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FRAGMENTS GENERATED BY THE RANGE
DESTRUCTION OR RANDOM FAILURE
OF ROCKET CASINGS AND TANKAGE**

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PREDICTING THE VELOCITY AND AZIMUTH OF FRAGMENTS GENERATED BY THE RANGE DESTRUCT OR RANDOM FAILURE OF ROCKET CASINGS AND TANKAGE*

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ABSTRACT

The proliferation of space vehicle launch sites and the projected utilization of these facilities portends an increase in the number of on-pad, ascent, and on-orbit solid-rocket motor (SRM) casings and liquid-rocket tanks which will randomly fail or will fail from range destruct actions. Beyond the obvious safety implications, these failures may have serious resource implications for mission system and facility planners. SRM-casing failures and liquid-rocket tankage failures result in the generation of large, high velocity fragments which may be serious threats to the safety of launch support personnel if proper bunkers and exclusion areas are not provided. In addition, these fragments may be indirect threats to the general public's safety if they encounter hazardous spacecraft payloads which have not been designed to withstand shrapnel of this caliber. They may also become threats to other spacecraft if, by failing on-orbit, they add to the ever increasing space-junk collision cross-section.

Most prior attempts to assess the velocity of fragments from failed SRM casings have simply assigned the available chamber impulse to available casing and fuel mass and solved the resulting momentum balance for velocity. This method may predict a fragment velocity which is high or low by a factor of two depending on the ratio of fuel to casing mass extant at the time of failure. Recognizing the limitations of existing methods, the authors devised an analytical approach which properly partitions the available impulse to each major system-mass component. This approach uses the Physics International developed PISCES code to couple the forces generated by an Eulerian modeled gas flow field to a Lagrangian modeled fuel and casing system.

The details of a predictive analytical modeling process as well as the development of normalized relations for momentum partition as a function of SRM burn time and initial geometry are discussed in this paper. Methods for applying similar modeling techniques to liquid-tankage-over-pressure failures are also discussed. These methods have been calibrated against observed SRM ascent failures and on-orbit tankage failures. Casing-quadrant sized fragments with velocities exceeding 100 m/s resulted from Titan 34D-SRM range destruct actions at 10 sec mission elapsed time (MET). Casing-quadrant sized fragments with velocities of approximately 200 m/s resulted from STS-SRM range destruct actions at 110 sec MET. Similar sized fragments for Ariane third stage and Delta second stage tankage were predicted to have maximum velocities of 260 m/s and 480 m/s respectively. Good agreement was found between the predictions and observations for five specific events and it was concluded that the methods developed have good potential for use in predicting the fragmentation process of a number of generically similar casing and tankage systems.

I. INTRODUCTION AND SUMMARY

Fairchild Space Company personnel began modeling the fragmentation of Solid Rocket Motors (SRM) in mid-1986, shortly after the Challenger (STS-51L) and Titan 34D-9 accidents. These accidents were carefully observed and provided the best available data base against which to calibrate an analytical model. The fragmentation modeling efforts were completed in June 1988. The modeling techniques developed for SRMs were applied to liquid rocket tankage (specifically Delta second stage and Ariane third stage tankage) in April and May 1987. The physical principles which govern the break-up of casings and tankage proved similar, and the extension of the SRM-casing modeling techniques to liquid rocket tankage was not difficult.

The modeling methods involved defining a gas flow field in an Eulerian coordinate system, defining a shell structure in a

Lagrangian coordinate system and coupling the two coordinate systems together. The flow field definition required knowledge of the vessel internal pressure at the time of failure and the physical properties of the expanding gas. The shell modeling required knowledge of the materials of construction of the vessel and its detailed geometry. All fragment velocity calculations were performed in two-dimensions using x-y translational symmetry arguments. The Physics-International-developed finite-difference continuum-mechanics code PISCES⁽¹⁾ was used to mechanize the computational process.

The fragment-flow-field interaction pattern shown in Figure 1 is typical of the results obtained using the described techniques. This particular model is of the forward cylinder of a center-aft segment of a STS-SRM undergoing random failure at an altitude of 36,600 m.

