done in the previously described computer code. The steps for determining the ratio of measured to predicted regression were:

1. Evaluate the mass transfer coefficient, h_D , using Equation 5, with values of h and C_p obtained from Reference (f).

2. Determine the mass fraction of carbon at the wall, $K_{C,w}$ for the local wall temperature and pressure from Figure A-1 of Reference (d). In the computer code this is done by a double linear interpolation in tabulated data from this figure.

3. Multiply $K_{C,w}$ by h_D and divide by density to determine the predicted regression rate.

4. The ratio of the measured regression rate to the computed value is the "DIFFUSION RATIO" listed in Enclosure (2).

A plot of DIFFUSION RATIO versus $1/\text{Temperature}$ is shown in Figure 2. The abscissa ($1/\text{Temperature}$) was selected rather than temperature to facilitate comparison with Figure 1. Correlation between theory and experiment would be considered good in regions where the ratio is equal to a value near unity. It is clear from an examination of Figure 2 that regression is not diffusion limited at temperatures below approximately 2500°R because

* This relationship is developed in Reference (i) from an analogy between heat and mass transfer at low mass transfer rates. With the same assumptions it is applicable to both laminar and turbulent flows.

of the low values for the plotted ratio. At all temperatures there is considerable width to the band of data points, some of which is directly attributable to the scatter in reported erosion depths. Nevertheless, the departure from a diffusion controlled process at temperatures below 2500°R is quite clear.

At higher temperatures (starting between 2500 and 2800°R), however, the sharp rise in the ratio stops and the width of the data band becomes approximately the same as the consistency in regression measurements. In this region the location of data points on Figure 2 are interpreted as meaning that no effect of temperature on the calculated ratio can be inferred. Further, this temperature range is the same as that indicated in Reference (j) as the approximate transition region between kinetically and diffusion limited processes. Based on these observations, the erosion process is taken to be diffusion limited for wall temperatures above approximately 2500°R and limited by some other mechanism at lower temperatures.

The ratio of measured to predicted regression rates has a nominal maximum of 1/3 rather than 1.0. However, it is felt that this much difference can be accounted for by a combination of the following factors.

1. Several assumptions were introduced in the computation of Schmidt number (see Reference e). A more refined calculation might reduce this number; however, in view of other uncertainties about the boundary layer characteristics, attempts to refine the value are not considered warranted.

2. The exponent to which the ratio of Prandtl to Schmidt number must be raised for the evaluation of Equation 5 may be different from 2/3 for the present system.

3. The actual subscale model wall temperature and heat transfer coefficient distribution may be somewhat different from that used in this analysis. These quantities are particularly difficult to evaluate because the hydrodynamic boundary layer may be in transition between laminar and turbulent flow over part of the model length. Further, the computed model surface temperatures depend to a great extent on the AGCarb thermal conductivity and reported values from various sources are in significant disagreement. This problem is discussed in detail in Reference (f).

Since these potential sources of error could account for the reduced value of the ratio of actual to predicted regression, the diffusion correlation at high temperatures is considered adequate.

It should be observed that the boundary layer characteristics for the full scale nozzle should be known more accurately than those in the subscale model. Consequently, any error resulting from the latter reason will be present to a reduced extent for calculations on the full scale system. Because of this possible effect when scaling and in order to predict conservative (high) full scale erosion rates, the predicted erosion at surface temperatures above 2500°R will be based on diffusion limited model (Equations 3 and 5) where the predicted regression is equal to 100 percent of the theoretical regression.

Calculations based on this conservative diffusion-limited model were carried out for the full scale NERVA nozzle for a chamber pressure of 450 psia and a stagnation temperature of 4250°R (Reference g). The resulting predictions are shown on Figure 3 for expansion ratios 24:1 to 50:1. The maximum predicted regression is 5.85 mils/hour at an expansion ratio of 24:1. This value reduced to 1.38 mils/hour at an expansion ratio of 50:1. Slightly beyond the location corresponding to 50:1, the wall temperature reduces to a value below 2500°R and the regression rate should reduce to a negligible value.

Valuable substantiation of the conclusion regarding the erosion mechanism reached in this report could be obtained by including test data from systems with significantly higher values of mass transfer coefficient. There are raw data available from NASS AGCarb erosion tests that should meet this requirement. At present there are no plans to reduce these data because the current NASS diffuser design excludes the use of AGCarb as a liner material. It is recommended that these data points be reduced and the results added to Figure 2 of the present report.

