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ASRM CASE INSULATION DESIGN AND DEVELOPMENT

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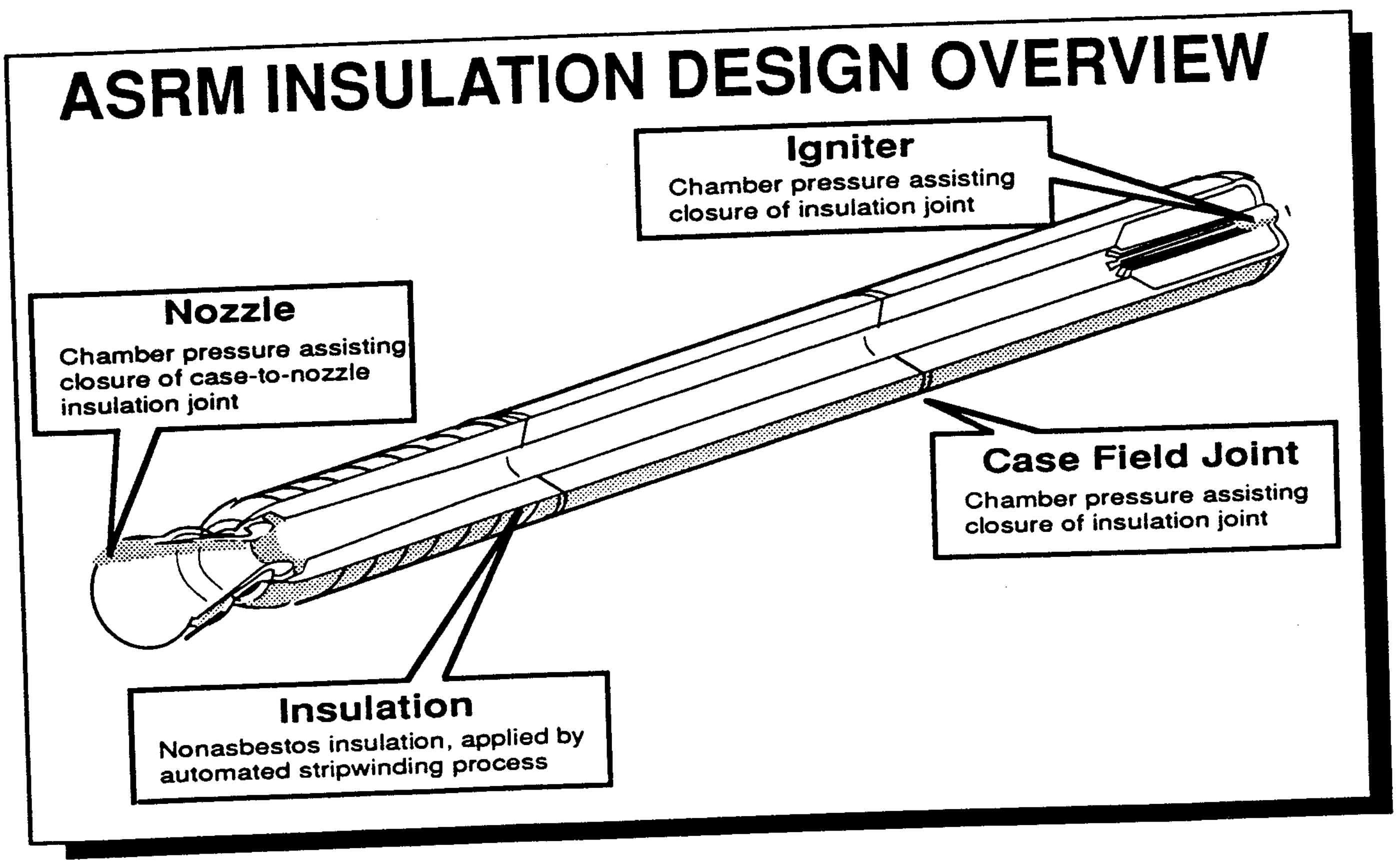
Introduction. This paper describes the achievements made on the Advanced Solid Rocket Motor (ASRM) case insulation design and development program. The ASRM case insulation system described herein protects the metal case and joints from direct radiation and hot gas impingement. Critical failure of solid rocket systems is often traceable to failure of the insulation design.

The wide ranging accomplishments included the development of a nonasbestos insulation material for ASRM that replaced the existing Redesigned Solid Rocket Motor (RSRM) asbestos-filled nitrile butadiene rubber (NBR) along with a performance gain of 300 pounds, and improved reliability of all the insulation joint designs, i.e., segmented case joint, case-to-nozzle and case-to-igniter joint. The insulation process development program included the internal stripwinding process. This process advancement allowed Aerojet to match or exceed the capability of other propulsion companies.

Background. Until the Challenger incident, the Space Shuttle Program was flying the High Performance Motor (HPM) design with an asbestos insulation that was hand laid-up on to the case. After the Challenger accident, NASA certified the Redesigned Solid Motor (RSRM) for flight through the mid 90s. In an attempt to gain greater safety, system reliability and flight performance, NASA issued incremental concept studies of the ASRM program to all five domestic propulsion manufacturers. Aerojet successfully completed the NASA-funded concept studies and poised to compete for the Design, Development, Test and Evaluation (DDT&E) program. At that time, it was recognized that a high performance nonasbestos case insulation was critically needed to support the proposal. Aerojet initiated an insulation material development program that eventually provided insulation performance data to support the ASRM DDT&E proposal. In light of the Challenger accident, the Aerojet proposal also featured improved RSRM insulation joint features to achieve a safe and reliable system. The ASRM system gained additional reliability by using automated equipment to install insulation. After the contract award, Aerojet Propulsion Division (APD) continued the case insulation design and development.