Figure 1. Flow Field Developing Around a Randomly Failed STS Forward Cylinder With Fragmentation Occurring 5 msec After Initial Casing Failure

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The Lagrangian shell model includes 6.5 cm of PBAN fuel bonded to the casing at the time of failure. Some fragments which had no fuel attached were recovered from the STS-51L event. These fragments would have higher velocities than those modeled as having fuel attached. Z-flow into the x-y translational symmetry Eulerian flow model was included to simulate the longitudinal flow which occurs in random failure events. The flow field variations and fragment positions which result as a function of time after initial casing failure are also shown.

The results obtained from these calculations will be useful in establishing mission rules as well as launch site exclusion radii and fragment threats to bunkers. For example, it was shown that on-orbit tankage which was burst by an internal pressure equal to its burst pressure will produce a very high velocity fragment field. Since fragments generated in this manner produce a significant collision hazard for other spacecraft, it may be wise for mission planners to require positive venting of spent upper stage tankage. Such an action would assure that remaining reactants would not over-pressure and burst spent upper stage tankage.

SRM casing fragmentation which occurs at low altitude constitutes a hazard to those within the launch complex. No

attempt has been made to predict fragment range resulting from such failures since the vehicle attitude, altitude, and velocity at time of failure will strongly influence this variable. The results presented here should be used as input to a six degree of freedom code to predict the potential range of fragments of the type analyzed and having these initial velocities. This type of analysis will be required for all cases in which atmospheric drag is significant.

A comparison of predicted and observed results for a variety of mission failure scenarios is shown in Table 1. The predictions made using the methods discussed in this paper were in good agreement with observations made by others. It should be noted that, with one exception, the authors made their analytical predictions before they knew the corresponding experimental results. This was purposely done to provide a single-blind experiment.

The methods discussed in this paper are believed to be well calibrated and applicable to a wide range of SRM casing and liquid rocket tankage failure modes. Their value lies in the degree to which they facilitate the prediction of the fragmentation response of new and/or different boosters.

Additional details concerning the analytical methods employed and the results obtained are presented in subsequent chapters.

Table 1. Summary of the Predicted and Observed Fragmentation Response of Several Vehicle Elements to a Number of Internal Pressure Environments

Booster / Event	Vessel Pressure at Time of Initial Failure	Altitude at Time of Failure	Fragmentation Time*	Predicted Range of Fragment Velocities	Observed Range of Fragment Velocities	Predicted Range of Fragment Rotation Rates	Observed Range of Fragment Rotation Rates
	Bar	m	msec	m/s	m/s	Hz	Hz
34D-9 Range Destruct	54.5	Sea Level	0-20	17-104	15-106 [†]	8-12	5-12
34D-9 Random** Failure	54.5	Sea Level	0-20 [‡]	15-111	15-114 [†]	8-12	5-12
STS-51L Range Destruct	31.0	36,600	0-20	6-162 [‡]	15-198	0-15	3-17
STS Random** Failure	31.0	36,600	0-20 [‡]	7-168 [‡]	N/A	1-15	N/A
Delta NOAA 3 R/B (2nd Stage)	27.6	On-Orbit	8	48-448	8-485	5-25	N/A
Delta Landsat (2nd Stage)	27.6	On-Orbit	8	26-432	10-400	15-47	N/A
Ariane SPOT-1 (3rd Stage)	3.7	On-Orbit					
H ₂ Tank			10	13-194	15-278	1-21	N/A
O ₂ Tank			10	11-230	15-278	2-23	N/A

*Time after initial failure (LSC or random crack) at which fragments are generated. The latest time at which shell stresses can be supported by casing-material's strength.

**A 320 m/s propagation rate is used to communicate the crack from segment to segment.

[†]Based on analyses of range data performed by Jaffe⁽²⁾ using a six degree of freedom code.

[‡]Instantaneous fragmentation is assumed in the randomly failed segment followed by subsequent segment failure up to 20 msec after the arrival of a propagating (320 m/s) crack at the relevant segment boundary.