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C*****00000010
C*          *00000020
C*    AGCARB DATA CORRELATION PROGRAM    J J WILLIAMS    5 MAY 1970    *00000030
C*          *00000040
C*****00000050
C          00000060
C    INPUT IS THE FOLLOWING BY FORMAT 2          00000070
C    (1) TEST NUMBER                               TN    00000080
C    (2) SPLCIMEN TYPE                             ST(4) 00000090
C    (3) DURATION, MIN                             TIME 00000100
C    (4) CHAMBER TEMPERATURE, DEG R                TC    00000110
C    (5) CHAMBER PRESSURE, PSIA                     PC    00000120
C    (6) SPECIFIC HEAT AT CONSTANT PRESSURE, BTU/LBM-DEG R CP    00000130
C    (7) MEASURED BACK SIDE TEMPERATURE, DEG R      TM    00000140
C    (8) PRANDTL/SCHMIDT NUMBLRS                   POS    00000150
C    (9) DENSITY, LB/CU FT                          DLN    00000160
C    (10) NOTES                                     STAT 00000170
C          *****START SECOND INPUT CARD HERE***** 00000180
C          00000190
C    (11) EXPANSION RATIO AT SECTIONS A AND E        CA    00000200
C    (12) WALL TEMPERATURE AT SECTIONS A AND E, DEG R TWA    00000210
C    (13) HEAT TRANS COEF AT SECTIONS A AND E, BTU/HR-SQ FT-HR HA    00000220
C    (14) EROSION AT STATION A, IN                  FRA    00000230
C    (15) EROSION AT STATION E, IN                  LRE    00000240
C    (16) PRESSURE AT STATION A, PSIA                 PI    00000250
C          *****START THIRD INPUT CARD HERE***** 00000260
C          00000270
C    (17) EXPANSION RATIO AT SECTIONS B AND F        EB    00000280
C    (18) WALL TEMPERATURE AT SECTIONS B AND F, DEG R TWB    00000290
C    (19) HEAT TRANS COEF AT SECTIONS B AND F, BTU/HR-SQ FT-HR HB    00000300
C    (20) EROSION AT STATION B, IN                   ERB    00000310
C    (21) EROSION AT STATION F, IN                   LRF    00000320
C    (22) PRESSURE AT STATION B, PSIA                  P2    00000330
C          *****START FOURTH INPUT CARD HERE***** 00000340
C          00000350
C    (23) EXPANSION RATIO AT SECTIONS C AND G        EC    00000360
C    (24) WALL TEMPERATURE AT SECTIONS C AND G, DEG R TWC    00000370
C    (25) HEAT TRANS COEF AT SECTIONS C AND G, BTU/HR-SQ FT-HR HC    00000380
C    (26) EROSION AT STATION C, IN                    ERC    00000390
C    (27) EROSION AT STATION G, IN                    ERG    00000400
C    (28) PRESSURE AT STATION C, PSIA                   P3    00000410
C          *****START FIFTH INPUT CARD HERE***** 00000420
C          00000430
C    (29) EXPANSION RATIO AT SECTIONS D AND H        ED    00000440
C    (30) WALL TEMPERATURE AT SECTIONS D AND H, DEG R TWD    00000450
C    (31) HEAT TRANS COEF AT SECTIONS D AND H, BTU/HR-SQ FT-HR HD    00000460
C    (32) EROSION AT STATION D, IN                    ERD    00000470
C    (33) EROSION AT STATION H, IN                    LRH    00000480
C    (34) PRESSURE AT STATION D, PSIA                   P4    00000490
C          00000500
C    DIMENSION ST(4),STAT(5),TITLE(5),HTAB(6,11),PTAB(6,11),TTAB(11)
C    DATA FASET,EBSET,ECSET,LDSET/2.927,4.627,6.595,8.954/
C    DATA PTAB/.2,.5,1.25,3.04,10.,30.,2,.5,1.25,3.04,10.,30.,
C    1.2,.5,1.25,3.04,10.,30.,2,.5,1.25,3.04,10.,30.,
C    2.2,.5,1.25,3.04,10.,30.,2,.5,1.25,3.04,10.,30.,
C    3.2,.5,1.25,3.04,10.,30.,2,.5,1.25,3.04,10.,30.,
C    4.2,.5,1.25,3.04,10.,30.,2,.5,1.25,3.04,10.,30.,
C    5.2,.5,1.25,3.04,10.,30.,
C    DATA TTAB/1800.,2000.,2200.,2400.,2600.,2800.,3000.,3200.,
C    13400.,3600.,3800./
C    DATA HTAB/.0078,.0190,.0460,.10.,26.,64.,00265.,0066.,0163,
C    1.038,.11.,28.,00108.,0027.,0067.,016.,05.,13.,00051.,00124,
C    2.00317.,00765.,025.,069.,00032.,00072.,0017.,0040.,013.,039,
C    3.00037.,00062.,0017.,0025.,00785.,023.,00079.,00094.,00129,
C    4.0022.,0056.,015.,0019.,00205.,0023.,00285.,0051.,0112,
C    5.0042.,00452.,0049.,00522.,00698.,0112.,008.,0093.,0098,
C    6.0103.,0117.,0149.,0157.,0175.,0186.,0197.,0218.,0238/
C    1 FORMAT('1')
C    2 FORMAT(A4,4A4,7F6.1,5A2/6F10.1/6F10.1/6F10.1/6F10.1)
C    3 FORMAT(/2X,'TEST' SPLCIMEN TYPE DURATION TC PC,5X)
0001
0002
0003
0004
0005
0006
0007
0008
```


FORTRAN IV G LEVEL 1. MOD 3

MAIN

DATE = 70146

13/18/51

PAGE 0003

0036	RATIOB=XMDB/HDB	00001410
0037	RATIOC=XMDC/HDC	00001420
0038	RATIOD=XMDD/HDD	00001430
0039	RATIOE=XMDE/HDE	00001440
0040	RATIOF=XMDF/HDF	00001450
0041	RATIOG=XMDG/HDG	00001460
0042	RATIOH=XMDH/HDD	00001470
0043	K=0	00001480
0044	IF (ABS(EA-EASET).GT.0.005) K=1	00001490
0045	IF (ABS(LB-EBSET).GT.0.005) K=1	00001500
0046	IF (ABS(EC-ECSET).GT.0.005) K=1	00001510
0047	IF (ABS(ED-EDSET).GT.0.005) K=1	00001520
0048	IF (K.EQ.1) WRITE(6,9)	00001530
0049	IF (K.EQ.1) GO TO 10	00001540
0050	AA=60.E3*ERA/TIME/P1	00001550
0051	AE=60.E3*ELRE/TIME/P1	00001560
0052	AH=60.E3*ELRU/TIME/P2	00001570
0053	AF=60.E3*ERF/TIME/P2	00001580
0054	AC=60.E3*ERC/TIME/P3	00001590
0055	AG=60.E3*ERG/TIME/P3	00001600
0056	AD=60.E3*ERD/TIME/P4	00001610
0057	AH=60.E3*ERH/TIME/P4	00001620
0058	WRITE(6,4) P1,ERA,TWA,HA,RATIOA,AA,P1,ERE,TWA,HA,RATIOE,AE	00001630
0059	WRITE(6,5) P2,ERB,TWB,HB,RATIOB,AB,P2,ERF,TWB,HB,RATIOF,AF	00001640
0060	WRITE(6,6) P3,ERC,TWC,HC,RATIOC,AC,P3,ERG,TWC,HC,RATIOG,AG	00001650
0061	WRITE(6,7) P4,ERD,TWD,HD,RATIOD,AD,P4,ERH,TWD,HD,RATIOH,AH	00001660
0062	CALL DINTP(PTAB,TTAB,HTAB,6,11,P1,TWA,HA,E)	00001670
0063	CALL DINTP(PTAB,TTAB,HTAB,6,11,P2,TWB,HB,F)	00001680
0064	CALL DINTP(PTAB,TTAB,HTAB,6,11,P3,TWC,HC,G)	00001690
0065	CALL DINTP(PTAB,TTAB,HTAB,6,11,P4,TWD,HD,H)	00001700
0066	RA=RATIOA/FAE	00001710
0067	RE=RATIOE/FAE	00001720
0068	RB=RATIOB/HBF	00001730
0069	RF=RATIOF/HBF	00001740
0070	RC=RATIOC/HCG	00001750
0071	RG=RATIOG/HCG	00001760
0072	RD=RATIOD/HDH	00001770
0073	RH=RATIOH/HDH	00001780
0074	TW11=10000./TWA	00001790
0075	TW12=10000./TWB	00001800
0076	TW13=10000./TWC	00001810
0077	TW14=10000./TWD	00001820
0078	WRITE(6,200) TWA,TW11,RA,RE,TWB,TW12,RF,TWC,TW13,RC,RG,	00001830
	1 TWD,TW14,RD,RH	00001840
0079	GO TO 10	00001850
0080	100 WRITE(6,8)	00001860
0081	STOP	00001870
0082	END	00001880

TEST	SPECIMEN TYPE	DURATION (MIN)	TC (DEG R)	PC (PSIA)	SPECIFIC HEAT (BTU/LBM-DEG R)	BACK SIDE TEMP (DEG R)	PR/SC (-)	DENSITY (LB/CU FT)	NOTES
W110	PAR. CONTOUR	30.00	4511.0	217.0	5.23	2954.0	0.65	85.00	
LOCATION A	PRESS = 11.91 PSIA	EROSION = 0.00460 IN	TW = 2078. DEG R	H = 451. B/HR-FT-R	HD/M = 0.001006	R/P = 0.7725	MILS/HR/P		
LOCATION E	PRESS = 11.91 PSIA	EROSION = 0.00430 IN	TW = 2078. DEG R	H = 451. B/HR-FT-R	HD/M = 0.000941	R/P = 0.7221	MILS/HR/P		
LOCATION B	PRESS = 5.21 PSIA	EROSION = 0.00090 IN	TW = 2834. DEG R	H = 242. B/HR-FT-R	HD/M = 0.000367	R/P = 0.3455	MILS/HR/P		
LOCATION F	PRESS = 5.21 PSIA	EROSION = 0.00150 IN	TW = 2834. DEG R	H = 242. B/HR-FT-R	HD/M = 0.000612	R/P = 0.5758	MILS/HR/P		
LOCATION C	PRESS = 2.53 PSIA	EROSION = 0.00080 IN	TW = 2897. DEG R	H = 155. B/HR-FT-R	HD/M = 0.000509	R/P = 0.6324	MILS/HR/P		
LOCATION G	PRESS = 2.53 PSIA	EROSION = 0.00090 IN	TW = 2897. DEG R	H = 155. B/HR-FT-R	HD/M = 0.000573	R/P = 0.7115	MILS/HR/P		
LOCATION D	PRESS = 1.64 PSIA	EROSION = 0.00030 IN	TW = 1881. DEG R	H = 123. B/HR-FT-R	HD/M = 0.000241	R/P = 0.3659	MILS/HR/P		
LOCATION H	PRESS = 1.64 PSIA	EROSION = 0.00030 IN	TW = 1881. DEG R	H = 123. B/HR-FT-R	HD/M = 0.000241	R/P = 0.3659	MILS/HR/P		

PLOT DATA

WALL TEMPERATURE 1/TW * 10000

DIFFUSION RATIOS

2078.	4.8123	0.0101156	0.0094559
2834.	3.5286	0.0901383	0.1502306
2897.	3.4518	0.2454356	0.2761151
1881.	5.3163	0.0056112	0.0056112

TEST	SPECIMEN TYPE	DURATION (MIN)	TC (DEG R)	PC (PSIA)	SPECIFIC HEAT (BTU/LBM-DEG R)	BACK SIDE TEMP (DEG R)	PR/SC (-)	DENSITY (LB/CU FT)	NOTES
W111	PAR. CONTOUR	30.00	4628.0	186.0	5.27	2968.0	0.65	85.00	
LOCATION A	PRESS = 9.83 PSIA	EROSION = 0.00130 IN	TW = 2033. DEG R	H = 415. B/HR-FT-R	HD/M = 0.000311	R/P = 0.2645	MILS/HR/P		
LOCATION E	PRESS = 9.83 PSIA	EROSION = 0.00160 IN	TW = 2033. DEG R	H = 415. B/HR-FT-R	HD/M = 0.000383	R/P = 0.3255	MILS/HR/P		
LOCATION B	PRESS = 4.41 PSIA	EROSION = 0.00070 IN	TW = 2829. DEG R	H = 216. B/HR-FT-R	HD/M = 0.000322	R/P = 0.3175	MILS/HR/P		
LOCATION F	PRESS = 4.41 PSIA	EROSION = 0.00090 IN	TW = 2829. DEG R	H = 216. B/HR-FT-R	HD/M = 0.000414	R/P = 0.4082	MILS/HR/P		
LOCATION C	PRESS = 2.16 PSIA	EROSION = 0.00050 IN	TW = 2919. DEG R	H = 137. B/HR-FT-R	HD/M = 0.000363	R/P = 0.4630	MILS/HR/P		
LOCATION G	PRESS = 2.16 PSIA	EROSION = 0.00050 IN	TW = 2919. DEG R	H = 137. B/HR-FT-R	HD/M = 0.000363	R/P = 0.4630	MILS/HR/P		
LOCATION D	PRESS = 1.40 PSIA	EROSION = 0.0	TW = 1880. DEG R	H = 109. B/HR-FT-R	HD/M = 0.0	R/P = 0.0	MILS/HR/P		
LOCATION H	PRESS = 1.40 PSIA	EROSION = 0.00010 IN	TW = 1880. DEG R	H = 109. B/HR-FT-R	HD/M = 0.000091	R/P = 0.1429	MILS/HR/P		

PLOT DATA

WALL TEMPERATURE 1/TW * 10000

DIFFUSION RATIOS

2033.	4.9188	0.0031626	0.0038924
2829.	3.5348	0.0914820	0.1176198
2919.	3.4258	0.1997260	0.1997260
1880.	5.3191	0.0	0.0024287

TEST	SPECIMEN TYPE	DURATION (MIN)	TC (DEG R)	PC (PSIA)	SPECIFIC HEAT (BTU/LBM-DEG R)	BACK SIDE TEMP (DEG R)	PR/SC (-)	DENSITY (LB/CU FT)	NOTES
W112	PAR. CONTOUR	60.00	4593.0	206.0	5.23	2124.0	0.65	85.00	
LOCATION A	PRESS = 11.19 PSIA	EROSION = 0.00420 IN	TW = 1843. DEG R	H = 448. B/HR-FT-R	HD/M = 0.000462	R/P = 0.3753 MILS/HR/P			
LOCATION E	PRESS = 11.19 PSIA	EROSION = 0.00450 IN	TW = 1843. DEG R	H = 448. B/HR-FT-R	HD/M = 0.000496	R/P = 0.4021 MILS/HR/P			
LOCATION B	PRESS = 5.02 PSIA	EROSION = 0.00220 IN	TW = 2280. DEG R	H = 292. B/HR-FT-R	HD/M = 0.000372	R/P = 0.4382 MILS/HR/P			
LOCATION F	PRESS = 5.02 PSIA	EROSION = 0.00220 IN	TW = 2280. DEG R	H = 292. B/HR-FT-R	HD/M = 0.000372	R/P = 0.4382 MILS/HR/P			
LOCATION C	PRESS = 2.39 PSIA	EROSION = 0.00120 IN	TW = 2211. DEG R	H = 157. B/HR-FT-R	HD/M = 0.000377	R/P = 0.5021 MILS/HR/P			
LOCATION G	PRESS = 2.39 PSIA	EROSION = 0.00160 IN	TW = 2211. DEG R	H = 157. B/HR-FT-R	HD/M = 0.000503	R/P = 0.5695 MILS/HR/P			
LOCATION D	PRESS = 1.53 PSIA	EROSION = 0.00100 IN	TW = 1531. DEG R	H = 120. B/HR-FT-R	HD/M = 0.000411	R/P = 0.6536 MILS/HR/P			
LOCATION H	PRESS = 1.53 PSIA	EROSION = 0.00080 IN	TW = 1531. DEG R	H = 120. B/HR-FT-R	HD/M = 0.000329	R/P = 0.5229 MILS/HR/P			

PLOT DATA

WALL TEMPERATURE 1/TW * 10000

DIFFUSION RATIOS

1943.	5.4259	0.0018673	0.0020007
2280.	4.3860	0.0181860	0.0181860
2211.	4.5228	0.0307567	0.0410076
1531.	6.5317	0.0040627	0.0032502

TEST	SPECIMEN TYPE	DURATION (MIN)	TC (DEG R)	PC (PSIA)	SPECIFIC HEAT (BTU/LBM-DEG R)	BACK SIDE TEMP (DEG R)	PR/SC (-)	DENSITY (LB/CU FT)	NOTES
W114	PAR. CONTOUR	58.00	4588.0	207.0	5.23	3373.0	0.65	85.00	
LOCATION A	PRESS = 11.27 PSIA	EROSION = 0.00410 IN	TW = 2263. DEG R	H = 440. B/HR-FT-R	HD/M = 0.000476	R/P = 0.3763 MILS/HR/P			
LOCATION I	PRESS = 11.27 PSIA	EROSION = 0.00540 IN	TW = 2263. DEG R	H = 440. B/HR-FT-R	HD/M = 0.000626	R/P = 0.4957 MILS/HR/P			
LOCATION B	PRESS = 5.04 PSIA	EROSION = 0.00260 IN	TW = 3442. DEG R	H = 220. B/HR-FT-R	HD/M = 0.000603	R/P = 0.5337 MILS/HR/P			
LOCATION F	PRESS = 5.04 PSIA	EROSION = 0.00190 IN	TW = 3442. DEG R	H = 220. B/HR-FT-R	HD/M = 0.000441	R/P = 0.3900 MILS/HR/P			
LOCATION C	PRESS = 2.40 PSIA	EROSION = 0.00240 IN	TW = 3643. DEG R	H = 137. B/HR-FT-R	HD/M = 0.000894	R/P = 1.0345 MILS/HR/P			
LOCATION G	PRESS = 2.40 PSIA	EROSION = 0.00180 IN	TW = 3643. DEG R	H = 137. B/HR-FT-R	HD/M = 0.000671	R/P = 0.7759 MILS/HR/P			
LOCATION D	PRESS = 1.55 PSIA	EROSION = 0.00100 IN	TW = 2287. DEG R	H = 115. B/HR-FT-R	HD/M = 0.000444	R/P = 0.6674 MILS/HR/P			
LOCATION H	PRESS = 1.55 PSIA	EROSION = 0.00070 IN	TW = 2287. DEG R	H = 115. B/HR-FT-R	HD/M = 0.000399	R/P = 0.6007 MILS/HR/P			

PLOT DATA

WALL TEMPERATURE 1/TW * 10000

DIFFUSION RATIOS

2263.	4.4189	0.0102299	0.0134736
3442.	2.9053	0.0890766	0.0650944
3643.	2.7450	0.0739093	0.0554320
2287.	4.3725	0.0696467	0.0626820

TEST	SPECIMEN TYPE	DURATION (MIN)	TC (DEG R)	PC (PSIA)	SPECIFIC HEAT (BTU/LBM-DEG R)	BACK SIDE TEMP (DEG R)	PR/SC (-)	DENSITY (LB/CU FT)	NOTES
W115	PAR. CONTOUR	60.00	4638.0	147.0	5.43	3017.0	0.65	85.00	
LOCATION A	PRESS = 7.76 PSIA	EROSION = 0.00560 IN	TW = 2009. DEG R	H = 351. B/HR-FT-R	HD/M = 0.000818	R/P = 0.7216 MILS/HR/P			
LOCATION E	PRESS = 7.76 PSIA	EROSION = 0.00620 IN	TW = 2009. DEG R	H = 351. B/HR-FT-R	HD/M = 0.000905	R/P = 0.7990 MILS/HR/P			
LOCATION B	PRESS = 3.53 PSIA	EROSION = 0.00270 IN	TW = 2860. DEG R	H = 187. B/HR-FT-R	HD/M = 0.000740	R/P = 0.7649 MILS/HR/P			
LOCATION F	PRESS = 3.53 PSIA	EROSION = 0.00230 IN	TW = 2860. DEG R	H = 187. B/HR-FT-R	HD/M = 0.000630	R/P = 0.6516 MILS/HR/P			
LOCATION C	PRESS = 1.70 PSIA	EROSION = 0.00210 IN	TW = 3942. DEG R	H = 119. B/HR-FT-R	HD/M = 0.000905	R/P = 1.2353 MILS/HR/P			
LOCATION G	PRESS = 1.70 PSIA	EROSION = 0.00140 IN	TW = 3942. DEG R	H = 119. B/HR-FT-R	HD/M = 0.000603	R/P = 0.8235 MILS/HR/P			
LOCATION D	PRESS = 1.11 PSIA	EROSION = 0.00030 IN	TW = 1868. DEG R	H = 97. B/HR-FT-R	HD/M = 0.000159	R/P = 0.2703 MILS/HR/P			
LOCATION H	PRESS = 1.11 PSIA	EROSION = 0.00160 IN	TW = 1868. DEG R	H = 97. B/HR-FT-R	HD/M = 0.000845	R/P = 1.4414 MILS/HR/P			

PLOT DATA

WALL TEMPERATURE	1/TW * 10000	DIFFUSION RATIOS
2009.	4.9776	0.0096577
2360.	3.4965	0.2633264
3942.	2.5368	0.0358500
1868.	5.3533	0.0049603

TEST	SPECIMEN TYPE	DURATION (MIN)	TC (DEG R)	PC (PSIA)	SPECIFIC HEAT (BTU/LBM-DEG R)	BACK SIDE TEMP (DEG R)	PR/SC (-)	DENSITY (LB/CU FT)	NOTES
W116	PAR. CONTOUR	30.00	4651.0	147.0	5.43	3912.0	0.65	85.00	
LOCATION A	PRESS = 7.98 PSIA	EROSION = 0.00460 IN	TW = 2308. DEG R	H = 347. B/HR-FT-R	HD/M = 0.001359	R/P = 1.1529 MILS/HR/P			
LOCATION E	PRESS = 7.98 PSIA	EROSION = 0.00530 IN	TW = 2308. DEG R	H = 347. B/HR-FT-R	HD/M = 0.001566	R/P = 1.3283 MILS/HR/P			
LOCATION B	PRESS = 3.58 PSIA	EROSION = 0.00130 IN	TW = 3532. DEG R	H = 160. B/HR-FT-R	HD/M = 0.000833	R/P = 0.7263 MILS/HR/P			