Insulation Material Development. Asbestos-filled



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nitrile butadiene rubber (NBR) is the baselined case insulation for the HPM/RSRM. The asbestos-NBR family is an outstanding insulation material with applications on the Minuteman, Titan and other large solid boosters. However with the awareness that the asbestos is carcinogenic, there was an effort to replace the asbestos on all new solid rocket motor programs. There are numerous silica-filled ethylene propylene diene monomer (EPDM) formulations available in the industry, but none was capable of matching the versatile ablation performance of the asbestos-NBR in the wide-ranging SRM internal flow environments. Research and development performed by the propulsion community in the 80's has identified an aramid fiber, Kevlar (DuPont trademark) as the most effective fiber in replacing asbestos. Aerojet, in its three-year independent research and development(IR&D), had also concluded that the Kevlar pulp was the state-of-the-art replacement for asbestos. The ASRM program undertook an insulation development project to optimize Aerojet's Kevlar-filled insulation using the Taguchi design of experiment to enhance ablation and producibility performance for the ASRM case insulation.

The insulation material development plan is shown in **Figure 1**. Phase 1 optimizes the insulation formulation. The experimental approach is shown in **Figure 2.** The tests are categorized in four major areas: ablation performance in 12-in. dia. motors, material properties, processibility and bonding/short-term aging. Phase 2 confirms the insulation formulation with 12 production-size lots. As part of the confirmation, property tolerances are established and ingredient lot-to-lot effect is evaluated. Phase 3 characterizes the insulation for material allowables to support structural and thermal analyses.