[‡]Calculations were performed assuming the attachment of 6.5 cm of fuel. Some recovered fragments had all of the fuel consumed. These fragments, as well as fragments from the upper dome, would be expected to have higher velocities than those shown.

II. TECHNICAL DISCUSSION

The material presented in this chapter describes the methods used to predict fragment velocities, azimuths and rotation rates generated by:

- A. SRM Range Destruct Actions
- B. SRM Random Failures
- C. Liquid-Rocket Tankage On-Orbit Failures

Significant differences were found to exist between early time SRM failures when there were substantial amounts of unburned PBAN grain remaining and late time events when the grain was less than about 15 cm thick. The reasons for these differences are discussed and the results for all cases analyzed by Fairchild Space Company personnel are presented in the following sections.

A. SRM Fragmentation Resulting From Range Destruct Actions

Initial calculations were performed to determine if the available codes and models could be used to make approximately correct predictions of fragment velocities resulting from range destruct actions. These calculations were also used in an attempt to define mechanistic SRM casing failure models. Even when traveling stress waves generated by the linear shaped charge (LSC) were included, the predicted stress levels never exceeded the yield strength of the D6A steel used in the SRM casings. It rapidly became clear that the time at which the SRM casing fragmented was controlled by statistical phenomena such as the location of crack nucleation sites and the notch sensitivity of the casing

steel. These observations led the authors to search for a means of assessing the likely time after the occurrence of the initial failure at which the casing would fragment. It was reasoned that the ground location of the fragments resulting from the 34D-9 failure would give reliable witness to the time after initial casing failure at which these fragments were generated. Combining these early mission elapsed time (MET) range data with late MET STS-51L photo data would provide a reasonable data base against which an analytical model could be calibrated.

It was known that the shock transit time of the 34D-9 casing was approximately 2.5 msec. It was unlikely therefore, that fragmentation could occur less than 2.5 msec after the formation of the first casing-crack free surface. Crack propagation in the PBAN fuel is significantly slower than in steel and flame propagation is even slower. Therefore, it was reasoned that very little energy, beyond that which was stored in the hot chamber gases, would be added during a SRM failure. Sensitivity studies were carried out using various assumed energy addition rates and this notion was found correct. It is true that contained, local, hot spots caused by inhibitor debonding could cause random failures of SRM casings. But it must be remembered that this energy is still small in relation to the energy stored in the hot chamber gases.

A number of sensitivity calculations were performed once the above ground rules were established. A summary of the sensitivity calculation predictions for SRM fragments generated 20 msec after range destruct actions were initiated is presented in Figure 2. The chamber-pressure-time-histories resulting from

Figure 2. SRM Fragment Geometries and Velocities (m/s) 20 msec After a Range Destruct Action at Three Mission Elapsed Times (MET) Assuming No Casing-Grain Debonding

Figure 3. Comparison of the Effect of MET and Geometry on SRM Chamber-Pressure Decrease Following a Range Destruct Action

SRM failures at a number of mission elapsed times (MET) are presented in Figure 3. These two-dimensional Eulerian-Lagrangian coupled calculations tied the rate of chamber pressure decrease to the movement of the SRM casing. The casing movement was assumed to be a "clamshell," opening about a hinge point located 180 degrees from the initial casing fracture. These initial calculations were based on the assumption that the chamber pressure acted only on the inside diameter of the PBAN grain and accelerated the chamber casing and grain as a single body.

The forces acting on the PBAN grain were predicted using a 5,000 zone Eulerian model of the gas flow field which had a minimum cell size of 15 cm x 30 cm and was further defined by the nature of the PBAN gas and its current pressure. The rate at which the SRM casings "clammed" open was controlled by the strength of the 182 zone Lagrangian modeled casings, grains, and their inertias. Component inertia was by far the controlling effect. Initial predictions made for early MET were found to be in error because they did not consider the flow field which resulted if PBAN-casing debonding occurred. This debonding led to a very different model of the forces applied to the SRM casing. As a result, it was necessary to develop separate models for fragmentation when there was a large difference in the PBAN grain inertia and the casing inertia. Debonding due to inertia differences had to be considered when PBAN grain thicknesses were greater than 15 cm. These models are called "thick grain" and "thin grain." They will be discussed in turn.