LOCATION F	PRESS = 3.58 PSIA	EROSION = 0.00190 IN	TW = 3532. DEG R	H = 160. B/HR-FT-R	HD/M = 0.001217	R/P = 1.0615 MILS/HR/P			
LOCATION C	PRESS = 1.70 PSIA	EROSION = 0.00120 IN	TW = 3741. DEG R	H = 97. B/HR-FT-R	HD/M = 0.001268	R/P = 1.4118 MILS/HR/P			
LOCATION G	PRESS = 1.70 PSIA	EROSION = 0.00150 IN	TW = 3741. DEG R	H = 97. B/HR-FT-R	HD/M = 0.001585	R/P = 1.7647 MILS/HR/P			
LOCATION D	PRESS = 1.10 PSIA	EROSION = 0.00010 IN	TW = 2336. DEG R	H = 89. B/HR-FT-R	HD/M = 0.000115	R/P = 0.1618 MILS/HR/P			
LOCATION H	PRESS = 1.10 PSIA	EROSION = 0.00040 IN	TW = 2336. DEG R	H = 89. B/HR-FT-R	HD/M = 0.000461	R/P = 0.7273 MILS/HR/P			

PLOT DATA

WALL TEMPERATURE	1/TW * 10000	DIFFUSION RATIOS
2308.	4.3328	0.0464749
3532.	2.8313	0.0958406
3741.	2.6731	0.0781127
2336.	4.2808	0.0304637

TEST	SPECIMEN TYPE	DURATION (MIN)	TC (DEG R)	PC (PSIA)	SPECIFIC HEAT (BTU/LBM-DEG R)	BACK SIDE TEMP (DEG R)	PR/SC (-)	DENSITY (LB/CU FT)	NOTES
W117	PAR. CONTOUR	29.00	4640.0	143.0	5.47	3805.0	0.65	85.00	
LOCATION A	PRESS = 7.45 PSIA	EROSION = 0.00200 IN	TW = 2109. DEG R	H = 339. B/HR-FT-R	HD/M = 0.000630	R/P = 0.5554 MILS/HR/P			
LOCATION E	PRESS = 7.45 PSIA	EROSION = 0.00150 IN	TW = 2109. DEG R	H = 339. B/HR-FT-R	HD/M = 0.000473	R/P = 0.4166 MILS/HR/P			
LOCATION B	PRESS = 3.43 PSIA	EROSION = 0.00070 IN	TW = 3283. DEG R	H = 156. B/HR-FT-R	HD/M = 0.000479	R/P = 0.4222 MILS/HR/P			
LOCATION F	PRESS = 3.43 PSIA	EROSION = 0.00100 IN	TW = 3283. DEG R	H = 156. B/HR-FT-R	HD/M = 0.000685	R/P = 0.6032 MILS/HR/P			
LOCATION C	PRESS = 1.64 PSIA	EROSION = 0.00080 IN	TW = 3588. DEG R	H = 98. B/HR-FT-R	HD/M = 0.000872	R/P = 1.0093 MILS/HR/P			
LOCATION G	PRESS = 1.64 PSIA	EROSION = 0.00110 IN	TW = 3588. DEG R	H = 98. B/HR-FT-R	HD/M = 0.001199	R/P = 1.3877 MILS/HR/P			
LOCATION D	PRESS = 1.07 PSIA	EROSION = 0.00010 IN	TW = 2209. DEG R	H = 88. B/HR-FT-R	HD/M = 0.000121	R/P = 0.1934 MILS/HR/P			
LOCATION H	PRESS = 1.07 PSIA	EROSION = 0.00050 IN	TW = 2209. DEG R	H = 88. B/HR-FT-R	HD/M = 0.000607	R/P = 0.9608 MILS/HR/P			

PLOT DATA

WALL TEMPERATURE 1/TW * 10000

DIFFUSION RATIOS

2109.	4.7416	0.0107725	0.0080793
3283.	3.0460	0.1214153	0.1734504
3588.	2.7871	0.0907692	0.1248077
2209.	4.5269	0.0216651	0.1083253

TEST	SPECIMEN TYPE	DURATION (MIN)	TC (DEG R)	PC (PSIA)	SPECIFIC HEAT (BTU/LBM-DEG R)	BACK SIDE TEMP (DEG R)	PR/SC (-)	DENSITY (LB/CU FT)	NOTES
W118	PAR. CTR. LINE	60.00	4606.0	205.0	5.23	2999.0	0.65	85.00	
LOCATION A	PRESS = 10.89 PSIA	EROSION = 0.00370 IN	TW = 2070. DEG R	H = 436. B/HR-FT-R	HD/M = 0.000419	R/P = 0.3398 MILS/HR/P			
LOCATION E	PRESS = 10.89 PSIA	EROSION = 0.00330 IN	TW = 2070. DEG R	H = 436. B/HR-FT-R	HD/M = 0.000373	R/P = 0.3030 MILS/HR/P			
LOCATION B	PRESS = 4.95 PSIA	EROSION = 0.00330 IN	TW = 2826. DEG R	H = 227. B/HR-FT-R	HD/M = 0.000717	R/P = 0.6667 MILS/HR/P			
LOCATION F	PRESS = 4.95 PSIA	EROSION = 0.00420 IN	TW = 2826. DEG R	H = 227. B/HR-FT-R	HD/M = 0.000913	R/P = 0.8485 MILS/HR/P			
LOCATION C	PRESS = 2.40 PSIA	EROSION = 0.00190 IN	TW = 2880. DEG R	H = 145. B/HR-FT-R	HD/M = 0.000646	R/P = 0.7917 MILS/HR/P			
LOCATION G	PRESS = 2.40 PSIA	EROSION = 0.00170 IN	TW = 2880. DEG R	H = 145. B/HR-FT-R	HD/M = 0.000578	R/P = 0.7083 MILS/HR/P			
LOCATION D	PRESS = 1.56 PSIA	EROSION = 0.00080 IN	TW = 1878. DEG R	H = 116. B/HR-FT-R	HD/M = 0.000340	R/P = 0.5128 MILS/HR/P			
LOCATION H	PRESS = 1.56 PSIA	EROSION = 0.00070 IN	TW = 1878. DEG R	H = 116. B/HR-FT-R	HD/M = 0.000298	R/P = 0.4487 MILS/HR/P			

PLOT DATA

WALL TEMPERATURE 1/TW * 10000

DIFFUSION RATIOS

2070.	4.8309	0.0043992	0.0039236
2826.	3.5386	0.1828232	0.2326839
2880.	3.4722	0.3216807	0.2878196
1878.	5.3248	0.0081809	0.0071583

TEST	SPECIMEN TYPE	DURATION (MIN)	TC (DEG R)	PC (PSIA)	SPECIFIC HEAT (BTU/LBM-DEG R)	BACK SIDE TEMP (DEG R)	PR/SC (-)	DENSITY (LB/CU FT)	NOTES
W119	PAR. CONTOUR	60.00	4639.0	151.0	5.43	2123.0	0.65	85.00	
LOCATION A	PRESS = 7.76 PSIA	EROSION = 0.00280 IN	TW = 1732. DEG R	H = 394. B/HR-FT-R	HD/M = 0.000364	R/P = 0.3608 MILS/HR/P			
LOCATION E	PRESS = 7.76 PSIA	EROSION = 0.00370 IN	TW = 1732. DEG R	H = 394. B/HR-FT-R	HD/M = 0.000481	R/P = 0.4768 MILS/HR/P			
LOCATION B	PRESS = 3.45 PSIA	EROSION = 0.00390 IN	TW = 2173. DEG R	H = 211. B/HR-FT-R	HD/M = 0.000947	R/P = 1.1304 MILS/HR/P			
LOCATION F	PRESS = 3.45 PSIA	EROSION = 0.00300 IN	TW = 2173. DEG R	H = 211. B/HR-FT-R	HD/M = 0.000729	R/P = 0.8696 MILS/HR/P			
LOCATION C	PRESS = 1.70 PSIA	EROSION = 0.00080 IN	TW = 2126. DEG R	H = 134. B/HR-FT-R	HD/M = 0.000306	R/P = 0.4706 MILS/HR/P			
LOCATION G	PRESS = 1.70 PSIA	EROSION = 0.00120 IN	TW = 2126. DEG R	H = 134. B/HR-FT-R	HD/M = 0.000459	R/P = 0.7059 MILS/HR/P			
LOCATION D	PRESS = 1.12 PSIA	EROSION = 0.00080 IN	TW = 1467. DEG R	H = 102. B/HR-FT-R	HD/M = 0.000402	R/P = 0.7143 MILS/HR/P			
LOCATION H	PRESS = 1.12 PSIA	EROSION = 0.00050 IN	TW = 1467. DEG R	H = 102. B/HR-FT-R	HD/M = 0.000251	R/P = 0.4464 MILS/HR/P			

PLOT DATA

WALL TEMPERATURE	1/TW * 10000	DIFFUSION RATIOS
1732.	5.7737	0.0014578
2173.	4.6019	0.0445321
2126.	4.7037	0.0222665
1467.	6.8166	0.0046868

TEST	SPECIMEN TYPE	DURATION (MIN)	TC (DEG R)	PC (PSIA)	SPECIFIC HEAT (BTU/LBM-DEG R)	BACK SIDE TEMP (DEG R)	PR/SC (-)	DENSITY (LB/CU FT)	NOTES
W123	PAR. CONTOUR	49.00	4597.0	239.0	5.16	2132.0	0.65	85.00	
LOCATION A	PRESS = 12.96 PSIA	EROSION = 0.00370 IN	TW = 1909. DEG R	H = 489. B/HR-FT-R	HD/M = 0.000451	R/P = 0.3496 MILS/HR/P			
LOCATION E	PRESS = 12.96 PSIA	EROSION = 0.00240 IN	TW = 1909. DEG R	H = 489. B/HR-FT-R	HD/M = 0.000293	R/P = 0.2268 MILS/HR/P			
LOCATION B	PRESS = 5.69 PSIA	EROSION = 0.00170 IN	TW = 2302. DEG R	H = 264. B/HR-FT-R	HD/M = 0.000384	R/P = 0.3658 MILS/HR/P			
LOCATION F	PRESS = 5.69 PSIA	EROSION = 0.00170 IN	TW = 2302. DEG R	H = 264. B/HR-FT-R	HD/M = 0.000384	R/P = 0.3658 MILS/HR/P			
LOCATION C	PRESS = 2.70 PSIA	EROSION = 0.00210 IN	TW = 2221. DEG R	H = 171. B/HR-FT-R	HD/M = 0.000732	R/P = 0.9524 MILS/HR/P			
LOCATION G	PRESS = 2.70 PSIA	EROSION = 0.00170 IN	TW = 2221. DEG R	H = 171. B/HR-FT-R	HD/M = 0.000593	R/P = 0.7710 MILS/HR/P			
LOCATION D	PRESS = 1.76 PSIA	EROSION = 0.00040 IN	TW = 1563. DEG R	H = 130. B/HR-FT-R	HD/M = 0.000194	R/P = 0.2783 MILS/HR/P			
LOCATION H	PRESS = 1.76 PSIA	EROSION = 0.00120 IN	TW = 1563. DEG R	H = 130. B/HR-FT-R	HD/M = 0.000551	R/P = 0.8349 MILS/HR/P			

PLOT DATA

WALL TEMPERATURE	1/TW * 10000	DIFFUSION RATIOS
1909.	5.2383	0.0020744
2302.	4.3440	0.0179023
2221.	4.5025	0.0544470
1563.	6.3980	0.0017074

TEST	SPECIMEN TYPE	DURATION (MIN)	TC (DEG R)	PC (PSIA)	SPECIFIC HEAT (BTU/LBM-DEG R)	BACK SIDE TEMP (DEG R)	PR/SC (-)	DENSITY (LB/CU FT)	NOTES
W130	R. CONTOUR	60.00	4645.0	245.0	5.15	3032.0	0.65	85.00	
LOCATION A	PRESS = 13.47 PSIA	EROSION = 0.00390 IN	TW = 2177. DEG R	H = 490. B/HR-FT-R	HD/M = 0.000884	R/P = 0.6607	MILS/HR/P		
LOCATION E	PRESS = 13.47 PSIA	EROSION = 0.00300 IN	TW = 2177. DEG R	H = 490. B/HR-FT-R	HD/M = 0.000794	R/P = 0.5939	MILS/HR/P		
LOCATION B	PRESS = 6.13 PSIA	EROSION = 0.00240 IN	TW = 2913. DEG R	H = 26. B/HR-FT-R	HD/M = 0.000449	R/P = 0.3915	MILS/HR/P		
LOCATION F	PRESS = 6.13 PSIA	EROSION = 0.00280 IN	TW = 2913. DEG R	H = 26. B/HR-FT-R	HD/M = 0.000524	R/P = 0.4568	MILS/HR/P		
LOCATION C	PRESS = 2.9 PSIA	EROSION = 0.00150 IN	TW = 2958. DEG R	H = 1. B/HR-FT-R	HD/M = 0.000442	R/P = 0.5172	MILS/HR/P		
LOCATION G	PRESS = 2.9 PSIA	EROSION = 0.00210 IN	TW = 2958. DEG R	H = 1. B/HR-FT-R	HD/M = 0.000619	R/P = 0.5172	MILS/HR/P		
LOCATION D	PRESS = 1.8 PSIA	EROSION = 0.00070 IN	TW = 1940. DEG R	H = 1. B/HR-FT-R	HD/M = 0.000262	R/P = 0.3743	MILS/HR/P		
LOCATION I	PRESS = 1.8 PSIA	EROSION = 0.00120 IN	TW = 1940. DEG R	H = 1. B/HR-FT-R	HD/M = 0.000449	R/P = 0.5172	MILS/HR/P		

PLOT DATA

TEMPERATURE

W * 10000

DIFFUSION RATIOS

2177.	4.5935	0.0121761	0.010944
2913.	3.4329	0.1059011	0.1235513
2958.	3.3807	0.2006082	0.2808515
1940.	5.1546	0.0072959	0.0125073

TEST	SPECIMEN TYPE	DURATION (MIN)	TC (DEG R)	PC (PSIA)	SPECIFIC HEAT (BTU/LBM-DEG R)	BACK SIDE TEMP (DEG R)	PR/SC (-)	DENSITY (LB/CU FT)	NOTES
W139	PAR, CTR, LINE	60.00	4666.0	202.0	5.23	3801.0	0.65	85.00	
LOCATION A	PRESS = 10.0 PSIA	EROSION = 0.00380 IN	TW = 2271. DEG R	H = 484. B/HR-FT-R	HD/M = 0.000386	R/P = 0.2564	MILS/HR/P		
LOCATION B	PRESS = 10.0 PSIA	EROSION = 0.00310 IN	TW = 2271. DEG R	H = 484. B/HR-FT-R	HD/M = 0.000314	R/P = 0.2473	MILS/HR/P		
LOCATION C	PRESS = 4.4 PSIA	EROSION = 0.00380 IN	TW = 3440. DEG R	H = 208. B/HR-FT-R	HD/M = 0.000783	R/P = 0.6618	MILS/HR/P		
LOCATION D	PRESS = 4.4 PSIA	EROSION = 0.00380 IN	TW = 3440. DEG R	H = 208. B/HR-FT-R	HD/M = 0.000712	R/P = 0.6128	MILS/HR/P		
LOCATION E	PRESS = 2.7 PSIA	EROSION = 0.00220 IN	TW = 3651. DEG R	H = 129. B/HR-FT-R	HD/M = 0.000860	R/P = 0.9829	MILS/HR/P		
LOCATION F	PRESS = 2.7 PSIA	EROSION = 0.00190 IN	TW = 3651. DEG R	H = 129. B/HR-FT-R	HD/M = 0.000727	R/P = 0.6120	MILS/HR/P		
LOCATION G	PRESS = 1.52 PSIA	EROSION = 0.00190 IN	TW = 2295. DEG R	H = 109. B/HR-FT-R	HD/M = 0.000543	R/P = 0.7895	MILS/HR/P		
LOCATION H	PRESS = 1.52 PSIA	EROSION = 0.00080 IN	TW = 2295. DEG R	H = 109. B/HR-FT-R	HD/M = 0.000362	R/P = 0.5263	MILS/HR/P		

PLOT DATA

WALL TEMPERATURE

1/TW * 10000

DIFFUSION RATIOS

2271.	4.4033	0.0073677	0.0071046
3440.	2.9070	0.1172979	0.1066344
3651.	2.7390	0.0706956	0.0584007
2295.	4.3573	0.0893167	0.0595445

TEST	SPECIMEN TYPE	DURATION (MIN)	TC (DEG R)	PC (PSIA)	SPECIFIC HEAT (BTU/LBM-DEG R)	BACK SIDE TEMP (DEG R)	PR/SC (-)	DENSITY (LB/CU FT)	NOTES
W140	PAR. CONTOUR	38.00	4659.0	251.0	5.13	3827.0	0.65	85.00	
LOCATION A	PRESS = 13.72 PSIA	EROSION = 0.00850 IN	TW = 2358. DEG R	H = 483. B/HR-FT-R	HD/M = 0.001347	R/P = 0.9782	MILS/HR/P		
LOCATION E	PRESS = 13.72 PSIA	EROSION = 0.00800 IN	TW = 2358. DEG R	H = 483. B/HR-FT-R	HD/M = 0.001267	R/P = 0.9207	MILS/HR/P		
LOCATION B	PRESS = 6.36 PSIA	EROSION = 0.00300 IN	TW = 3502. DEG R	H = 246. B/HR-FT-R	HD/M = 0.000933	R/P = 0.7448	MILS/HR/P		
LOCATION F	PRESS = 6.36 PSIA	EROSION = 0.00210 IN	TW = 3502. DEG R	H = 246. B/HR-FT-R	HD/M = 0.000653	R/P = 0.5214	MILS/HR/P		
LOCATION C	PRESS = 3.05 PSIA	EROSION = 0.00220 IN	TW = 3684. DEG R	H = 155. B/HR-FT-R	HD/M = 0.001086	R/P = 1.1389	MILS/HR/P		
LOCATION G	PRESS = 3.05 PSIA	EROSION = 0.00170 IN	TW = 3684. DEG R	H = 155. B/HR-FT-R	HD/M = 0.000839	R/P = 0.8801	MILS/HR/P		
LOCATION D	PRESS = 1.95 PSIA	EROSION = 0.00120 IN	TW = 2351. DEG R	H = 126. B/HR-FT-R	HD/M = 0.000729	R/P = 0.9717	MILS/HR/P		
LOCATION H	PRESS = 1.95 PSIA	EROSION = 0.00060 IN	TW = 2351. DEG R	H = 126. B/HR-FT-R	HD/M = 0.000364	R/P = 0.4858	MILS/HR/P		

PLOT DATA

WALL TEMPERATURE 1/TW * 10000

DIFFUSION RATIOS

2358.	4.2409	0.0338015	0.0318132
3502.	2.8555	0.1089827	0.0762879
3684.	2.7144	0.0762165	0.0588945
2351.	4.2535	0.1166308	0.0583154

TEST	SPECIMEN TYPE	DURATION (MIN)	TC (DEG R)	PC (PSIA)	SPECIFIC HEAT (BTU/LBM-DEG R)	BACK SIDE TEMP (DEG R)	PR/SC (-)	DENSITY (LB/CU FT)	NOTES
W142	PAR. CONTOUR	60.00	3038.0	195.0	3.92	3045.0	0.65	85.00	
LOCATION A	PRESS = 10.35 PSIA	EROSION = 0.01140 IN	TW = 1616. DEG R	H = 375. B/HR-FT-R	HD/M = 0.001125	R/P = 1.1014	MILS/HR/P		
LOCATION E	PRESS = 10.35 PSIA	EROSION = 0.00950 IN	TW = 1616. DEG R	H = 375. B/HR-FT-R	HD/M = 0.000937	R/P = 0.9179	MILS/HR/P		
LOCATION B	PRESS = 4.89 PSIA	EROSION = 0.00190 IN	TW = 2526. DEG R	H = 185. B/HR-FT-R	HD/M = 0.000380	R/P = 0.3885	MILS/HR/P		
LOCATION F	PRESS = 4.89 PSIA	EROSION = 0.00170 IN	TW = 2526. DEG R	H = 185. B/HR-FT-R	HD/M = 0.000340	R/P = 0.3476	MILS/HR/P		
LOCATION C	PRESS = 2.31 PSIA	EROSION = 0.00210 IN	TW = 2795. DEG R	H = 114. B/HR-FT-R	HD/M = 0.000682	R/P = 0.9091	MILS/HR/P		
LOCATION G	PRESS = 2.31 PSIA	EROSION = 0.00120 IN	TW = 2795. DEG R	H = 114. B/HR-FT-R	HD/M = 0.000390	R/P = 0.6195	MILS/HR/P		
LOCATION D	PRESS = 1.45 PSIA	EROSION = 0.00140 IN	TW = 1716. DEG R	H = 93. B/HR-FT-R	HD/M = 0.000557	R/P = 0.9655	MILS/HR/P		
LOCATION H	PRESS = 1.45 PSIA	EROSION = 0.00100 IN	TW = 1716. DEG R	H = 93. B/HR-FT-R	HD/M = 0.000398	R/P = 0.6897	MILS/HR/P		

PLOT DATA

WALL TEMPERATURE 1/TW * 10000

DIFFUSION RATIOS

1616.	6.1881	0.0027569	0.0022975
2526.	3.9590	0.0443768	0.0397056
2795.	3.5774	0.0317243	0.1895568
1716.	5.8275	0.0084372	0.0060265

TEST	SPECIMEN TYPE	DURATION (MIN)	TC (DEG R)	PC (PSIA)	SPECIFIC HEAT (BTU/LBM-DEG R)	BACK SIDE TEMP (DEG R)	PR/SC (-)	DENSITY (LB/CU FT)	NOTES
W143	PAR. CONTOUR	60.00	3042.0	199.0	3.92	2117.0	0.65	85.00	
LOCATION A	PRESS = 10.38 PSIA	EROSION = 0.00090 IN	TW = 1382. DEG R	H = 382. B/HR-FT-R	HD/M = 0.000087	R/P = 0.0367 MILS/HR/P			
LOCATION B	PRESS = 10.38 PSIA	EROSION = 0.00090 IN	TW = 1382. DEG R	H = 382. B/HR-FT-R	HD/M = 0.000087	R/P = 0.0367 MILS/HR/P			
LOCATION C	PRESS = 4.65 PSIA	EROSION = 0.00080 IN	TW = 1915. DEG R	H = 200. B/HR-FT-R	HD/M = 0.000148	R/P = 0.1720 MILS/HR/P			
LOCATION D	PRESS = 4.65 PSIA	EROSION = 0.00080 IN	TW = 1915. DEG R	H = 200. B/HR-FT-R	HD/M = 0.000148	R/P = 0.1720 MILS/HR/P			
LOCATION E	PRESS = 2.28 PSIA	EROSION = 0.00060 IN	TW = 1994. DEG R	H = 126. B/HR-FT-R	HD/M = 0.000176	R/P = 0.2032 MILS/HR/P			
LOCATION F	PRESS = 2.28 PSIA	EROSION = 0.00060 IN	TW = 1994. DEG R	H = 126. B/HR-FT-R	HD/M = 0.000176	R/P = 0.2032 MILS/HR/P			
LOCATION G	PRESS = 1.50 PSIA	EROSION = 0.00030 IN	TW = 1348. DEG R	H = 97. B/HR-FT-R	HD/M = 0.000088	R/P = 0.1316 MILS/HR/P			
LOCATION H	PRESS = 1.50 PSIA	EROSION = 0.00030 IN	TW = 1348. DEG R	H = 97. B/HR-FT-R	HD/M = 0.000088	R/P = 0.1316 MILS/HR/P			
LOCATION I	PRESS = 1.50 PSIA	EROSION = 0.00040 IN	TW = 1348. DEG R	H = 97. B/HR-FT-R	HD/M = 0.000229	R/P = 0.4000 MILS/HR/P			
LOCATION J	PRESS = 1.50 PSIA	EROSION = 0.00040 IN	TW = 1348. DEG R	H = 97. B/HR-FT-R	HD/M = 0.000153	R/P = 0.2667 MILS/HR/P			

PLOT DATA

WALL TEMPERATURE 1/TW * 10000

DIFFUSION RATIOS

1382.	7.2359	0.0001479	0.0001479
1915.	5.2219	0.0016501	0.0016501
1994.	5.0110	0.0058250	0.0029125
1348.	7.4184	0.0017482	0.0011655

TEST	SPECIMEN TYPE	DURATION (MIN)	TC (DEG R)	PC (PSIA)	SPECIFIC HEAT (BTU/LBM-DEG R)	BACK SIDE TEMP (DEG R)	PR/SC (-)	DENSITY (LB/CU FT)	NOTES