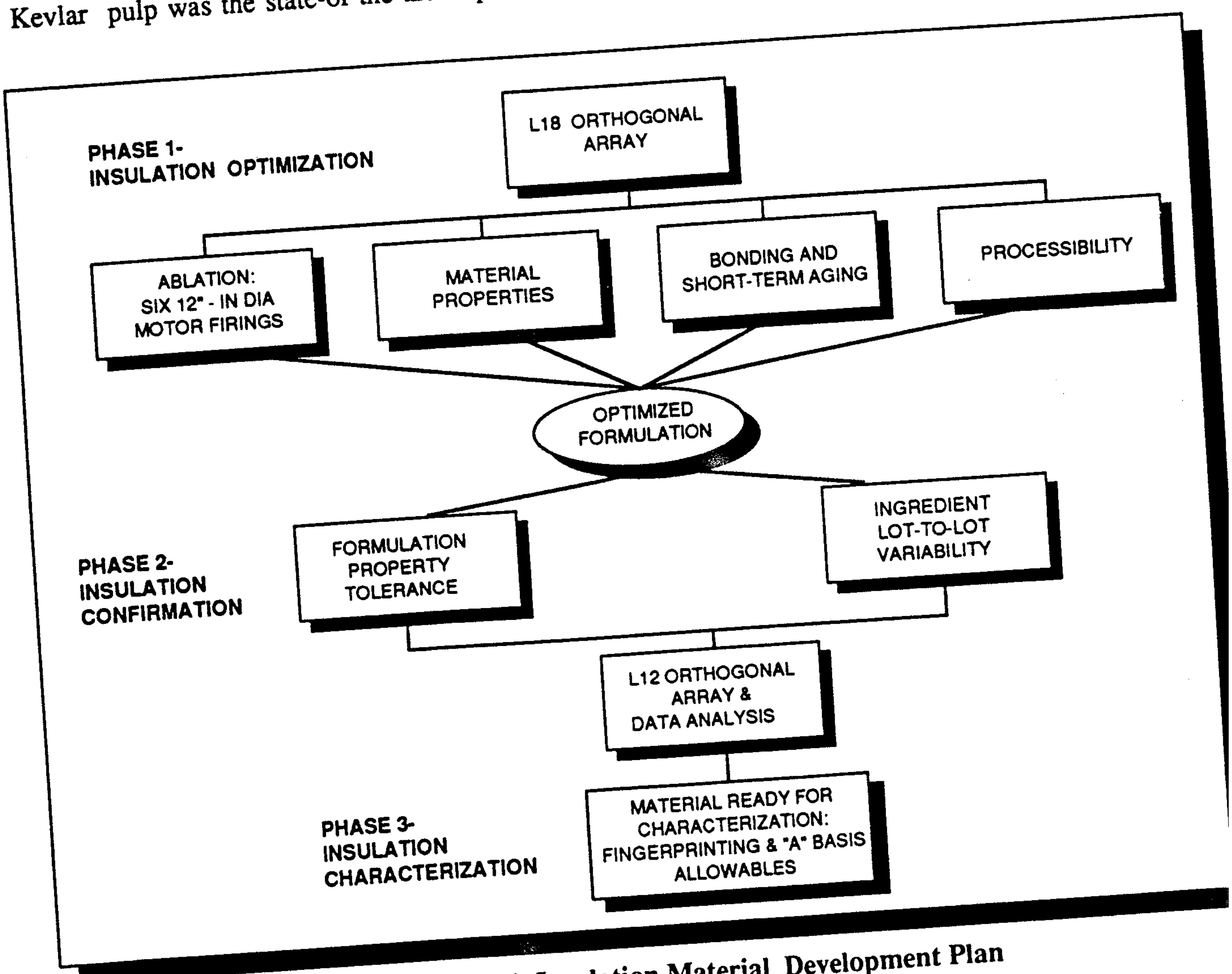


Figure 1. Insulation Material Development Plan

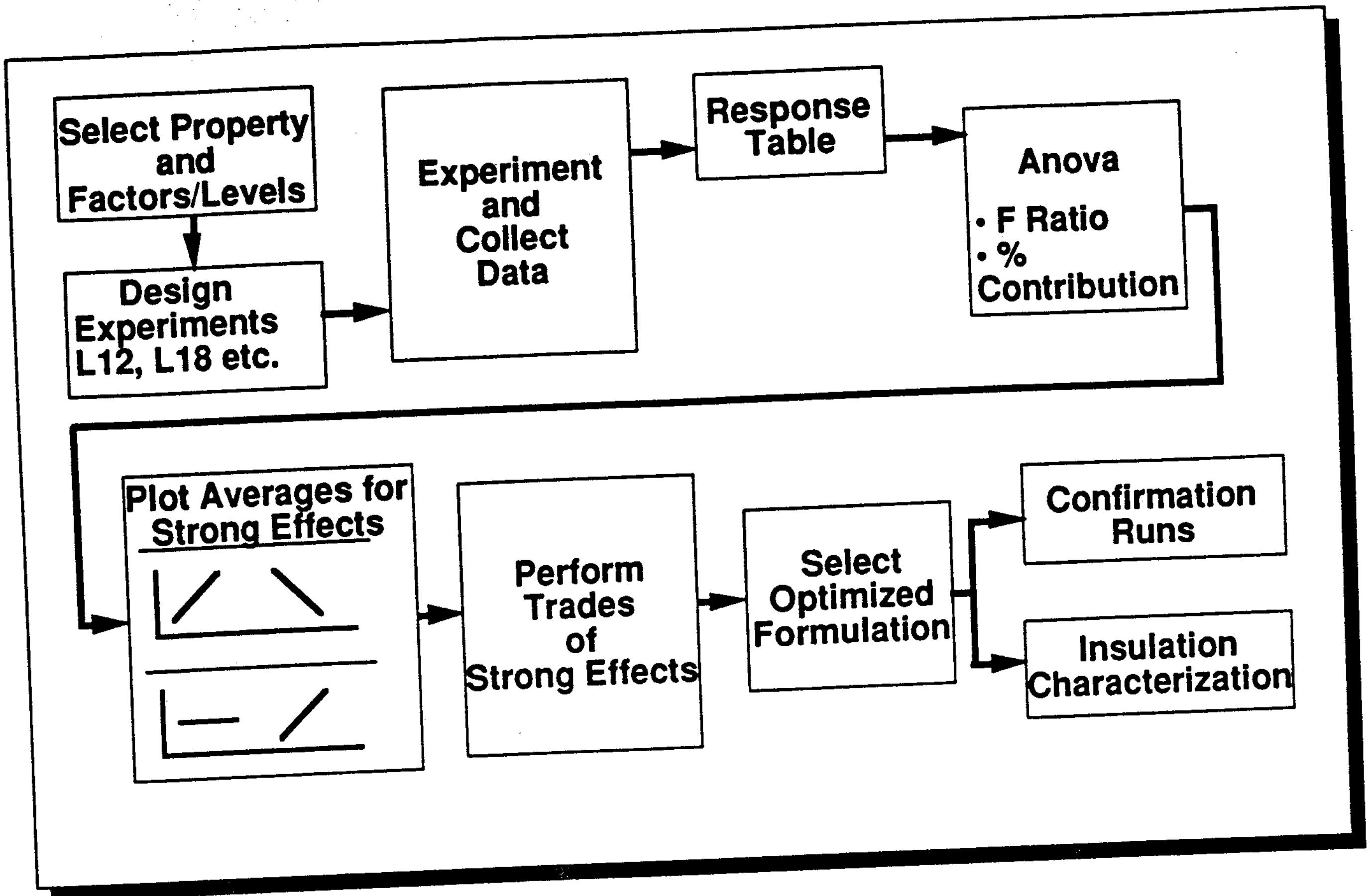


Figure 2. Insulation Formulation Optimization Process

The optimization insulation formulation was selected based on the Taguchi design of experiment as shown **Figure 3**. The Taguchi method advocated the use of an orthogonal array to study a small fraction of the possible combinations of factors and levels in an experiment. The test results from the experiments were interpreted through the use of a statistical software package, ANOVA TM. The ANOVA TM performed the analysis of variance on the effects of various factors simultaneously. The calculated results were F-values and percent contributions for each ingredient factor. **Figure 4** shows the weight factor system used to make the necessary trade-offs when different properties suggest different optimum levels. The % contribution of a significant ingredient was multiplied by the weight factor of the particular test. The weighted % contributions were accumulated for each insulation ingredient. The optimized insulation formulation composed of ingredients and factor levels with the highest weighted % contribution scores. The Pareto plot, shown in **Figure 5**, illustrated the relative ranking of the ingredients and factor levels for formulation optimization.