1. Early MET Failure (Thick Grain Models)

While performing the calculations reported above, it was noted that the strain energy stored in the SRM casing was released very quickly after the initial fracture. The strain energy stored in the PBAN is much less than that stored in the SRM casing. Because of its lower stored energy, lower sound speed, and greater mass, a considerable debonding force occurs at the PBAN-casing interface when the linear shaped charge (LSC) is initiated in a destruct action. The circumferential "twang" of the casing and the resultant debonding creates a cavity between the casing and the grain. This cavity then fills with hot gas from the chamber and exerts a force directly on the casing. Computational methods currently in use are based on the assumption that the cavity pressure and chamber pressure are equal. This assumption is incorrect because it invokes a static pressure field and ignores the pressure drop which occurs between the chamber and the cavity. In the highly dynamic flow field which occurs during SRM fragmentation, it is patently unreasonable to assume that the velocity of the gas flow into the cavity is subsonic. A very detailed (one cm square zoning) model of the cavity and chamber flow interaction was developed to assess the magnitude of the static pressure which would occur in this cavity during SRM fragmentation.

In addition to the above, several investigators have pointed out that there is a gap between the grains where each cylinder is joined. Gas from the chamber can flow through that gap and into the cavity formed between the fuel and the casing. Indeed, there can be a three dimensional flow field; however, this flow field must be properly defined. The maximum cavity pressure will be set by a complex material balance between what flows into and what flows out of the cavity. The supersonic nature of the flow field must be modeled and any assumption of equal cavity and chamber pressures is demonstrably incorrect.

A simplified, 2-D model of the actual problem geometry is presented in Figure 4. While this model does not include cavity feed from the cylinder ends (z-flow), it does include stagnation and circumferential flow effects. The degree to which a casing fragment is in the lee of a grain fragment affects the ability of the cavity pressure to reach its theoretical maximum. Orientation becomes a statistical variable by which to account for the observed fragment velocity distribution. The assumption of a casing lip projecting into the supersonic flow stream provides a mechanism for pressurizing the cavity which is essentially correct regardless of the details of the flow and fragmentation process. A detail of the coupled Eulerian-Lagrangian model which shows the interaction of the various flow and mass components is presented in Figure 5.

Figure 4. Early-MET-Model Formulation Showing Case Separation, Cavity Development, Grain Fragmentation and Casing Fragmentation

Figure 5. Developing Flow Field in the Grain-Casing Cavity at Various Times After a 34D-SRM Casing Failure at 10 sec MET

Calculations of this type were performed for a number of SRM geometries at various mission elapsed times (MET). These calculations varied SRM diameter, casing areal density, grain thickness and chamber pressure. They were generated to provide forcing functions for a study of the sensitivity of the fragmentation process to these variables. While assembling these results, Peter Jaffe⁽³⁾ noted that it was possible to normalize across the MET and SRM-type domains and to produce a set of curves which related cavity pressure to chamber pressure for any MET and time-after-initial-casing failure. These curves are presented in Figure 6. The existence of a single functional relation for cavity and chamber pressures across the MET and SRM-type domains greatly simplified the problem of predicting SRM fragmentation response.

The Titan 34D-9 event was useful not only in that it provided fragmentation information against which the analytical model could be calibrated, but also because it contained both a randomly failed booster (SRM-2) and a range destructed booster. As in the case of the 51L⁽⁴⁾, the 34D-9 casing had fragmented into large sections which could be defined approximately as octants, quadrants and halves of the casing. Only the single randomly failed segment of SRM-2 was fragmented into a significant number of pieces smaller than an octant.

Figure 6. Normalized Chamber and Cavity Pressure-Time Histories - After Jaffe
(This figure is based on Eulerian-Lagrangian coupled calculations the details of which were shown in Figure 5.)