W144	PAR. CTR. LINE	24.00	3871.0	202.0	4.26	3547.0	0.65	85.00	
LOCATION A	PRESS = 11.91 PSIA	EROSION = 0.00190 IN	TW = 1925. DEG R	H = 374. B/HR-FT-R	HD/M = 0.000510	R/P = 0.3988 MILS/HR/P			
LOCATION B	PRESS = 11.91 PSIA	EROSION = 0.00200 IN	TW = 1925. DEG R	H = 374. B/HR-FT-R	HD/M = 0.000537	R/P = 0.4198 MILS/HR/P			
LOCATION C	PRESS = 5.24 PSIA	EROSION = 0.00020 IN	TW = 3108. DEG R	H = 177. B/HR-FT-R	HD/M = 0.000113	R/P = 0.0954 MILS/HR/P			
LOCATION D	PRESS = 5.24 PSIA	EROSION = 0.00200 IN	TW = 3108. DEG R	H = 177. B/HR-FT-R	HD/M = 0.001135	R/P = 0.9542 MILS/HR/P			
LOCATION E	PRESS = 2.40 PSIA	EROSION = 0.00170 IN	TW = 3360. DEG R	H = 106. B/HR-FT-R	HD/M = 0.001611	R/P = 1.7708 MILS/HR/P			
LOCATION F	PRESS = 2.40 PSIA	EROSION = 0.00150 IN	TW = 3360. DEG R	H = 106. B/HR-FT-R	HD/M = 0.001421	R/P = 1.5625 MILS/HR/P			
LOCATION G	PRESS = 1.52 PSIA	EROSION = 0.00030 IN	TW = 2061. DEG R	H = 93. B/HR-FT-R	HD/M = 0.000324	R/P = 0.4934 MILS/HR/P			
LOCATION H	PRESS = 1.52 PSIA	EROSION = 0.00120 IN	TW = 2061. DEG R	H = 93. B/HR-FT-R	HD/M = 0.001296	R/P = 1.9737 MILS/HR/P			

PLOT DATA

WALL TEMPERATURE 1/TW * 10000

DIFFUSION RATIOS

1925.	5.1548	0.0026855	0.0026268
3108.	3.2175	0.0330933	0.3309329
3360.	2.9762	0.3512063	0.3098879
2061.	4.8520	0.0201557	0.0806230

TEST	SPECIMEN TYPE	DURATION (MIN)	TC (DEG R)	PC (PSIA)	SPECIFIC HEAT (BTU/LBM-DEG R)	BACK SIDE TEMP (DEG R)	PR/SC (-)	DENSITY (LB/CU FT)	NOTES
W147	PAR. CONTOUR	55.00	3046.0	199.0	3.92	2521.0	0.65	85.00	
LOCATION A	PRESS = 10.51 PSIA	EROSION = 0.00290 IN	TW = 1515. DEG R	H = 375. B/HR-FT-R	HD/M = 0.000312	R/P = 0.3010	MILS/HR/P		
LOCATION E	PRESS = 10.51 PSIA	EROSION = 0.00120 IN	TW = 1515. DEG R	H = 375. B/HR-FT-R	HD/M = 0.000129	R/P = 0.1246	MILS/HR/P		
LOCATION B	PRESS = 4.69 PSIA	EROSION = 0.00100 IN	TW = 2214. DEG R	H = 191. B/HR-FT-R	HD/M = 0.000211	R/P = 0.2326	MILS/HR/P		
LOCATION F	PRESS = 4.69 PSIA	EROSION = 0.00030 IN	TW = 2214. DEG R	H = 191. B/HR-FT-R	HD/M = 0.000063	R/P = 0.0098	MILS/HR/P		
LOCATION C	PRESS = 2.27 PSIA	EROSION = 0.00040 IN	TW = 2354. DEG R	H = 119. B/HR-FT-R	HD/M = 0.000136	R/P = 0.1922	MILS/HR/P		
LOCATION G	PRESS = 2.27 PSIA	EROSION = 0.00030 IN	TW = 2354. DEG R	H = 119. B/HR-FT-R	HD/M = 0.000102	R/P = 0.1142	MILS/HR/P		
LOCATION D	PRESS = 1.49 PSIA	EROSION = 0.00060 IN	TW = 1522. DEG R	H = 94. B/HR-FT-R	HD/M = 0.000258	R/P = 0.4393	MILS/HR/P		
LOCATION H	PRESS = 1.49 PSIA	EROSION = 0.00040 IN	TW = 1522. DEG R	H = 94. B/HR-FT-R	HD/M = 0.000172	R/P = 0.2429	MILS/HR/P		

PLOT DATA

WALL TEMPERATURE	1/TW * 10000	DIFFUSION RATIOS
1515.	6.6007	0.0006354
2214.	4.5167	0.0091055
2354.	4.2481	0.0189244
1522.	6.5703	0.0025615

TEST	SPECIMEN TYPE	DURATION (MIN)	TC (DEG R)	PC (PSIA)	SPECIFIC HEAT (BTU/LBM-DEG R)	BACK SIDE TEMP (DEG R)	PR/SC (-)	DENSITY (LB/CU FT)	NOTES
W148	PAR. CTR. LINE	60.00	3569.0	202.0	4.16	2120.0	0.65	85.00	
LOCATION A	PRESS = 10.88 PSIA	EROSION = 0.00210 IN	TW = 1593. DEG R	H = 392. B/HR-FT-R	HD/M = 0.000210	R/P = 0.1930	MILS/HR/P		
LOCATION E	PRESS = 10.88 PSIA	EROSION = 0.00110 IN	TW = 1593. DEG R	H = 392. B/HR-FT-R	HD/M = 0.000110	R/P = 0.1011	MILS/HR/P		
LOCATION D	PRESS = 4.79 PSIA	EROSION = 0.00060 IN	TW = 2186. DEG R	H = 208. B/HR-FT-R	HD/M = 0.000113	R/P = 0.1253	MILS/HR/P		
LOCATION F	PRESS = 4.79 PSIA	EROSION = 0.00120 IN	TW = 2186. DEG R	H = 208. B/HR-FT-R	HD/M = 0.000227	R/P = 0.2505	MILS/HR/P		
LOCATION G	PRESS = 2.32 PSIA	EROSION = 0.00120 IN	TW = 2052. DEG R	H = 132. B/HR-FT-R	HD/M = 0.000357	R/P = 0.5172	MILS/HR/P		
LOCATION C	PRESS = 2.32 PSIA	EROSION = 0.00070 IN	TW = 2052. DEG R	H = 132. B/HR-FT-R	HD/M = 0.000208	R/P = 0.3017	MILS/HR/P		
LOCATION D	PRESS = 1.52 PSIA	EROSION = 0.00080 IN	TW = 1378. DEG R	H = 101. B/HR-FT-R	HD/M = 0.000311	R/P = 0.5263	MILS/HR/P		
LOCATION H	PRESS = 1.52 PSIA	EROSION = 0.00060 IN	TW = 1378. DEG R	H = 101. B/HR-FT-R	HD/M = 0.000233	R/P = 0.3247	MILS/HR/P		

PLOT DATA

WALL TEMPERATURE	1/TW * 10000	DIFFUSION RATIOS
1593.	6.2775	0.0004765
2186.	4.5746	0.0042334
2052.	4.8733	0.0143670
1378.	7.2569	0.0024474

Figure 1 - AGCARG EROSION CORRELATION FOR A KINETIC LIMITED PROCESS

Figure 2 - AGCARB EROSION CORRELATION FOR A DIFFUSION CONTROLLED PROCESS

FIGURE 3 - PREDICTED EROSION FOR THE FULL SCALE NERVA NOZZLE

M E M O R A N D U M

WS 96 BACK 1P

TO: J. L. Watkins 2 October 1970
FROM: M. J. Ditore MJD:res 7734:099
Ext. 7432:Bldg. 2019
SUBJECT: Nozzle Performance Loss Analyses
COPIES: R. H. Coppo, O. J. Demuth, L. A. Shurley, M. H. Smoot,
File

- REFERENCES:
- (a) ICRPG Liquid Propellant Thrust Chamber Performance Evaluation manual, Aerojet-General Corporation TCER 9642:0085 dated 30 September 1968.
  - (b) Computing Sciences Report No. E-3, "Real Gas Supersonic Flow", R. D. Glausz, J. D. Hwang and C. H. Lundelius dated 28 March 1968.
  - (c) ICRPG Turbulent Boundary Layer Nozzle Analysis Computer Program, Pratt and Whitney Aircraft Report dated July 1968. (Contract NAS7-443 3N-82-105)
  - (d) "Comparison and Evaluation of Computer Program Results for Rocket Engine Performance Prediction", Chapter V, Boundary Layer Friction and Heat Transfer, I. E. Alber dated April 1968. (Contract No. NAS7-443 SN-82)
  - (e) "ICRPG One-Dimensional Kinetic Reference Program" H. M. Frey, et al, Dynamic Science Report No. AD 841 201 dated July 1968.
  - (f) "Computer Program for Calculating Turbulent Mixing with Chemical Reactions", J. D. Mockenhaupt dated 15 September 1970.
  - ✓ (g) "Effects on Specific Impulse of Low-Temperature Peripheral Chamber Flow", memorandum to L. A. Shurley from O. J. Demuth No. 7734-051, dated 18 June 1970.
  - ✓ (h) "Performance Prediction Variability for NERVA", Memorandum to C. K. Leeper from O. J. Demuth No. 7734:077 dated 3 September 1970.

I. SUMMARY

Performance loss values have been estimated for NERVA nozzles having expansion ratio of 70:1, 100:1 and 140:1 and operating at nominal chamber conditions of $P_c = 450$ psia and $T_c = 4250^\circ\text{R}$. In addition, derating factors were estimated for the nominal nozzle expansion ratio of 100:1 and for a selected range of operating conditions. A summary of computed derating

CLASSIFICATION CATEGORY	
UNCLASSIFIED	
CLASSIFYING OFFICER	DATE

factors is presented in Table V. These values were computed using the best known analytical techniques, however, the end results are subject to variabilities because of inaccuracies in the numerical schemes and/or the property data used in the analyses. The computed one-dimensional equilibrium performance was 846.4 lbf-sec/lbm and a total derating factor was computed to be 2.82% for the nominal operating conditions. These results imply a nominal delivered specific impulse of 822.4 lbf-sec/lbm. A preliminary estimate of the overall variability in calculated delivered performance was found to be 0.56% (3σ) as reported in Reference h. Thus the nominal attainable performance of 822.4 sec is judged to range between 827.0 sec and 817.8 sec due to the uncertainty of the analyses. The reported results of Table V include reasonable engineering estimates for the effects of nozzle geometry imperfection and vibration since these values are yet to be computed.

II. INTRODUCTION

The purposes of this memorandum are to document the method of approach used to determine the performance derating factor for the NERVA nozzle and to formally present the significant results of conducted analyses. Complete descriptions of the analytical techniques are contained in the references. The results of analyses performed to date are presented in tables and graphs for easy reference. Since refinements to the methods of analyses are continuously being made, the reported results are subject to change pending completion of additional computer runs. Performance and derating factors are presented for the nominal 100:1 expansion ratio nozzle and for eight selected operating conditions. Also presented are the derating factors for nozzles having expansion ratios of 70:1 and 140:1 operating at the nominal chamber conditions of $P_c = 450$ psia and $T_c = 4250^\circ\text{R}$.

At the outset, the reference performance to which the derating factor applies is the one-dimensional isentropic-equilibrium (ODE) specific impulse. This value is generally accepted as the maximum performance value a propellant system can produce in the absence of losses. All performance losses are computed as individual and independent degradations of the ODE performance. Thus, the sum of all performance losses is equal to the total degradation of ideal ODE specific impulse. The attainable (or delivered) specific impulse is given by:

$$I_{SD} = I_{sODE} \left[1 - (\text{derating factor})_{\text{total}} \right] \quad (1)$$

Individual performance loss may be obtained by:

$$\Delta I_{s_{\text{ind}}} = I_{sODE} \cdot (\text{derating factor})_{\text{ind}} \quad (2)$$

III. CALCULATION PROCEDURE AND RESULTS

As indicated above, the method of approach in arriving at the delivered specific impulse is to evaluate the ODE performance and then to determine the magnitude of performance losses anticipated. These results are substituted into equation (1) to obtain the desired performance value. Essentially the method involves a correction to the ODE performance value because of losses resulting from nozzle flow divergence, chemical kinetics, heat transfer and friction, etc.

A. ONE-DIMENSIONAL EQUILIBRIUM PERFORMANCE

The one-dimensional equilibrium performance is determined from thermochemical calculations. These calculations establish the chemical composition of propellant systems at a specified temperature and pressure. Using the composition, the thermodynamic properties of the composite can be determined from the JANAF tables. In particular, the enthalpy in the chamber and at each specified nozzle exit pressures (or corresponding expansion ratios) are of primary importance. The ideal specific impulse is proportional to the square-root of the difference in enthalpy values, and given by

$$I_{sp} = K \sqrt{H_c - H_e}. \quad (3)$$

It is assumed in these calculations that the exhaust flow direction is parallel to the nozzle axis independent of how this flow condition was achieved, i.e., the flow is one-dimensional.

Two computer programs have been developed at Aerojet to accomplish the thermochemical calculations, (1) 166 Chem-Comp program and (2) Thermo-Cal program (E23102) (Ref. a). The former can be run on the IBM 7094 computer (or 360 emulation) where as the latter is available on the IBM 360/65 computer. The results of both programs are identical at high pressure and temperature. Because of the more extensive property data included in the JANAF tables of the Thermo-Cal program, it provides better performance results for lower temperature and pressure conditions than the Chem-Comp program. In fact, the 166 Chem-Comp program will terminate calculations where property data required exceed the tabulated list. In contrast, the Thermo-Cal program approximates the tabulated thermodynamic properties of the JANAF table by a high order polynomial which may be subsequently used to extrapolate beyond the input values. As would be expected, a polynomial curve fit of the data will introduce minor errors in calculation of performance values, however, these errors are not expected to be significant, as indicated by comparative studies. An estimate of the 3% error which may accumulate because of this numerical

technique is 0.14 percent at the nominal operating condition of $P_c = 450$ psia and $T_c = 4250^\circ\text{R}$. This error does not include the effect of assuming ideal gas expansion, i.e., the effect of compressibility or variance from the classical perfect gas law. This latter influence will be reviewed during the next funding increment and corrections made to the reported results, if necessary.

For the purpose of evaluating ideal performance for the NERVA engine, the Thermo-Cal program was used. This program contains the option of computing the frozen flow performance as well as the equilibrium specific impulse. Both values were determined and the results are presented in Table I. As expected, chamber temperature and expansion ratio are the two most significant parameters influencing the ideal performance. The chamber pressure has little influence on vacuum specific impulse, because of the second order effect on chemical composition and subsequent expansion. Ideal performance values as a function of expansion ratio and chamber pressure and temperature are presented in Figure 1.

B. NOZZLE FLOW DIVERGENCE LOSS

Maximum performance, for a given expansion ratio, is achieved when the nozzle is designed so that the exhaust flow is parallel to the nozzle axis. These nozzle designs, however, are excessively long and because of other considerations such as performance-weight trade-off, increased heat transfer and friction losses, etc., are not "optimum" from a system design standpoint. Typically, nozzle designs are of shorter length than the parallel flow nozzle and as a consequence the exhaust flow direction is not parallel to the axis (except for flow along the axis). The corresponding reduction in the axial component of impulse is defined as the divergence loss when compared with the impulse of a parallel flow nozzle.

The numerical method of analysis for both nozzle design and performance evaluation incorporates the axisymmetric method of characteristics solution of the governing equations. This numerical method is used to define the flow conditions in the supersonic region of the nozzle. Initial conditions, required for starting the marching type solution, are obtained from linearized equations which define the flow properties in the transonic region. This latter analysis is restricted to mild throat radius of curvatures (i.e., $r_u/r_t \geq 2$) and provides the throat total mass flow and thrust by integration of properties along a specified surface. The characteristic solution of the supersonic flow field provides,