Kevlar pulp was the most significant factor. Ablation performance is directly affected by the Kevlar content in the insulation formulation. Low-cost fibers or fillers cannot replace Kevlar for ablation performance. The low-molecular weight ethylene propylene diene monomer, EPDM (Trilene 67) was the second most significant factor. The low-molecular weight EPDM serves as a processing plasticizer. There is an another advantage that the Trilene, unlike other plasticizers, is chemically similar to the bulk EPDM, Nordel 2522. The ablation motor tests showed the use of Trilene has no deleterious effect on ablation performance. Sulfur cure system was found to be the third most significant factor. The level of cure or crosslink density associated with sulfur cure slightly improved the ablation performance of the insulation compound. The tackifier Wingtack was the fourth most significant factor. It contributes to the hot tack strength of the insulation. Hot tack strength promotes bonding between insulation strips, which is key to successful internal stripwinding.

TAGUCHI DESIGN OF EXPERIMENT

FACTORS	LEVELS (PARTS/100 PARTS RUBBER) 1	2	3
A. FERRIC OXIDE	0	2	-
B. EPDM/LIQUID POLYMER	TRILENE 66	TRILENE 67	KALENE 1300
C. DECHLORANE PLUS	15	25	35
D. ANTIMONY OXIDE	10	20	25
E. KEVLAR PULP	0	20	40
F. WINGTACK 95	0	4	8
G. BOROSILICATE FIBER	0	5	10
H. CURATIVE	PEROXIDE, DICUP 40KE (10)	SULFUR (1)	SULFUR (2)

Figure 3. Insulation Formulation Optimization Test Matrix

Properties	Target Goals	Weight Factors	Weight Factor Distribution
Ablation at M=0.05	0.01 in./s max	5	25
Ablation at M=0.07	0.015 in./s max	5	
Ablation at M=0.10	0.023in./s max	5	
Ablation at M=0.15	0.030 in./s max	5	
Ablation at M=0.20	0.045 in./s max.	5	
Specific Gravity	1.300 max	2	25
Tensile (Parallel) @77°F	500 psi min.	0.5	
Tensile (Parallel) @-9°F	500 psi min.	0.5	
Elongation (Parallel) @77°F	5 % min	1	
Elongation (Parallel) @-9°F	5 % min	1	
Modulus (Parallel) @77°F	5,000 psi max	1	
Modulus (parallel) @-9°F	5,000 psi max	1	
Tear (Parallel)	5,000 psi max	1	
Tensile (perpendicular) @77°F	500 psi min.	0.5	
Tensile (perpendicular) @-9°F	500 psi min.	0.5	
Elongation (perpendicular) @77°F	5 % min	1	
Elongation (perpendicular) @-9°F	5 % min	1	
Modulus(perpendicular) @77°F	5,000 psi max	1	
Modulus(perpendicular) @-9°F	5,000 psi max	1	
Tear (perpendicular)	5,000 psi max	1	
Specific Heat	0.3 BTU/lb°F min	3	
Thermal Conductivity	0.150 BTU/hr°F Ft	3	
Relaxation Modulus (Parallel)	Projected 100/500 psi in 1yr	2.5	
Relaxation Modulus (Perpendicular)	Projected 100/500 psi in 1yr	2.5	
Mooney Viscosity	100 max	2	25
Cure Time	60 minutes max	1	
Extruded Strip Quality	25 points	17	
Hot Tack	2 psi min	5	
Cross Ply Bond	200 psi min	3	25
Unaged Peel (Parallel)	5 points min	1	
Aged Peel (Parallell)	5 points min	3	
Aged Tensile	+/-20% Unaged	6	
Aged Elongation	+/-20% Unaged	6	
Aged Modulus	+/-20% Unaged	6	