A detailed model of the Titan 34D-9 event was prepared. The model geometry approximated that of the fragments from SRM-1 and SRM-2 known to exist. The initial stress distribution within the casing and PBAN was developed by applying the chamber pressure extant at 10 sec MET as a stress boundary to the inner surface of the PBAN prior to the initiation of the casing failure. A casing fault was introduced into the model and the relevant cavity pressure time history from Figure 6 was applied to the casing and the grain outer diameter. The relevant chamber pressure time history was simultaneously applied to the grain inner diameter.

The development of the fragmentation pattern typical of the boosters studied is shown in Figure 7. The sensitivity of fragment geometry and velocity to the time after initial fracture at which fragmentation occurs is shown in Figure 8. A study of Figure 9 is especially instructive. It shows, in general, that:

- 1) Fragments adjacent to the initial failure point attain the highest velocities.
- 2) Given the same orientation to the point of initial failure, smaller fragments reach higher velocities than do larger fragments.
- 3) Up to a point, fragment velocity increases with increasing time between initial casing failure and casing fragmentation (fragmentation time).

Further examination of Figure 9 shows that maximum fragment velocity is not a strong function of casing fragmentation time for early MET range destruct cases. It is difficult therefore to establish casing fragmentation time by comparing the predicted fragment velocities to the velocities inferred from the range and the abort positions at which the fragments were recovered. It was reasoned that fragment azimuth might be more sensitive to casing fragmentation time than velocity would be. The azimuths of the fragments presented in Figure 8 and Figure 9 are presented in Figure 10. Examination of Figure 10 shows that the azimuth of the fragments adjacent to the initial fracture surface is relatively sensitive to casing fragmentation time. In addition, it is seen that the azimuth of the smaller fragment (fragment 4) is more sensitive than is the azimuth of the larger fragment (fragment 1).

Given that the smaller fragment adjacent to the location of initial casing failure is the most sensitive indicator, it was reasoned that grouping the four fast fragments (fragment 4) shown in Figure 9 might be instructive. The results of this cross plot are shown in Figure 11. It is seen that fragment velocity is not a sensitive indicator of fragmentation time but azimuth is.

A detailed comparison of the results of sensitivity calculations to the observations made for the 34D-9 event is presented in Table 2. The effects of arbitrarily reducing the predicted cavity pressure are also shown in this table.

Figure 7. 34D-SRM Casing Geometry at Various Times After a Range Destruct Action and for an Assumed Fragmentation Time of 5 msec After Initial Casing Failure

Figure 8. 34D-SRM Casing Geometry for Four Assumed Fragmentation Times 20 msec After a Range Destruct Action

Figure 9. Time History of Fragment Velocities Resulting From the Range Destruction of a 34D-SRM for Four Assumed Fragmentation Times (Squared Numbers Refer to Fragments Shown in Figure 8)

Table 2. Comparison of the Observed and Predicted Fragment Velocity and Azimuth Resulting From the Range Destruct of SRM-1 in the 34D-9 Event

Observations Based On T34D-9 Range Data						Predictions Based On Hydrocode Calculations					
	Segment	Piece	Range (m)	Azimuth* (deg)	Velocity (m/s)	AZ* (deg)	FT† (ms)	VEL (m/s)	AZ* (deg)	FT† (ms)	VEL (m/s)
Long Range	1	497	418	108	105	Kp** = 0.8			Kp** = 1.0		
		493	362	115	105	107	18	89	107	18	105
		500	350	84	99	110	18	91	110	18	106
		427	346	76	88	86	10	84	85	10	102
		1564	356	-58	100	86	10	82	86	10	99
Short Range	5	1564	356	-58	100	-78	8	98	-76	8	119
						Kp** = 0.2			Kp** = 0.4		
						-86	12	38	-86	12	59
						-91	10	27	-91	10	41
						91	10	27	91	10	41
	4	484	251	128	53	109	18	45	109	18	59
		1077	133	-63	27	-91	10	29	-91	10	45
	5/6	483	206	117	43	106	18	22	106	18	64

*Initial Casing Failure at 0 Degree

**Arbitrary Cavity-Pressure Reduction Factor Used to Match Observed Results⁽⁶⁾

†Fragmentation Time.