in addition to velocity, density, temperature, etc., the pressure distribution along the nozzle wall. This data and the nozzle geometry are sufficient to determine the thrust contribution of the expansion nozzle by pressure-area integration. The total nozzle thrust may be computed, also, by integrating the momentum, from calculated properties, along the last characteristic surface in the nozzle. Either method of approach yields the same calculated performance and thus is selected on the basis of convenience. The latter approach to evaluating performance is used in the nozzle design option where as the wall pressure-area integration technique is normally used in evaluating the performance of a given geometry.

The above analysis was originally formulated assuming constant gas properties (i.e., constant gamma) and subsequently was modified to account for variation in fluid properties (Ref. b). The results of thermochemical calculations were incorporated into the computational scheme to define the local speed of sound and density as a function of Mach number. These quantities are then used as local properties for the varying-property calculations.

The computer program which accomplishes this latter gas dynamic analysis was recently reprogrammed for the IBM 360/65 computer. This computer program (E21220 or E21222) includes three major options which allow (1) generation of performance maps to define a range of optimum expansion ratios for given nozzle lengths, (2) design of optimum thrust nozzle for given envelope or exit conditions and (3) performance evaluation of given nozzle geometries. This latter option was used to evaluate the performance of the NERVA nozzle configuration. In using the computer program two significant features need special consideration. The first is that a sufficient number of nozzle coordinates ($N \geq 60$) must be used and second the definition of properties in the region of the throat should be carefully specified.

The divergence loss is determined by comparing the performance, obtained from the above gas dynamic analysis, with the equilibrium performance of a parallel flow nozzle (or the Thermo-Cal ODE performance). The divergence loss is calculated from

$$\% I_{s_{LOSS}} = \frac{I_{s_{ODE}} - I_{s_{CALC}}}{I_{s_{ODE}}} \times 100 \quad (4)$$

The results of these calculations are presented in Table II. A significant trend in derating factor was noted as a function of expansion ratio which indicates that the percent performance loss decreased with increasing expansion ratio. Further, these results indicate that for "optimum" thrust nozzle designs, the larger expansion ratios provide more nearly parallel flow at the exit.

C. HEAT TRANSFER AND FRICTION LOSSES

The analysis to determine the thrust loss resulting from the coupled effect of heat transfer and friction is accomplished by numerically solving the boundary layer integral equations. The method of analysis is described in Reference c and a complete evaluation of the method is given in Reference d. The procedure includes the influence of a variable specific heat. The momentum and energy integral equations are solved using the 1/7 power law velocity profile and stagnation enthalpy distribution. This velocity profile assumes a turbulent boundary layer flow and further that similarity in velocity distribution exists at any station. Of the many assumptions, the one most significantly affecting the solution of thrust loss is the manner in which skin friction is computed. The programmed procedure assumed the "Coles" skin friction correlation where as, Alber of Reference d suggests the use of "Spalding-Chi" skin friction correlation. Because the "Coles" correlation has been verified only for adiabatic flow and with zero pressure gradient, some question exists relative to which correlation is the most applicable for the NERVA engine. Calculated difference in specific impulse loss between the two methods were found to be conservatively 0.3 percent and could amount to as much as 0.5 percent. Additional experimental correlation studies will be studied in order to resolve this question relative to which correlation should be used. This effort will be accomplished during the next fiscal increment and the program modified to include the "Spalding-Chi" correlation, if necessary.

The turbulent boundary layer (TBL) computer program (E25204) requires as input the gas thermophysical properties such as stagnation viscosity and Prandtl number, specific heat as a function of temperature, etc. Free stream conditions are input in the form of Mach number distribution at specified nozzle coordinates. Further, the wall temperature and heat flux at each station is also required to complete the solution. Of significant importance in evaluating performance loss is the source of data used in the program. The stagnation thermophysical properties are computed as part of the thermochemical analysis, thus the output of the Thermo-Cal program specifies these data including the variation in specific heat with temperature. The generalized nozzle performance program, used to evaluate (divergence loss) equilibrium nozzle specific impulse provides the "potential flow" Mach number distribution. Finally, the wall temperature and heat flux distributions are obtained from the Thermodynamics Group as a result of complete heat transfer calculations. The program computes the thrust loss by comparison with the thrust magnitude of a potential flow nozzle (i.e., without a boundary layer). By an iterative procedure the displacement effect of the boundary layer on the main stream (potential) flow could be considered, however, an estimate of this influence on the computed thrust loss indicated that for this application the effect is negligible and need not be included.

The TBL program assumes smooth nozzle walls, whereas the NERVA chamber-nozzle, up to an expansion ratio of 24:1, has a scalloped configuration as a result of the coolant passages. The scalloped configuration results in a higher total heat transferred and corresponding thrust loss. Therefore the preliminary results obtained from the TBL program are corrected by insuring consistency in total heat flux between calculated values from the TBL program and values obtained from the heat transfer calculations. This correction essentially compensates for the difference in surface area between tubular (or scalloped) and smooth surfaces in the regenerative cooled portion of the chamber-nozzle region. The corrected thrust loss is then divided by the mass flow, calculated for the specific nozzle throat upstream radius of curvature and chamber operating conditions, to arrive at a specific impulse decrement. This decrement is further divided by the ODE performance to obtain the desired heat transfer and friction derating factor.

Using the above (TBL program) approach, derating factors were computed for both start-of-life (SOL) and end-of-life conditions (EOL) and for several selected chamber pressure and temperatures. The computed values are presented in Table III. The main difference between SOL and EOL performance loss values results from the differences in wall temperature and heat flux distribution. The variation in derating factor with chamber temperature and pressure is shown in Figures 3 and 4 respectively. The data variation with temperature, at a chamber pressure of 360 psia, appears reasonable, however, the radical change observed in derating factor with chamber pressure for the lower temperature ($T = 2800^{\circ}\text{R}$ curve) is unexplainable at this time. Additional performance loss runs are planned to verify (or refute) the lower temperature variation in derating factor.

D. KINETICS LOSS

At the outset of attempting to upgrade the derating factors for the NERVA nozzle, the ICRPG one-dimensional kinetics reference program, Reference e was used to determine equilibrium, frozen and kinetic performance values. This program was formulated for the specific purpose of evaluating kinetics performance by considering the dissociation-recombination reactions using finite rate chemical reactivity for the specific chamber-nozzle geometry and corresponding pressure-temperature environment. The program options included calculation of equilibrium and frozen composition performance similar to the Thermo-Cal program. Use of these latter calculated results were compared with kinetics performance to determine the performance decrement due to finite rate chemistry.

Initial calculated results, for the NERVA chamber-nozzle geometry and chamber operating conditions, using the ODK program were somewhat in question. A parametric study was conducted to determine the variability in performance loss values, for the expansion of hydrogen, with variation in input values. These studies revealed the strong sensitivity of integration

step size on the computed results. This was evidenced by the fact that under certain conditions the kinetic performance exceeded the equilibrium performance, which is unreasonable. These results are not to be interpreted to mean that the ODK program is "totally" invalid but rather that the magnitude of the performance loss was so small that minor inaccuracies in the numerical methods overshadowed the answers; at least for the hydrogen reactions. The significant result, however, was establishing that the kinetic losses were small (i.e., of the order of .1%).

The numerical procedure, in the ODK program, solves the governing equation for kinetic performance using a finite difference representation where as the equilibrium (as well as frozen) performance is obtained from a two point solution for equilibrium composition i.e., in the chamber and at the nozzle exit. The differences between the two methods could easily account for the observed discrepancies and thus a consistent method of calculation was sought.

To overcome the above problem, an existing Aerojet mixing and kinetics program (Reference f) was modified to incorporate an identical finite difference numerical solution scheme, as is normally used to obtain kinetic performance, to compute equilibrium performance. This program accomplishes the performance computation in much the same manner as the ODK program, however, its sensitivity to integration step size was found to be less, and further, in all cases the kinetics performance was found to lie between the equilibrium and frozen performance values. Since the computed results appeared to be much more consistent than those obtained using the ODK program, the Aerojet program was used to evaluate the kinetics losses as a function of operating conditions. } ←

As noted in Table I, the performance values for equilibrium and frozen composition for chamber temperatures equal to or less than $T_c = 3600^\circ R$ were found to be identical. It is obvious, therefore, that no kinetic losses are expected for these lower operating temperatures irrespective of pressure. The kinetic losses at the higher chamber temperature of $4250^\circ R$ were determined and are presented in Table IV. The reported performance results for equilibrium and frozen composition in Table IV are slightly higher than those presented in Table I. This apparent (minor) difference is attributed to the accumulative error of the finite difference numerical scheme used to arrive at the results of Table IV and further presents a partial explanation of the aforementioned questionable results observed with use of the ODK program. Additional calculations of other propellant systems will be necessary, however, before this latter conclusion is completely verified. The one-dimensional equilibrium and frozen performance values of Table I are believed to be the most accurate. The values presented in Table IV were used only to determine the difference between kinetic and equilibrium performance using a consistent method of analysis. →

The data, of Table IV, show a mild influence on kinetic losses with pressure. The trend indicates that kinetic losses increase with decreasing temperature, but, that the overall performance should increase, as was indicated by the equilibrium ODE performance values. This result, however, should be tempered (or qualified) by the fact that the differences in performance values between the high pressure of 450 psia and the low pressure of 270 psia are believed to be within the accuracy of the finite rate constants used in the analysis. The trend does substantiate the notion that a higher dissociation energy exists in the chamber at lower pressures. The questionable area, however, is related to the degree of recovery of this energy by recombination during the kinetically controlled expansion process. Nevertheless, the reported results are believed to be representable of expected performance loss resulting from kinetic expansion of hydrogen.

E. VELOCITY AND TEMPERATURE MALLDISTRIBUTION

The nonuniformity in velocity and temperature of the hydrogen exiting from the reactor core may influence the delivered performance. The magnitude of performance loss will depend upon the degree of non-uniformity as well as the degree of mixing achieved, which in turn is influenced by radial temperature and velocity gradients. The fluid flow may be assumed to consist of discrete concentric tubes each containing dissimilar temperature and velocity fluid. In addition, the outer stream tube may contain the mass flow required for peripheral cooling.