Figure 4. Properties are Weighted for Trade Study

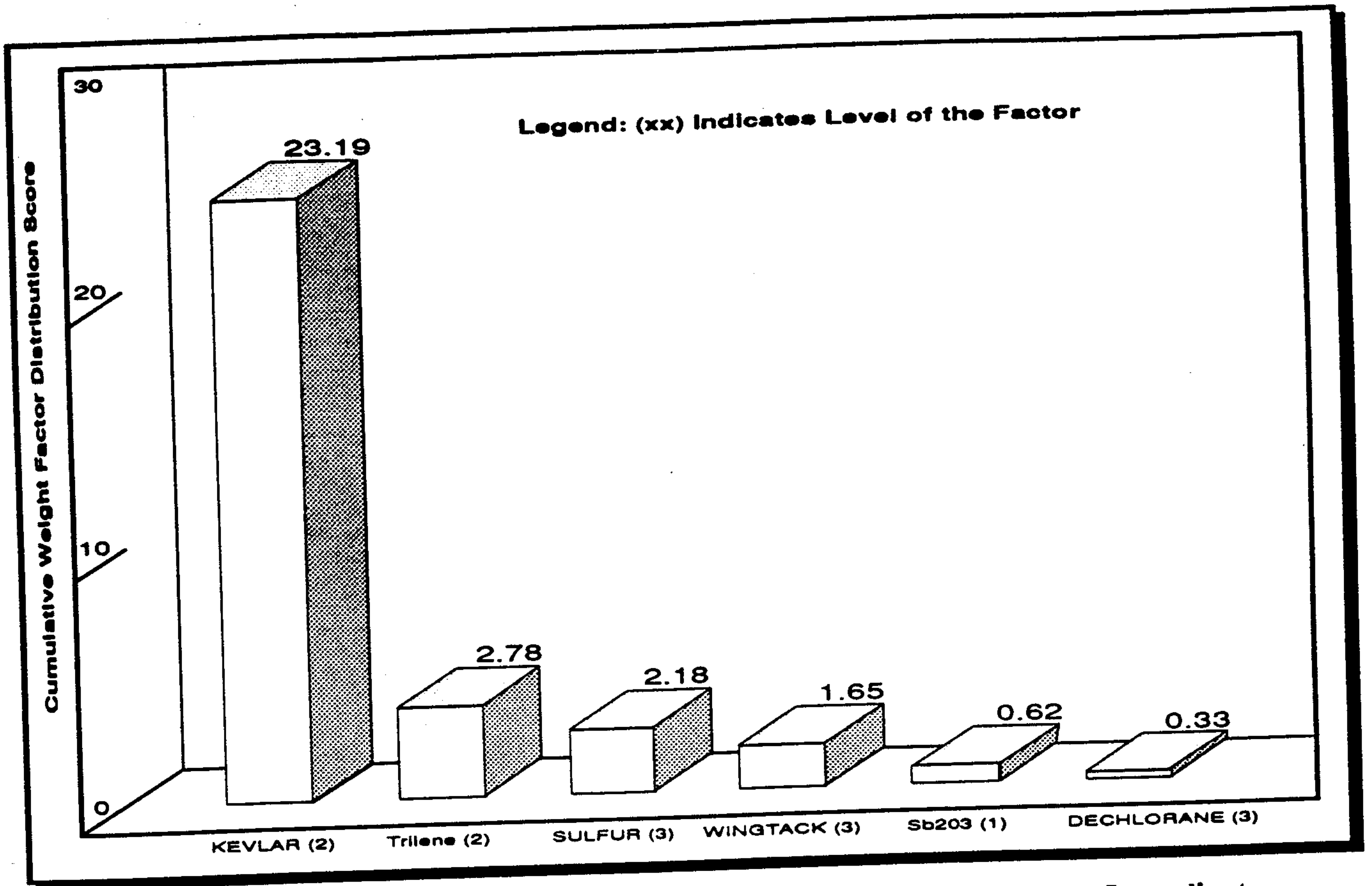


Figure 5. A Pareto Plot of Cumulative Weighted % Distribution oF Significant Ingredients

Antimony oxide was the fifth significant factor. Dechlorane (a chlorine donor) was the sixth significant factor. They are flame retardants added to reduce insulation ablation at low motor flow environments. Since their contributions to the overall performance of the insulation were minor, they were rated low in the design of experiment. Ferric oxide and borosilicate fiber were also added to enhance the ablation performance of the insulation. They did not enhance any insulation properties and were deleted from the formulation. The optimized insulation formulation is shown in **Figure 6**.

Confirmation testing of the optimized formulation has been completed satisfactorily. It involved an additional four 12-in. dia. test motor firings and other mechanical property tests. Detailed fingerprinting and characterization of the insulation are in-process.

The insulation formulation has been designated as ASRM specification, ASRM-44010. It is available for use in other SRM programs.

OPTIMIZED FORMULATION

INGREDIENT	WEIGHT %
Nordel 2522 EPDM	27.94
Trilene 67 EPDM	18.63
Dechlorane Plus Flame Retardant	16.30
Antimony Oxide Flame Retardant	4.66
Kevlar Pulp	13.97
Wingtack 95 Tackifier	3.73
Sulfur	0.93
Captax Accelerator	0.93
Monex Accelerator	0.35
Stearic Acid Activator	0.46
Zinc Oxide Activator	2.33
Hisil 233 Silica	9.31
Agerite Resin D Antioxidant	0.46
Total	100.00

Figure 6. ASRM OptimizedInsulation Formulatio

Thermal Design. The insulation thicknesses were sized using an empirical approach based on similarity between the RSRM forward fin grain design and the ASRM grain design. The empirical similarity approach is accepted by the industry when there is no full scale ablation performance data for thickness sizing. An Aerojet-developed database derived from the firing of 26 RSRM motors was used to obtain upper tolerance limits for ablation rates, accounting for data variance between and within motors. Ballistic codes provided local exposure times. Subscale 48-in. dia. test motors provided side-by-side comparison of ASRM and RSRM insulation ablation performance as show in **Figure 7**. The ablation rates were adjusted to reflect ASRM'S superior performance. Empirically derived design thicknesses include a manufacturing tolerance of 0.03 in. and a minimum safety factor of 2.0, which incorporated the thermal protection thickness requirements in the same manner as RSRM. The design approach resulted in a payload gain of 300 pounds compared to RSRM.

Insulation Joint Design. Insulation joint configurations are shown in **Figure 8**. The igniter-to-case, case-to-case and case-to-nozzle insulation joints are sealed by chamber pressure to provide a zero-opening seal. This seal design is tolerant of flaws and remains closed even when known leak paths are present at the joint interface. For redundant protection, a tortuous joint path precludes direct radiation and flame impingement on the metal interface. In the unlikely event of a leak, theoretical gas flow is low enough that the metal surface temperature will not exceed 300°F. Further redundancy is provided by a third O-ring, added as a thermal barrier for protection of the joint.