Figure 10. Effect of Initial Location and Fragmentation Time on the Azimuth of Fragments Generated by a 34D-SRM Range Destruct Action at 10 sec MET (Squared Numbers Refer to Fragments Shown in Figure 8)

Figure 11. Effect of Fragmentation Time on the Velocity and Azimuth of the Highest Velocity 34D-SRM Fragments (Number 4, Fast Octants) Shown in Figure 8

The computational methods described slightly overpredicted the maximum velocities observed in the 34D-9 event. Detail differences which were noted when comparing lower velocity fragment observations to predictions all fell on the side of lower apparent cavity pressures existing in the event than were predicted. The entire fragment velocity domain of the 34D-9 event could be captured using a 20 to 100 percent range for the cavity pressure forcing function shown in Figure 6. This variation may be dependent upon the degree to which the particular casing fragment is in the lee of a grain fragment. It should be noted that these same observed lower velocities (labeled short range in Table 2) can be predicted by assuming that the casing and PBAN grain move as a single body (Figure 2). The agreement obtained was considered sufficiently good to establish the efficacy of the modeling process.

2. Late MET Failures (Thin Grain Models)

Late MET is defined as the time at which the grain has burned down to a thickness small enough such that its extant inertia and stored strain energy allow the grain to track the circumferential "twang" of the casing. Under these conditions no debonding occurs, and no cavity between the grain and casing is formed. It is much less difficult to model late MET failures than early MET failures. In late MET failures the fragmentation forcing function is generated by simply applying the chamber pressure to the inner grain surface.

A typical late time (110 sec MET) failure model of a STS-SRM forward cylinder of an aft center segment is shown in Figure 12. The fragmentation approximates that observed in the 51L event (4)(5). Plots of predicted velocity as a function of time after initial failure are shown in Figure 13. Examination of Figure 13 shows that the smaller fragment (fragment 1) next to the failure site has the highest velocity. Also, it is seen that the magnitude of this velocity is much more sensitive to casing fragmentation time than was the case for early late MET failure. Examination of Figure 14 reveals the expected sensitivity of the azimuth of the fast fragments to the casing fragmentation time. The fastest fragments shown in Figure 13 are cross plotted on Figure 15 to show the sensitivity of maximum fragment velocity to casing fragmentation time. It is interesting to note that the velocity of the fastest fragments increases by 25 percent when comparing late MET events with break times varying from 5 msec to 20 msec. Similar comparisons for early MET failures resulted in velocity increases of less than 10 percent.

B. SRM Random Failures

Range destruct induced SRM fragmentation produces essentially the same fragment velocity distribution for each SRM segment. Random failure induced SRM fragmentation produces fragment velocity distributions which are dependent upon the segment-of-interest's stack location and the stack location of the randomly failed segment. Preliminary evaluations of 34D-9 SRM-2 indicated that the upper-segment fragments had a lower average velocity than did those of the range destructed SRM-1. These considerations greatly complicated the analytical modeling of the random failure of SRM segments. These complications were brought about by the need to account for longitudinal flow (z-flow) in the gas flow-field modeling.

Longitudinal flow of the gas stored in the SRM chamber has two effects. First, the flow tends to increase the impulse available to accelerate fragments generated in the randomly failed segment. Second, by reducing the chamber pressure along the longitudinal axis of the SRM, the existence of this flow tends to reduce the velocity of fragments generated from those segments which were initially sound. In general, the failure of segments other than the randomly failed segment occurs because propagating cracks produce stress concentrations in structures which are otherwise sound. If the crack propagation rate is slow enough, segments at longitudinal positions distant from the failed segment may have their chamber pressure reduced by this flow below their failure threshold before a significant stress riser appears at the segment boundary. In this case the segment will not fragment.

An axisymmetrical model of the Titan 34D-SRM was generated to test the sensitivity of the temporal variation in the longitudinal chamber pressure distribution to various crack propagation rates. This model was divided into five segments (eight for the STS) and the rate of radial flow from each segment was established from the appropriate chamber blow-down curve shown previously in Figure 3. A delay time to begin radial flow from each segment was selected using crack propagation rates of 534 and 320 m/s. The results of these calculations are presented in Figure 16. Examination of this figure shows that upper segment pressure reductions of a factor of two can occur for these crack propagation rates.