The AGC Mixing and Kinetic program (Reference f) has the capability of determining the flow properties as a function of radial and axial distances for a limited number of stream tubes. The program considers the degree of mixing resulting from radial gradient in temperature, velocity enthalpy and species concentration and also includes the effect of kinetically controlled chemical reactions. The program's capability needs to be extended to include additional stream tubes which will refine the calculated results of the otherwise coarse approximation of its present capability. Modification of the program is in progress and upon completion, the influence of non-uniformity will be evaluated.

In the interim, a simplified analysis, Reference g, was performed to assess the approximate magnitude of the temperature-distribution loss. The gross effect on specific impulse was evaluated of a small mass flow of peripheral cooling which was assumed to be completely unmixed. The results indicated that for typical coolant mass flows and coolant to mainstream temperature ratio, the specific impulse loss was approximately 0.1 percent. In lieu of more exact calculations, this value of performance loss is assumed to be the maximum representative loss of the existing NERVA engine design.

F. NOZZLE GEOMETRY IMPERFECTION AND VIBRATION

Preliminary analysis required to upgrade original estimates of performance losses attributed to nozzle geometry imperfections and vibration was recently initiated, however, results are not as yet available. The basic plan, to evaluate these losses, includes use of two different programs. The first being the Generalized Nozzle Performance for Equilibrium Flow Program (E21222) to evaluate probable nozzle imperfections at various stations which are symmetric about the nozzle axis. For unsymmetric contour imperfections the second program, consisting of a three-dimensional method of characteristic solution, will be used to evaluate performance decrements. Further, the three-dimensional method of characteristic program will be used to evaluate the time-integral of specific impulse loss resulting from the most significant vibratory modes as determined by dynamic analyses.

M. J. DITORE, Engr. Supv.
Gas Dynamics

APPROVED:

O. J. DEMUTH, Manager
Gas Dynamics
Engineering Department

TABLE I

ONE-DIMENSIONAL EQUILIBRIUM AND FROZEN COMPOSITION PERFORMANCE*

<u>Chamber Conditions</u>		<u>Expansion Ratio</u>	<u>Specific Impulse</u>	
<u>Pressure</u> (psia)	<u>Temperature</u> (°R)		<u>Equilibrium</u> (lbf-sec/lbm)	<u>Frozen</u> (lbf-sec/lbm)
450	4250	70	841.3	-
450	4250	140	850.0	-
450	4250	100	846.4	843.7
360	4250	100	846.7	843.7
270	4250	100	847.3	843.7
360	3600	100	768.9	768.8
360	2800	100	670.1	670.1
270	2800	100	670.1	670.1
164	2800	100	670.1	670.1
70	1500	100	481.0	481.0

* Program E23102 - Thermo-Cal

TABLE II

FLOW DIVERGENCE PERFORMANCE LOSS

<u>Chamber Conditions</u>		<u>Expansion Ratio</u>	<u>Computed Specific Impulse*</u> lbf-sec/lbm	<u>Derating Factor</u> (Percent)
<u>Pressure</u> (psia)	<u>Temperature</u> (°R)			
450	4250	70	835.6	0.67
450	4250	140	847.9	0.25
450	4250	100	842.4	0.47
360	4250	100	842.8	0.46
270	4250	100	842.9	0.51
360	3600	100	765.3	0.47
360	2800	100	666.9	0.48
270	2800	100	666.7	0.51
164	2800	100	666.5	0.54
70	1500	100	477.5	0.74

* Program E21222 - Generalized nozzle performance for equilibrium flow

TABLE III
HEAT TRANSFER AND FRICTION PERFORMANCE LOSS

Chamber Pressure (psia)	Conditions Temperature (°R)	Expansion Ratio	Weight Flow lbm/sec	Life	Thrust Loss (Corrected) lbf	Isp Decrement lbf-sec/lbm	Derating Factor %
450	4250	70	92.46	NOM.	1248.6	13.5	1.60
450	4250	140	92.46	NOM.	1316.0	14.2	1.67
450	4250	100	92.46	NOM.	1253.1	13.6	1.61
450	4250	100	92.46	SOL	1271.1	13.75	1.62
				EOL	1247.3	13.49	1.59
360	4250	100	73.94	SOL	1075.9	14.55	1.72
				EOL	1063.2	14.4	1.70
270	4250	100	55.42	SOL	876.0	15.8	1.87
				EOL	866.9	15.6	1.85
360	3600	100	81.04	SOL	982.4	12.1	1.58
				EOL	969.8	12.0	1.56
360	2800	100	92.55	SOL	901.8	9.7	1.45
				EOL	884.5	9.6	1.43
270	2800	100	69.41	SOL	668.6	9.63	1.44
				EOL	665.5	9.59	1.43
164	2800	100	42.16	SOL	482.0	11.43	1.71
				EOL	478.9	11.36	1.70

PROGRAM - E25204 Turbulent Boundary Layer Nozzle Analysis Computer Program ("COLES" Skin Friction Correlation)

TABLE IV

KINETIC PERFORMANCE LOSSES
(100:1 Expansion Ratio)

Chamber Conditions		Specific Impulse lbf-sec/lbm			Derating Factor %
Pressure	Temperature	Equilibrium	Frozen	Kinetic	
450	4250	847.0	844.2	845.9	0.13
360	4250	847.6	844.4	845.8	0.21
270	4250	848.1	844.4	846.1	0.24

for comparison
only - accurate
values in TABLE I

TABLE V - NERVA NOZZLE DERATING FACTORS

Expansion Ratio	70	140	100							
Temperature Pressure	4250 450	4250 450	4250 450	4250 360	4250 270	3600 360	2800 360	2800 270	2800 164	1500 70
Theo. Performance, Sec.	841.3	850.0	846.4	846.7	847.3	768.9	670.1	670.1	670.1	481.0
Divergence Loss, %	0.67	0.25	0.47	0.46	0.51	0.47	0.48	0.51	0.54	0.74
Boundary Layer Loss, %	1.60	1.67	1.62/1.59	1.72/1.70	1.89/1.85	1.58/1.56	1.45/1.43	1.44/1.43	1.71/1.70	--
*Kinetic Loss, %	0.13	0.13	0.13	0.21	0.24	--	--	--	--	--
**Contour Imperfec- tion, %	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
**Vibration, %	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
**Maldistribution, %	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
*Total Loss (Derating Factor), %	3.0	2.65	2.82/2.79	2.99/2.97	3.22/3.20	2.65/2.63	2.53/2.51	2.55/2.54	2.85/2.84	--
*Attainable (nom.) Performance, Sec.	816.1	827.5	822.6/822.8	821.4/821.6	820/820.2	748.5/748.7	653.2/653.3	653/653.1	651/651.1	--

* Legend— Start-of-Life/End-of-Life

** Estimated values, actual losses yet to be determined

ONE-DIMENSIONAL EQUILIBRIUM PERFORMANCE

1(a) - Expansion Ratio

1(b) - Chamber Temperature

1(c) - Chamber Pressure

NOZZLE DIVERGENCE DERATING FACTOR VERSUS EXPANSION RATIO

Figure 2
10-2-70

HEAT TRANSFER AND FRICTION LOSS DERATING FACTOR VERSUS CHAMBER TEMPERATURE

$P_c = 360$ psia

HEAT TRANSFER AND FRICTION LOSS DERATING FACTOR VERSUS CHAMBER PRESSURE

Figure 4
10-2-70

WS 96 BACK UP

M E M O R A N D U M

TO: L. A. Shurley 18 June 1970
FROM: O. J. Demuth OJD:res 7734:051
Ext. 7133:Bldg. 2015
SUBJECT: Effects on Specific Impulse of Low-Temperature Peripheral
Chamber Flow
COPIES: W. E. Campbell, M. J. Ditore, I. L. Odgers, M. Smoot,
J. L. Watkins, File
ENCLOSURE: Figure 1 - Approximate Loss in Specific Impulse Due to
Nonmixed Peripheral Flow

INTRODUCTION

One potential contributor to a small reduction of specific impulse for the NERVA engine, is a nonuniform temperature distribution across the thrust chamber. For either a given maximum temperature, or a given mixed-mean temperature, the specific impulse is maximum if the flow is completely mixed in the chamber before being accelerated through the nozzle; nonuniform flows degrade the performance. The ordinary nozzle flow and performance calculations have been made assuming a uniform temperature except for the temperature drop near the wall due to boundary-layer heat transfer. The purpose of this memo is to assess the approximate magnitude of one portion of the temperature-distribution loss, namely the effect on specific impulse of a small amount of cool peripheral flow which is assumed to be completely unmixed. The actual loss due to the peripheral flow will be less than this calculated one, because some degree of mixing will occur.

SUMMARY

The present calculations indicate that for a peripheral weight flow of 1.5% of the total flow, and for a peripheral-flow temperature of 1800°R (this corresponds to a ratio of cold-flow enthalpy to main-flow enthalpy of approximately 0.4), a loss in specific impulse of 0.8 seconds (0.1%) will result if the flow is completely unmixed. Additional results are shown parametrically in the enclosed figure. The conclusion reached is that the loss associated with the cool peripheral flow is strongly dependent on its temperature, and is small for expected flow rates and temperatures. Therefore the conduct of a more precise evaluation of this loss will await the determination of the loss associated with a less severe temperature variation across the entire core outlet, the magnitude of which has not yet been estimated.

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UNCLASSIFIED	
CLASSIFYING OFFICER	DATE

APPROACH

The basic approach adopted for this preliminary analysis was to assume a uniform temperature across the major portion of the core, with a small fraction of the flow entering the chamber at a reduced temperature. The specific impulse values for the completely mixed and nonmixed cases were calculated and subtracted. This difference represents the loss in mean specific impulse, relative to the value for completely mixed flow, for flows which do not mix.

Complete Mixing

An energy balance can be written to determine the mean stagnation enthalpy, $\bar{h}_{mix}$, of the two flows entering the chamber.

$$w_H h_H + w_c h_c = (w_H + w_c) \bar{h}_{mix} \quad (1)$$

where: w_H , w_c , h_H , and h_c are the weight flows and stagnation specific enthalpies of the hot and cold flows.

The specific impulse for the mixed flows is related to the specific impulse of a chamber flowing 100% hot flow through the same expansion ratio, by the following expression, assuming the flows have the same ratio of specific heats and behave substantially as perfect gases:

$$\frac{I_{mix}}{I_H} = \left(\frac{\bar{h}_{mix}}{h_H} \right)^{1/2} \quad (2)$$

where: I_{mix} is the specific impulse of the mixed flow, and I_H is the specific impulse of the hot flow alone. Combining equations (1) and (2) gives

$$\frac{I_{mix}}{I_H} = \left[\frac{1 + \frac{w_c}{w_H} \frac{h_c}{h_H}}{1 + \frac{w_c}{w_H}} \right]^{1/2} \quad (3)$$

Expanding equation (3) in a series and dropping terms of order $\left(\frac{w_c}{w_H}\right)^2$ results in

$$\frac{I_{mix}}{I_H} = 1 - \frac{1}{2} \frac{w_c}{w_H} \left(1 - \frac{h_c}{h_H} \right) \quad (4)$$

Unmixed Flows

For this case it is assumed, again, that the stagnation pressures and gas properties are substantially the same for the two steam tubes. Then each of the steam tubes expands through the same expansion ratio, and:

$$\frac{I_c}{I_H} = \left(\frac{h_c}{h_H}\right)^{1/2} \quad (5)$$

where I_c is the specific impulse of the cold steam tube. In this case the proper mean specific impulse for the total of the two flows ($\bar{I}_s$) equals the total thrust divided by the total weight flow or

$$I_H w_H + I_c w_c = \bar{I} (w_c + w_H) \quad (6)$$

combining equations (5) and (6)

$$\frac{\bar{I}}{I_H} = \frac{1}{1 + \frac{w_c}{w_H}} + \left(\frac{h_c}{h_H}\right)^{1/2} \frac{w_c}{w_H \left(1 + \frac{w_c}{w_H}\right)} \quad (7)$$

Again, expanding and discarding second order terms:

$$\frac{\bar{I}}{I_H} = 1 - \frac{w_c}{w_H} \left[1 - \left(\frac{h_c}{h_H}\right)^{1/2} \right] \quad (8)$$

The loss in specific impulse due to lack of mixing can be found by subtracting Equation (8) from Equation (4).

$$\frac{I_{mix} - \bar{I}}{I_H} = \frac{1}{2} \frac{w_c}{w_H} \left[1 - \left(\frac{h_c}{h_H}\right)^{1/2} \right]^2 \quad (9)$$

Also from Equation (4) it can be seen that, to first order,

$$\frac{I_{mix} - \bar{I}}{I_{mix}} = \frac{I_{mix} - \bar{I}}{I_H}$$

Then

$$(I_{mix} - \bar{I}) = \frac{1}{2} \frac{w_c}{w_H} \left[1 - \left(\frac{h_c}{h_H} \right)^{\frac{1}{2}} \right]^2 I_{mix} \quad (10)$$

This difference has been plotted in the enclosed figure as I_s loss as a function of $\frac{h_c}{h_H}$ for several values of $\frac{w_c}{w_H}$.

PLANNED EFFORT

It is planned to evaluate the effect on specific impulse of a more gradual temperature variation across the entire core face utilizing our turbulent-mixing computer program. The details of that effort have not been established, completely, at this time. Following this, a mixing analysis is planned to determine more precisely the expected loss due a small amount of cool peripheral flow. Both of these tasks will be fit in so as not to interfere with the performance-evaluation effort currently underway.

O. J. DEMUTH, Manager
Gas Dynamics
Engineering Department
Aerojet Nuclear Systems Company

NOTE: NOMINAL I_s BASED ON
MIXED MEAN STAGNATION
ENTHALPY.

APPROXIMATE LOSS IN SPECIFIC IMPULSE
DUE TO NONMIXED PERIPHERAL FLOW

6-15-70
OJD

Figure 1

M E M O R A N D U MWS96
BACKUPEnclosure (1)
Page 1 of 4
24 September 1970
7750:MI066

TO: J. L. Watkins 21 September 1970
 FROM: M. J. Ditore MJD:res 7734:090
 Ext. 7432:Bldg. 2019
 SUBJECT: Summary Report - Derating Factors for the NERVA Nozzle
 COPIES: R. H. Coppo, O. J. Demuth, L. A. Shurley, M. Smoot, File
 ✓REFERENCE: Memo 7750:MO793, L. A. Shurley to B. Mandell, same subject,
 13 February 1970.
 ENCLOSURE: (1) Table I - NERVA Nozzle Drating Factors

Performance losses for the NERVA nozzle were determined for various chamber operating conditions. In addition, refinements in the method of analysis have resulted in upgrading the derating factors for nozzles having expansion ratios of 70:1, 100:1 and 140:1 and operating at nominal chamber conditions. A summary of results of these analyses is presented in the enclosure. Further, the uncertainty in computed derating factor, for nominal operating conditions, was re-estimated and found to be ± 0.56 percent. This value is essentially the same as previously reported in the referenced memorandum.

For convenience, a brief summary of performance losses (percent of theoretical) and uncertainties (estimated 3 σ -values) for the 100:1 expansion ratio, operating at a chamber pressure of 450 psia and chamber temperature of 4250°R, is given below. For these conditions the nominal one-dimensional equilibrium performance was computed to be 846.4 lbf-sec/lbm.