The insulation joints were designed to withstand additional ablation associated with slag accumulation by incorporating conservative thermal safety factors. This approach was similar to HPM/RSRM designs, which have been substantiated by static and flight firings.

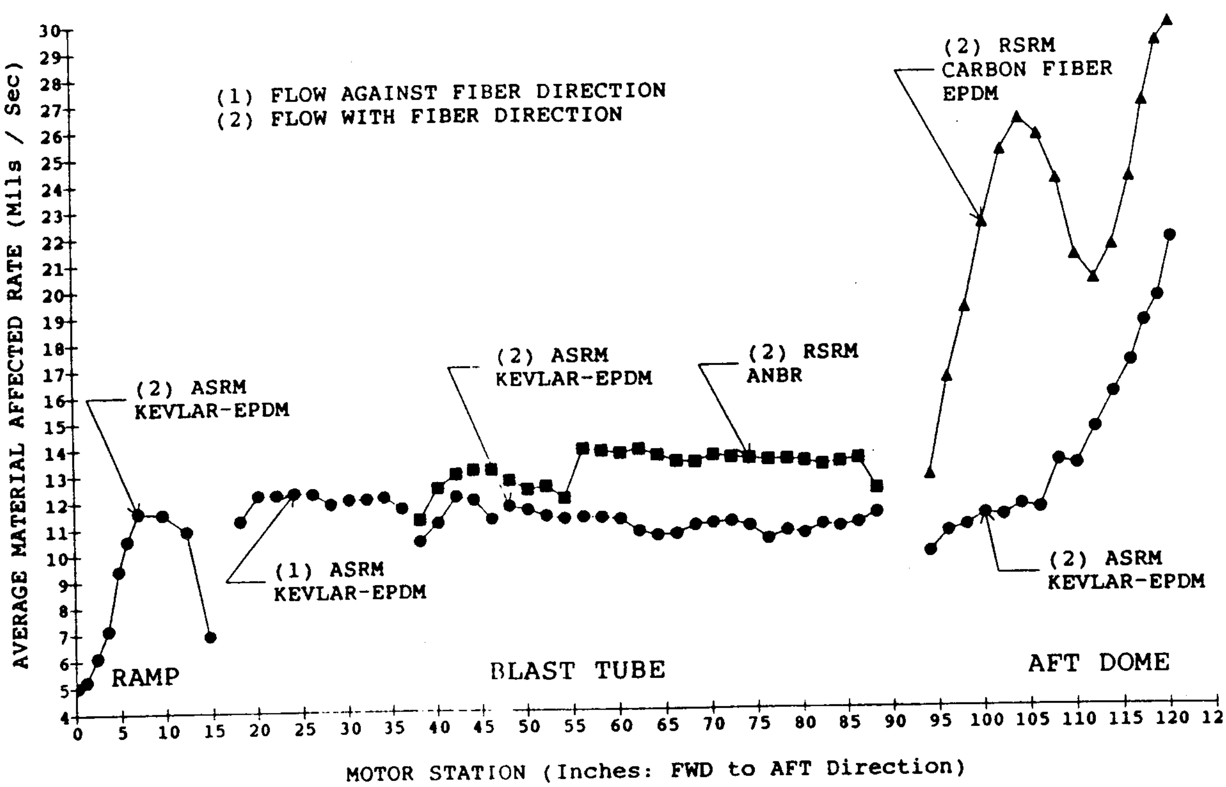


Figure 7. ASRM Nonasbestos Insulation Shows Improved Ablation Performance over the RSRM Materials in the 48-in.Dia. Motor