Similar models were prepared for the STS-SRM using a crack propagation rate of 534 m/s for both early and late MET. The results of these calculations are presented for two mission elapsed times in Figure 17. A factor of two pressure reduction is seen in both of these cases.

Figure 12. STS-SRM Casing Geometry for Four Assumed Fragmentation Times 20 msec After a Range Destruct Induced Casing Failure

Figure 13. Time History of Fragment Velocities Resulting From the Range Destruct Induced Failure of a STS-SRM for Four Assumed Fragmentation Times (Squared Numbers Refer to Fragments Shown in Figure 12)

Figure 14. Effect of Initial Location and Fragmentation Time on the Azimuth of Fragments Generated by a STS-SRM Range Destruct Action at 110 sec MET (Squared numbers refer to fragments shown in Figure 12.)

Figure 15. Effect of Fragmentation Time on the Velocity and Azimuth of the Highest Velocity STS-SRM Fragments (Number 1, Fast Occants) Shown in Figure 12

Figure 16. Comparison of Time History of the Chamber Pressure at Five Longitudinal Distances From the 34D-SRM Head End After Random Failure in the Aft Segment at 10 Seconds MET

Figure 17. Comparison of Time History of the Chamber Pressure at Eight Longitudinal Distances From the STS-SRM Head End After a Random Failure in the Aft Segment at METs of 10 Seconds and 110 Seconds

The impulse available to accelerate fragments from an early-MET segment failure can be obtained by correcting the integral of the relevant pressure-time history curve shown in Figure 16 by the normalization factor shown in Figure 6. The ratio of these values of impulse to a Figure 6 corrected integral of the relevant Figure 3 pressure-time history curve will provide a basis for assessing the effects of z-flow in SRM random failure events. Nance, *et. al.*⁽⁶⁾ noted that the peak value of fragment range observed from each segment of the randomly failed 34D-9 SRM-2 decreased as the longitudinal distance from the origin of the failed segment (Segment 1) increased. A comparison of impulse ratio calculated for two crack propagation rates to the impulse ratio inferred from fragment peak range data is shown in Figure 18. The agreement shown between calculated and observed results was considered acceptable to validate the modeling techniques.

The model used to generate the 110 sec MET pressure-time history shown in Figure 17 was also used to generate a z-flow argument into a late MET x-y translational symmetry model. This model was used as a check on the overall efficacy of the predictive process. The flow field and fragment geometry predictions for the randomly failed segment of a STS-SRM at 110 sec MET are presented in Figure 19. Fragment velocities and azimuths resulting from this same event are shown in Figure 20.

Figure 18. Correlation of Predicted and Observed Results From the 34D-9 SRM Random Failure

Figure 19. STS-SRM Casing Geometry for Four Assumed Fragmentation Times 20 msec After a Random Casing Failure

Figure 20. Time History of Fragment Velocities Resulting From the Random Failure of a STS-SRM for Four Assumed Fragmentation Times (Squared Numbers Refer to Fragments Shown in Figure 19)

Comparison of these results to the range destruct cases discussed previously, shows that at late MET the randomly failed segment will produce fragments which have approximately three percent higher velocity than will occur in range destruct cases. Concurrently, randomly failed SRM segments which are considerably displaced from the initially failed segment will have considerably less impulse to accelerate fragments than will range destructed segments. In the case of a STS-SRM at 110 sec MET, this reduction could be as much as a factor of two.

C. Liquid Rocket Tankage Fragmentation

The basic purpose of this modeling effort was to assess the probable fragment velocity distribution which would occur if liquid rocket tankage failed at its predicted burst pressure. The investigation was undertaken because there was speculation that fragment velocities which had been observed from on-orbit tankage failure could only be generated if significant amounts of energy were added to the residual reactants thought to be on board. This speculation was found to be unwarranted and it was shown that the observed fragmentation could be explained simply on the basis of a failure at tank burst pressure followed by the expansion of the residual propellants.