Estimated uncertainty in one-dimensional equilibrium performance	± 0.14
Divergence Loss	0.47 ± 0.17
Boundary Layer Loss	1.62 ± 0.50
Kinetic Loss (Lack of Reassociation)	0.13 ± 0.10
*Contour Imperfection	0.25 ± 0.05
*Vibration	0.25 ± 0.05
**Velocity and temperature maldistribution	0.10 ± 0.05
Total derating factor and uncertainty	$2.82\% \pm 0.56\%$

* Estimated values - actual yet to be determined

** Estimate based on preliminary analyses of the effects of peripheral cooling.

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UNCLASSIFIED	
CLASSIFIED OFFICER	DATE

Since the variability in computed derating factor was estimated to be $\pm 0.56\%$, the nominal attainable performance of 822.4 sec would range between 827.0 sec and 817.8 sec due to the uncertainty.

Nozzle divergence losses were evaluated using an equilibrium nozzle performance computer program (E21222). The numerical technique was recently reprogrammed for the IBM 360/65 computer and uses the output of the Thermocal equilibrium performance program (E23102) to define fluid properties as a function of local pressure and temperature. Upgraded performance loss values were obtained as a result of refining the property variation in the immediate vicinity of the throat region and including more boundary points to define the contour. Use of the revised program indicates that divergence losses are slightly less than previously reported, however, the differences are believed to be within the calculation accuracy and/or exhibit the minor influence in changing the numerical technique.

The heat transfer and friction losses were determined for start-of-life and end-of-life conditions at selected chamber temperatures and pressures. These computations used both wall heat flux and temperature distributions as computed by the thermodynamics group for the graphite skirt extension beginning at a 24:1 expansion ratios. The Turbulent Boundary Layer (TBL) computer program (E25204) was used to establish the thrust loss. The computed thrust loss values were corrected for differences in surface area between a tubular (or scalloped) and smooth surfaces in the regenerative cooled portion of the chamber-nozzle region. The equilibrium nozzle performance, assuming potential flow, was downgraded by the heat transfer and friction thrust loss to arrive at the specific impulse loss or derating factor. The present method of analyses assumes "Coles" skin friction correlation. A preliminary study was completed, to determine the difference in performance loss with use of the "Spalding-Chi" skin friction correlation. This latter analysis indicated that (1) the difference in performance loss could be as much as 0.5 percent and (2) use of the "Spalding-Chi" correlation yields higher performance loss value. The question relative to which correlation is the most applicable to the NERVA engine will be resolved in the near future and the heat transfer and friction losses modified, if necessary.

The reaction kinetic losses were evaluated using an Aerojet mixing and kinetics computer program. The inconsistency in the numerical technique previously utilized was corrected by evaluating both the theoretical equilibrium performance and the kinetic performance using the same finite difference numerical scheme. Thus the reported kinetic loss values are believed to be more realistic than previous estimates. It should be noted that for chamber temperatures less than 3600°R the equilibrium and frozen performance values are identical thus indicating no kinetic losses.

392
Shift
2.85
progen

For a chamber temperature of 4250°R and a chamber pressure of 450 psia, the difference between equilibrium and frozen flow performance values is 2.85 sec, thus indicating that kinetic performance loss is approximately 39 percent of this difference. At the lower pressure (270 psi) the kinetic loss is 54 percent of the difference between equilibrium and frozen flow.

The performance losses resulting from contour imperfection and nozzle vibration are estimates at this time. An existing three-dimensional method of characteristic program currently being made operational is planned to be used to evaluate these losses.

Determination of velocity and temperature maldistribution losses requires modification of the Aerojet mixing and kinetic computer program. At the completion of these modifications, evaluation of the magnitude in performance loss will be accomplished. In the interim, the conservative gross influence on performance resulting from peripheral cooling is estimated as reasonable performance loss.

M. J. Ditore

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Gas Dynamics

APPROVED:

O. J. Demuth

O. J. DEMUTH, Manager
Gas Dynamics
Engineering Department

TABLE I - NERVA NOZZLE DERATING FACTORS (START-OF-LIFE)

Expansion Ratio	70	140	100							
Temperature Pressure	4250 450	4250 450	4250 450	4250 360	4250 270	3600 360	2800 360	2800 270	2800 164	1500 70
Theo. Performance, Sec.	841.3	850.0	846.4	846.7	847.3	768.9	670.1	670.1	670.1	481.0
Divergence Loss, %	0.67	0.25	0.47	0.46	0.51	0.47	0.48	0.51	0.54	0.74
*Boundary Layer Loss, %	1.60	1.67	1.62/1.59	1.72/1.70	1.89/1.85	1.58/1.56	1.45/1.43	1.44/1.43	1.71/1.70	--
*Kinetic Loss, %	0.13	0.13	0.13	0.21	0.24	--	--	--	--	--
**Contour Imperfec- tion, %	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
**Vibration, %	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
**Valdistribution, %	0.10	0.1	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
*Total Loss (Derating Factor), %	3.0	2.65	2.82/2.79	2.99/2.97	3.22/3.20	2.65/2.63	2.53/2.51	2.55/2.54	2.85/2.84	--
*Attainable (nom.) Performance, Sec.	816.1	827.5	822.6/822.8	821.4/821.6	820/820.2	748.5/748.7	653.2/653.3	653/653.1	651/651.1	--

* Legend— Start-of-Life/End-of-Life

** Estimated values, actual losses yet to be determined

M E M O R A N D U M

TO: B. Mandell 13 February 1970
 FROM: L. A. Shurley RL:nls 7(50:MO)93
 Project No. 143

SUBJECT: Derating Factor for 100:1 NERVA Nozzle

DISTRIBUTION: J. H. Altseimer, D. Buden, R. E. Coppo, M. Kasahara,
 C. K. Leeper, W. W. Madison, T. Pasternak, D. L. Petite,
 W. E. Stevens, J. L. Watkins

Reference: (a) Memo, L. A. Shurley to J. J. Beereboom,
 dtd 2 October 1969, Subj: Derating Factors
 for Nozzle Performance

(b) Memo, R. Louison to L. A. Shurley, dtd
 21 January 1970, Subj: Derating Factor for
 100:1 NERVA Nozzle

The performance losses or derating factor for the full flow NERVA nozzle with a radiation cooled skirt extension at a chamber temperature of 4250°R and chamber pressure of 450 psia has been determined, as indicated in Reference (a), to be 2.94%. In addition to the derating factor, this memorandum defines the uncertainty with which the derating factor is associated. The uncertainty in the derating factor was determined to be $\pm \frac{.42\%}{.52\%}$. Thus, the specific impulse for the nozzle is nominally at 821.4 $\frac{sec}{\sqrt{sec}}$ and would range from 825.5 sec to 816.9 sec due to the uncertainty. 812 y 72 f

The breakdown of various losses and its uncertainties are as follows:

	.47 ± .17	
Divergence Loss	.64 ± .10	846 3 (no h +)
Boundary Layer Loss	1.60 ± .15 .25	
Kinetic Loss		
a. Lack of Equilibrium	.0 ± .02	
b. Lack of Reassociation	.13 .20 ± .05	
*Contour Imperfection	.25 ± .05	
*Vibration Loss	.25 ± .05	
	2.94% ± .42% .52%	782 ± 56

* Estimated values, actual yet to be determined

UNCLASSIFIED

J. H. Watkins 2-16-70

13 February 1970

The various losses and its uncertainty indicated above are essentially similar to that presented in Reference (a) with the exception of the divergence loss, the boundary layer loss and kinetic loss. These losses were recalculated using data that are compatible with the full flow cycle engine and in the case of divergence loss a different computer program was used to arrive at the present loss. Previously, the divergence loss was calculated using Program 10009. However, it was determined that Program 10016 yields a more reliable loss estimate although the loss is higher. The boundary layer loss is also higher, 1.60% as compared to 1.44% ($T_c = 4500^\circ R$). This is because the loss was first calculated as thrust lost and this was converted into specific impulse by dividing the thrust lost by flow rate. The flow rate used in arriving at 1.44% was the total engine rather than the flow rate through the throat.

The kinetic losses were reduced from .43% (.07% due to lack of equilibrium and .36% due to lack of reassociation) to .20%. The loss due to lack of equilibrium or finite reaction rate, was reduced to be insignificant due to the reduced chamber temperature. However, the uncertainty still remains the same because of the reaction rate constants used in the calculation remain to be accurately defined. The loss due to lack of reassociation is also reduced with the reduced chamber temperature.

Also, included in this memorandum, are the effects considering the changes in nozzle throat and exit diameter. They are listed as follows:

I_s CHANGE CAUSED BY THROAT AND EXIT AREA

- (1) For $\pm .010$ Change in Throat Dia. with Constant Exit Dia.

<u>D_t</u>	<u>D_e</u>	<u>ϵ</u>	<u>I_s (derated)</u>
11.200	112.10	100.18	821.44
11.210	112.10	100.0	821.41
11.220	112.10	99.82	821.37

- (2) For $\pm .010$ Change in Throat Dia. with $\Delta \pm .060$ on Exit Dia.
+ with $\Delta \pm .060$ from (2)

<u>D_t</u>	<u>D_e</u>	<u>ϵ</u>	<u>I_s (derated)</u>
11.200	112.16	100.29	821.46
11.210	112.10	100.0	821.41
11.220	112.04	99.71	821.35

- (3) For $\pm .010$ Change in Throat Dia. with $\Delta \pm .100$ on Exit Dia.

<u>D_t</u>	<u>D_e</u>	<u>ϵ</u>	<u>I_s (derated)</u> (+ .040 mandrel) (+ .060 part shrinkage)
11.200	112.26	100.47	821.49
11.210	112.10	100.0	821.41
11.220	111.94	99.54	821.32

13 February 1970

It should be noted that the uncertainties presented in this memorandum is limited to the given operating conditions of the nozzle, namely $P_c = 450$ psia and $T_c = 4250^\circ\text{R}$. Future work will consider the effects of variation in operating conditions and non-homogeneous of the hot gas. The uncertainty limits are the current best estimate as to the variation of the losses. As such, they could be considered to be the 3σ deviation of the performance loss.

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M E M O R A N D U M

WS 95 BACK up

TO: C. K. Leeper 3 September 1970
FROM: O. J. Demuth MJD:res 7734:077
Ext. 7432:Bldg. 2019
SUBJECT: Performance Prediction Variability for NERVA
COPIES: W. E. Campbell, M. J. Ditore, I. L. Odgers, L. A. Shurley,
J. L. Watkins, File
✓REFERENCE: Memo L. A. Shurley to B. Mandell, Subject: "Derating
Factors for 100:1 NERVA Nozzle", dated 13 February 1970
ENCLOSURE: Variation in Specific Impulse Due to Error in Enthalpy

INTRODUCTION AND SUMMARY

This memorandum summarizes our most recent estimates of calculated specific impulse variability. For the purpose of this analysis, it was assumed that no errors existed in the input data required. That is, the nozzle geometry, operating conditions, etc. are known at the outset of the analysis. The errors considered were those resulting from inaccuracies in numerical technique, table interpolation of variations in fluid property data, basic assumptions in the analysis, selection of integration step-size, density of flow field grid points, etc.

Previous estimates of performance uncertainty were presented in the referenced memorandum. The estimates presented here are essentially the same as previously reported, however, it should be noted that they are only approximations at this stage, based on using realistic assumptions relative to the source and magnitude of individual errors. A more complete analysis is planned for the next fiscal increment to support reliability studies.

The analytical technique used to predict "delivered" specific impulse is identical to the method recommended by the "Interagency Chemical Rocket Propulsion Group (ICRPG)". Basically, this method requires corrections to the one-dimensional equilibrium (ODE) performance because of anticipated specific impulse losses resulting from nozzle flow divergence, chemical kinetics, heat transfer and friction, etc. Each performance loss, as is the ODE performance, is determined separately. As a consequence, the probable error in the predicted performances is established as the proper combination of errors incurred in each individual analysis.

CLASSIFICATION CATEGORY	
UNCLASSIFIED	
<i>O. J. Demuth</i>	9-9-70
CLASSIFYING OFFICER	DATE

Based on previous experience with each computer program and preliminary analysis of results obtained from computer calculations, the following summary of 3σ -levels of performance variability was established:

One-dimensional equilibrium performance	$\pm 0.14\%$
Nozzle divergence loss	± 0.17
Heat transfer and friction loss	$\pm 0.5\%$
Kinetic loss	$\pm 0.1\%$
*Vibration loss	$\pm 0.05\%$
*Temperature and velocity maldistribution	$\pm 0.05\%$

The corresponding 3σ value of the combined variability in calculated specific impulse was found to be 0.56%. The nominal calculated specific impulse, based on the most recent re-evaluation of derating factors, is 824.1 lbf-sec/lbm. Thus, the 3σ range of delivered specific impulse could lie between 819.5 and 828.7 lbf-sec/lbm due to uncertainties in the analyses.

DISCUSSION

The factors which contribute to uncertainties in calculated values are different for each calculation or computer program. In some cases the integration step size significantly influences the calculated answers, where as in other programs (such as the Thermo-Cal program) the integration step size is of little consequence. It is impossible, therefore, to generalize the contributing factors and consequently, the following paragraphs present an attempt to identify the source of error in each calculation and the rationale in selecting the magnitude of inaccuracy.