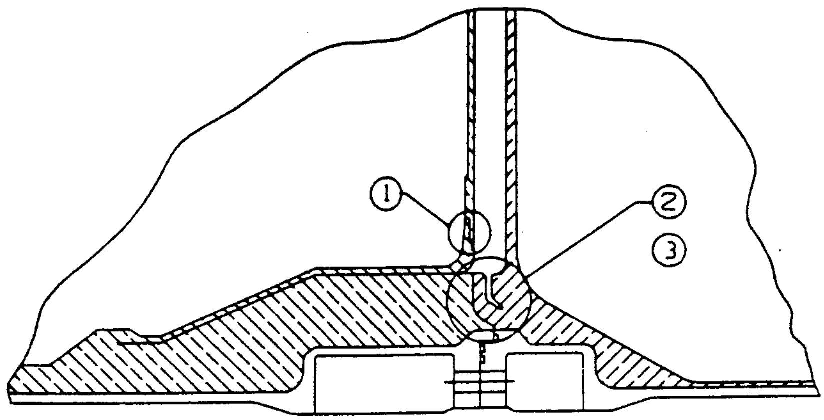
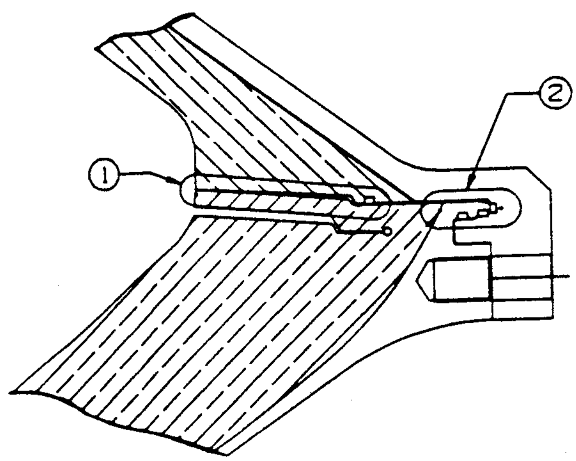
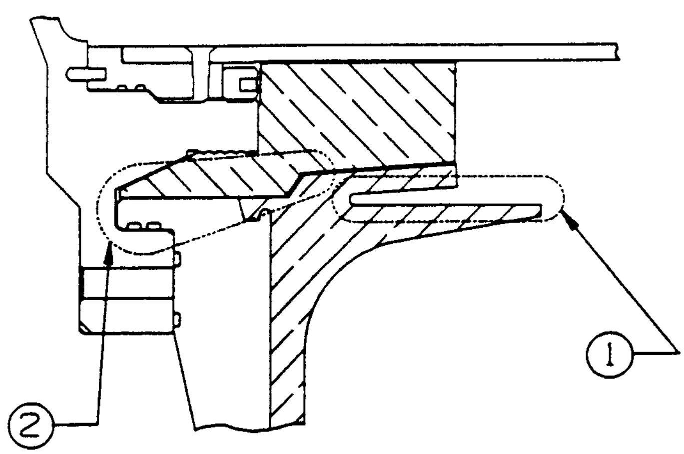
DESIGN DESCRIPTION	BENEFITS
	**Case-to-Case Field Joint** 1. Aft face grain inhibitor joint, remote from sidewall, eliminates possibility of jetting to sidewall insulation. 2. Field joint insulation interface, located in stagnant area behind stress relief flap, avoids direct exposure to hot gas flow. 3. Positive joint closing under chamber pressure eliminates possibility of hot gas flow through joint.
	**Case-to-Nozzle Joint** 1. Positive joint closing under chamber pressure eliminates possibility of hot gas flow through joint. 2. Tortuous gas path at metal joint provides gas cooling.
	**Igniter-to-Case Joint** 1. Positive joint closing under chamber pressure eliminates possibility of hot gas flow through joint. 2. Tortuous gas path at metal joint provides gas cooling.

Figure 8. All Insulation Joints Stay Sealed Under Chamber Pressure

Producibility For improved process repeatability over RSRM, the labor-intensive hand lay-up procedure was eliminated. To maximize the benefits of automation the Steelastic designed stripwinding process was selected as the method of applying the internal insulation. The development of internal stripwinding at Aerojet began with the modification of an existing external stripwinder. The modification enhanced laboratory resources, provided existing data base for the development of ASRM trade studies and produced an EXTERNAL/INTERNAL "convertible" piece of equipment all providing considerable cost savings to the activation of the Stripwinder Pilot Plant (SWPP). The Stripwinding process applies a controlled thickness of insulation on internal contoured and cylindrical surfaces. To ensure process repeatability, the Stripwinder (**Figure 9**) is microprocessor-controlled to maintain real time control of strip temperature, thickness, width and constant surface velocity from the point of preparation to the point of application. Sidewall-to-insulation and insulation-to-insulation adhesion is promoted by a mechanical stitcher (pressure) and the residual strip heat. The advantages of pressure/heat tackification are substantial in that the process eliminated the use of environmentally sensitive hydrocarbon solvent.