The modeling of liquid rocket tankage fragmentation was significantly less difficult than the modeling of SRM fragmentation. These models required relatively simple flow-field-shell-interactions and did not have the complications which were introduced by the presence of PBAN grain. They did require additional thermodynamic calculations to be performed to assess the effects of LH_2 -LOX detonations where appropriate, but these options were code-resident and were not difficult to execute.

Analyses performed on the Ariane SPOT-1 third stage showed that LH_2 -LOX detonations involving the probable residual reactant masses would have produced fragment velocities significantly greater than those observed. A simple expansion

from the design burst pressure (3.7 bars) of the gases boiled off from the residual cryogenics would be adequate to produce the observed fragment velocities. A comparison of the fragment velocities generated by various thermodynamic processes to the observed fragment velocities is presented in Table 3. The geometric model, predicted flow field, and fragment velocity distributions resulting from an assumed fragmentation pattern and various thermodynamic processes are shown in Figure 21. Examination of these results clearly shows that good agreement is obtained with the observed fragment velocity distribution when the simple expansion of residual cryogenics argument is invoked. The fragment velocities generated by a LH_2 -LOX detonation would be much higher than those observed.

Table 3. Effect of Fragmentation Pattern and Impulse Generation Method on the Fragment Velocities (m/s) Resulting From the Failure of Ariane Third Stage Tankage at its Burst Pressure

Fragment Geometry Model*	Impulse Generation Method			Observed Velocity
	Detonation of Mixture 7 kg LH_2 and 22 kg LOX	Expansion of 7 kg LH_2	Expansion of 22 kg LOX	
Radial Expansion (Octants)	670	105	137	15-278
Radial Expansion (2 Halves)	-	46-182	80-218	15-278
Clam	-	10-200	15-230	15-278

*Assumed Fragmentation Pattern

Figure 21. Comparison of Fragment Velocity Distributions Generated by Simple Expansion or Detonation of Residual Ariane Third Stage Propellants

Two Delta second stage events which produced high velocity fragments were available to provide additional calibrations. These were the Landsat and the NOAA 3 R/B events. The expansion of residual propellant reaction products was examined for these cases. Delta second stage tankage has varying thickness sections. The spherically shaped tank ends are roughly half the thickness of the cylindrical sections. The effects of this difference in mass on the velocity distribution resulting from the fragmentation of the Delta second stage tankage at its burst pressure (27.6 bars) and the subsequent expansion of 133 kg of residual propellant reaction products are shown in Table 4. Examination of Figure 22 shows that there is a fair correlation between maximum fragment velocity and fragmentation time for the first 4 msec of the expansion.

Table 4. Effect of Tank Thickness on the Velocity of Fragments Resulting From the Failure of a Delta Second Stage Propellant Tank at its Burst Pressure and the Expansion of Isothermal-Reaction Products of the Residual Propellants

Event	Predicted Velocity (Clam Model), m/s		Observed Velocity m/s
	Tank Thickness 1.1 mm	Tank Thickness 2.0 mm	
NOAA 3 R/B	20-448	20-432	8-485
Landsat	-	-	10-400

Figure 22. Fragment Velocity Distributions Resulting From the Failure of a Delta Second Stage Fuel Tank and the Expansion of 133 kg of Residual Propellant (Fragmentation patterns is assumed to be the same as was shown in Figure 21.)

These results indicate that it is likely that the Delta second stage tankage failed at its burst pressure and that it produced a fragment velocity distribution by "clamping" and fragmenting in the same general manner as was observed in the SRM cases. These predictions and the suggested mechanisms are consistent with the general observations of the tankage fragmentation made by others⁽⁷⁾.

III. CONCLUSIONS

Results obtained using the analytical methods described in this paper showed good agreement between predictions and observations for five specific events. It was shown that these methods have good potential for use in predicting the fragmentation process of a number of generically similar casing and tankage systems. It was concluded that coupled Eulerian-Lagrangian calculational methods of the type described in this paper provide a powerful tool for predicting SRM casing and liquid rocket tankage fragmentation response.

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