1. Theoretical One-Dimensional Equilibrium Performance

Calculation of theoretical specific impulse is normally accomplished using the Thermo-Cal computer program. This computation is an iterative procedure to define the chemical composition for selected pressure and temperature. The JANAF tables are available in the program to determine the composite thermophysical properties. Specific impulse is taken to be proportional to the square-root of the enthalpy difference between chamber and nozzle exit. Further the program assumes isentropic flow of an ideal gas.

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* Engineering estimates to be determined from planned analyses.

For the simple two specie composition of the NERVA engine, it was assumed that little or no error exists in establishing the equilibrium chemical composition and further that the real gas effects are negligible.* A remaining possible source of error is in determination of enthalpy. The program uses a curve fitting routine to determine thermophysical properties which, in most instances, is sufficiently accurate. The specific impulse is related to the difference in enthalpy i.e.,

$$I_{sp} = K \sqrt{H_c - H_e} \quad (1)$$

where I_{sp} = theoretical specific impulse

K = conversion constant

H_c = chamber enthalpy

H_e = nozzle exit enthalpy

If we assume that the maximum deviation between the curve fit value and the JANAF table value (ΔH) is the 3σ variation which could occur in both enthalpy values, then the error in specific impulse becomes (see enclosure for derivation):

$$\frac{\Delta I_{sp}}{I_{sp}} = \frac{\Delta H}{\sqrt{2} (H_c - H_e)} \quad (2)$$

To evaluate this error, a comparison of computed data from the Thermo-Cal program with the JANAF tables was made over the entire range of temperature and pressure between the chamber and nozzle exit. The maximum deviation in enthalpy between the JANAF tables and Thermo-Cal was found to be 27.7 Btu/lb. Substituting this value into the above equation we arrive at the above quoted 3σ variability of 0.14 percent in calculated ODE specific impulse.

2. Divergence Loss

Evaluation of nozzle flow divergence loss is accomplished by a gas dynamic analysis of the flow field in the nozzle. The flow field is defined using the method of characteristic solution of the governing equations. The most recent computer program considers the variation in properties (as a function of local pressure and temperature) using the output of the one-dimensional equilibrium program discussed above. The

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* These effects will be investigated as part of next year's reliability effort.

thermodynamic data is written on tape in the form of tables and parabolic interpolation is used to curve fit these data as required in the gas dynamic calculations. In addition, precise definition of the nozzle configuration in terms of wall coordinates and wall flow angle is required.

Experience in parametric studies has indicated two possible sources of error, one in the definition of thermodynamic data and the second in the definition of nozzle wall coordinates. Basically these errors are human errors, subtle and difficult to detect, however, they do influence performance values by inaccurate definition of thermodynamic properties and by establishing a coarse flow grid size.

Performance evaluations were performed using (1) the ODE program default pressure ratios to establish the table of thermophysical properties and (2) a more refined pressure ratio table to define the property data. A difference of 1.1 Isp points was noted between the two calculations. For the purpose of this analysis it was assumed that 50% of this value or 0.07 percent is the uncertainty in computed loss as a result of improper thermodynamic property definition.

To establish the uncertainty attributed to improper geometry definition two performance evaluations were performed. One in which thirty coordinate points were used to define the nozzle and the other seventy coordinate points were used. The difference in performance between these two calculations was found to be 1.3 Isp points or 0.15 percent. Considering that wall flow angle at each coordinate point significantly influences the method of characteristics solution to define performance and since these values are difficult to establish precisely from a manufactured part, the above noted difference of 1.3 Isp points was taken as the 3σ error.

The resulting 3σ error in Isp due to uncertainty in divergence loss is approximately 0.17%.

3. Heat Transfer and Friction Losses

Variability in calculation of heat transfer and friction losses is difficult to identify because of the approximate nature of the integral method of analysis used in the solution of the boundary layer equations. The analysis used to determine performance loss was carefully reviewed and found to provide reasonable results, however, these would be influenced by improper selection of input parameters such as viscosity temperature relation exponent, temperature to velocity profile interaction coefficient, velocity profile power law exponent, etc. Selection of these parameters are based upon recommendations of noted experts in the fields of heat transfer and boundary layer. Obviously, an extensive parametric study would be required to establish the variability in performance loss as a function of each input parameters. For this preliminary study, however, it was assumed that input parameters were selected appropriately and represent our best engineering estimate applicable to the NERVA engine.

More significantly however, the analysis uses an empirical ("Coles") skin friction correlation which was recommended by the originator of the overall analytical technique. Recently, several investigators have recommended the "Spalding-Chi" skin friction correlation. A comparison was made to determine the difference in computed heat transfer and friction loss between the two skin friction correlations. These latter analyses indicated that the differences between the two correlations could influence I_{sp} by as much as 0.5 percent. At the present time there is some question relative to which correlation is more applicable to the NERVA engine configuration. Additional studies will be necessary to determine the validity of using either one of these skin friction correlations in determining performance loss. Because of this uncertainty, the aforementioned difference between the two methods of defining skin friction was assumed to represent a 3σ error in the calculated specific impulse.

4. Kinetic Losses

Performance losses associated with reaction kinetics and non-equilibrium state of the expansion and exhaust species is determined from a rather complex computer program which is similar to the one-dimensional equilibrium program discussed above. The additional complexity is related to including the reaction rate equations to describe the dissociation and recombination and generation of species during the expansion process. The most recent reaction rate constants published in the literature, for hydrogen reactions, were used in the analysis. The specific impulse loss is taken as the difference between equilibrium and kinetic performance values. In attempts to use the ICRPG recommended "One-Dimensional Kinetic Program" (ODK), it was found that the equilibrium performance was determined by the one-step integration where as the kinetic performance is computed using a finite difference technique in the solution of governing equation; the latter being significantly influenced by integration step-size. For the small magnitudes of kinetic losses for NERVA reasonable results were not obtainable with use of this program (in fact negative losses were frequently indicated) and as a consequence, an existing AGC mixing and kinetic program was modified so as to compute the equilibrium performance using a finite difference technique identical to that used in obtaining kinetic performance. This latter program provided more realistic performance loss results and was found to be only moderately sensitive to integration step size. Since the ODK program indicated that kinetic losses were negligible where as the AGC mixing and kinetics program indicated that kinetic losses were 0.1%, it was assumed that the 3σ error in calculated loss could result in a 0.1 percent error in I_{sp} , as listed in the summary above.

5. Vibration Losses

Performance losses associated with vibration of the nozzle exit cone have not been computed. It is planned to use an existing three-dimensional method of characteristics gas dynamic program to evaluate the thrust loss of the anticipated asymmetric configurations. It is expected that vibrational deflections of the nozzle will be small and further that the thrust losses due to non-circular geometry of the nozzle exit cone will be small. Thus, a reasonable engineering estimate of the

3 σ variability was taken to be equivalent to the previous estimate of 0.05% Isp error, as reported in the reference memorandum. This estimate will be upgraded as calculation of actual nozzle deflections and subsequent performance loss are completed.

6. Velocity and Temperature Maldistribution

For the NERVA engine, it is expected that both velocity and temperature will be nonuniform in the immediate vicinity of the reactor core face. The expansion of nonuniform exhaust can influence the performance, and it is intended to evaluate this effect using a modified version of the AGC mixing and kinetics program. Calculations of performance loss associated with a maldistributed exhaust was not completed pending modification of the existing computer program.

A simple stream-tube analysis was performed, however, to evaluate the order of magnitude of performance loss. In this analysis, it was assumed that the lower temperature fluid was either completely mixed or remained unmixed during the expansion process. For typical mass flow and temperature ratio of cool peripheral flow to main flow, an approximate performance loss for unmixed flow was established as 0.1 percent. It is expected, for severe temperature and velocity gradients, that mixing between fluid particles would reduce this performance loss by at least 50 percent, and further that the error in calculations could be as much as 100 percent due to the unavailability of experimentally determined mixing parameters. Thus, the engineering estimate of the 3 σ variability was assumed to be as great as the estimated performance loss, or equivalent to 0.05 percent in specific impulse.

As indicated previously, the uncertainties quoted in this correspondence are mainly approximations based on experience with calculations performed to date. A more extensive analysis of the variance of each loss contributor will be necessary to improve these estimates; this effort is presently planned for next fiscal year.

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APPROVED:

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Aerojet Nuclear Systems Company

To: C. K. Leeper

Enclosure (1)

Page 1 of 2

7734:077

3 September 1970

VARIATION IN SPECIFIC IMPULSE DUE TO ERROR IN ENTHALPY

Specific impulse is given by

$$\begin{aligned} I_{sp} &= K \sqrt{H_c - H_e} \\ &= I_{sp}(H_c, H_e) \end{aligned} \quad (A)$$

The total difference is

$$\Delta I_{sp} = \frac{\partial I_{sp}}{\partial H_c} \Delta H_c + \frac{\partial I_{sp}}{\partial H_e} \Delta H_e \quad (B)$$

from A

$$\frac{\partial I_{sp}}{\partial H_c} = \frac{1}{2} K (H_c - H_e)^{-\frac{1}{2}}$$

and

$$\frac{\partial I_{sp}}{\partial H_e} = -\frac{1}{2} K (H_c - H_e)^{-\frac{1}{2}}$$

Substituting in (B) the total variation

$$\Delta I_{sp} = \frac{1}{2} K (H_c - H_e)^{-\frac{1}{2}} (\Delta H_c - \Delta H_e)$$

and the fractional difference is

$$\frac{\Delta I_{sp}}{I_{sp}} = \frac{1}{2} (H_c - H_e)^{-1} (\Delta H_c - \Delta H_e) \quad (C)$$

Since the error in enthalpies can be either positive or negative and further are assumed independent, the combined error is:

$$\frac{\Delta I_{sp}}{I_{sp}} = \left[\left(\frac{\Delta I_{sp}}{I_{sp}} \right)_{H_c}^2 + \left(\frac{\Delta I_{sp}}{I_{sp}} \right)_{H_e}^2 \right]^{\frac{1}{2}} \quad (D)$$

where

$$\left(\frac{\Delta I_{sp}}{I_{sp}} \right)_{H_c} = \text{percentage error in specific impulse due to } H_c$$

$$\left(\frac{\Delta I_{sp}}{I_{sp}} \right)_{H_e} = \text{percentage error in specific impulse due to } H_e$$

Finally equation (D) becomes

$$\frac{\Delta I_{sp}}{I_{sp}} = \frac{1}{2} (H_c - H_e)^{-1} (\Delta H_c^2 + \Delta H_e^2)^{\frac{1}{2}} \quad (E)$$

If we assume that $\Delta H_c = \Delta H_e = \Delta H$, i.e., the maximum deviation between the curve fit and table data then equation (E) becomes

$$\frac{\Delta I_{sp}}{I_{sp}} = \frac{\Delta H}{\sqrt{2} (H_c - H_e)} \quad (F)$$

REPORT NO

PAGE 1 OF 1

SUBJECT

NOZZLE PERFORMANCE LOSS ANALYSIS -
CONTOUR IMPERFECTION

DATE

5-5-71

WORK ORDER

1190-14-109

BY

R H Coppo

CHK BY

DATE

It is requested to extend the previous analysis (ref memo NB110: M1683) to include a circumferential contour discontinuity of .300 and .500 inches deep at an area ratio of $e = 24:1$. A total of 40 salary hours, 4 hourly hours, and \$100 computer time is allotted for this analysis. The work order charge number for this analysis is 1190-14-109. The required completion date is ~~July~~ ^{JUNE 3} 26, 1971. Notify R H Coppo X 3567 of any delays or expected over expenditure.