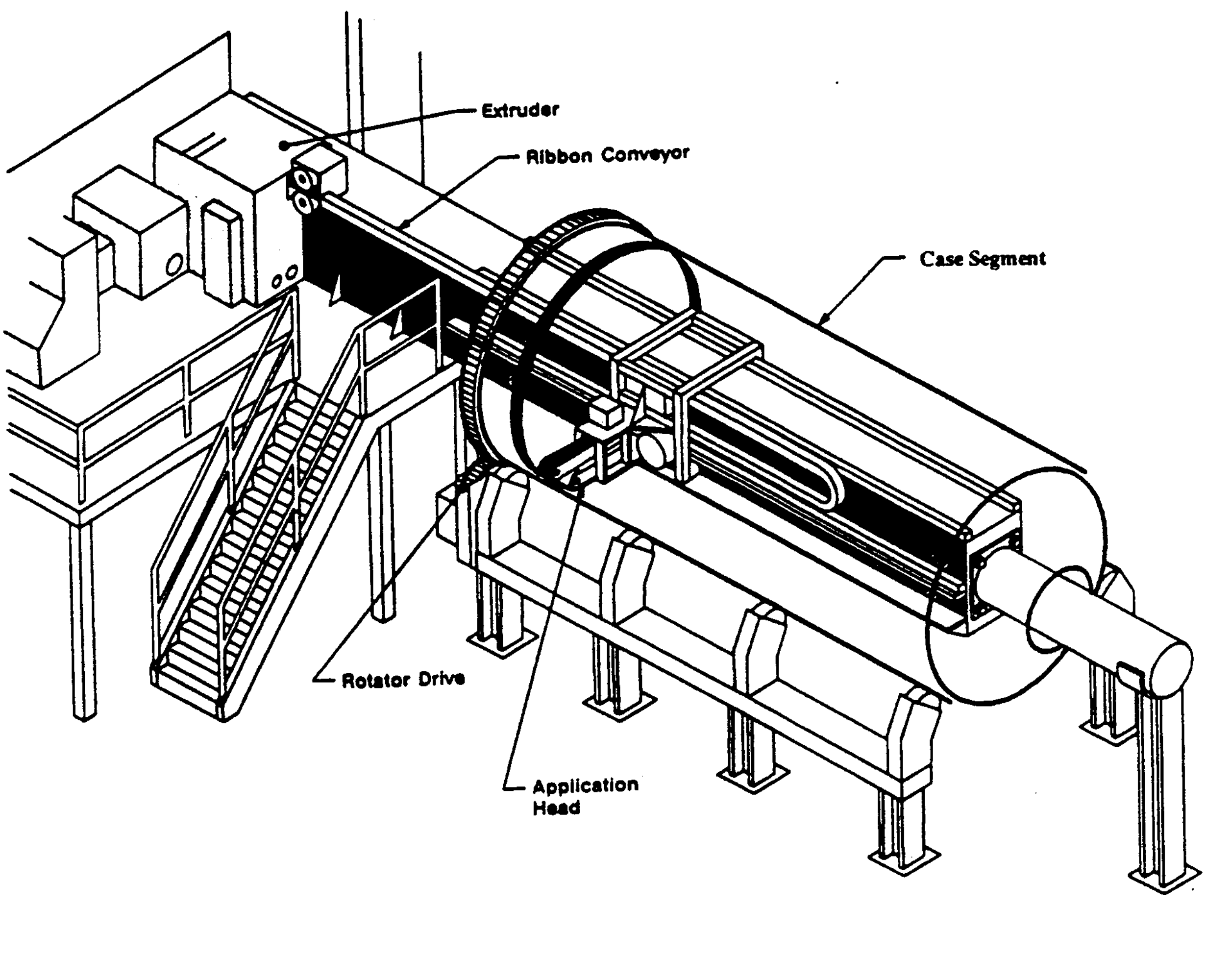


Figure 9. Automated Stripwinding Insulation Process

Safety. Before proceeding with the insulation process development, the internal stripwinding process was evaluated and approved by several Aerojet and NASA review committees including; the APD Critical Review Committee (CRC) in July 1988, the APD Executive Safety Advisory Committee (ESAC) in November 1988, ASRM Stripwinder Pilot Plant Critical Experiment Review (CER) on February 1991, and the Aerospace Safety Advisory Panel (ASAP) in August 1991.

SWPP Development. In order to support the D & V logic given in Figure 13, the SWPP activities were defined within the Stripwinder Developmental Specification. This specification included a total of four (4) phases. Phase priority considered schedule requirements and process development for the successful completion of all task and transfer of technology to full scale efforts in Iuka.

PHASE 1 - SELECTION OF OPTIMUM FORMULATION

PHASE 2 - CONFIRMATION OF OPTIMUM FORMULATION

PHASE 3 - DEMONSTRATION OF INTERNAL STRIPWINDING ON 150-IN DIA. TEST ARTICLES

PHASE 4 - 48 IN DIA. MOTOR PROCESSING

PHASES 1 & 2 - SWPP support efforts during the selection and confirmation phases of insulation development included the screening of insulation formulations for potential downstream processing problems. Extrudability of the candidate insulation would be examined concurrently by Engineering and Manufacturing. More detailed SWPP process parameters were documented in Process Quality Plans (PQP). Critical parameters were isolated and characterized using Taguchi design of experiment.

In one Taguchi experiment, the critical process parameters for extruding insulation strip were identified by the above analysis procedures. The parameters selected for experiment were extruder speed, upper roller temperature and extruder nozzle temperature. A series of extrudability runs was conducted using these design of experiment parameters. The extruded strips were then rated to Aerojet developed quality standards. A total of 18 candidate insulation formulations were evaluated. Sampling of each candidate run were measured for dimensional consistency and continuity, yielding 4320 measurements for Extrudibility results. The optimum settings were used for subsequent processing of the insulation in later phases.

The extrudability results showed that non-Kevlar filled formulations displayed optimum edges but poor thickness continuity. High Kevlar filled formulations displayed optimum thickness continuity but poor strip edge ratings. Formulations with 20 parts per hundred parts rubber (PHR) Kevlar displayed optimum thickness continuity and good edge ratings. The low-molecular weight polymer, Trilene, played a very significant role in enhancing the insulation for stripwinding. These results were considered in the final selection of the insulation formulation. Through this TQM procedure, the Stripwinder Pilot Plant was able to meet its development goals in an efficient fashion.

Sheet stock material was fabricated on the SWPP in order to support Engineering studies. Over 4000 square feet of candidate material was extruded and applied to an external drum, removed, cured, and delivered in support of Selection and Confirmation.

After the extrudability study, the stripwinding process was demonstrated on large diameter motor analogs. During PHASE 3, full scale 150-in. dia. test articles were successfully stripwound with insulation, as shown in **Figures 10 and 11.** The lessons-learned were transferred to AAD, in Iuka for their stripwinder activation process. During PHASE 4, 48-in. dia. motor blast tubes were also successfully stripwound and hot fired to evaluate the effect of stripwinding angle and direction with respect to the hot gas flow direction. The results showed no appreciable stripwinding angle and direction effect on ablation performance.

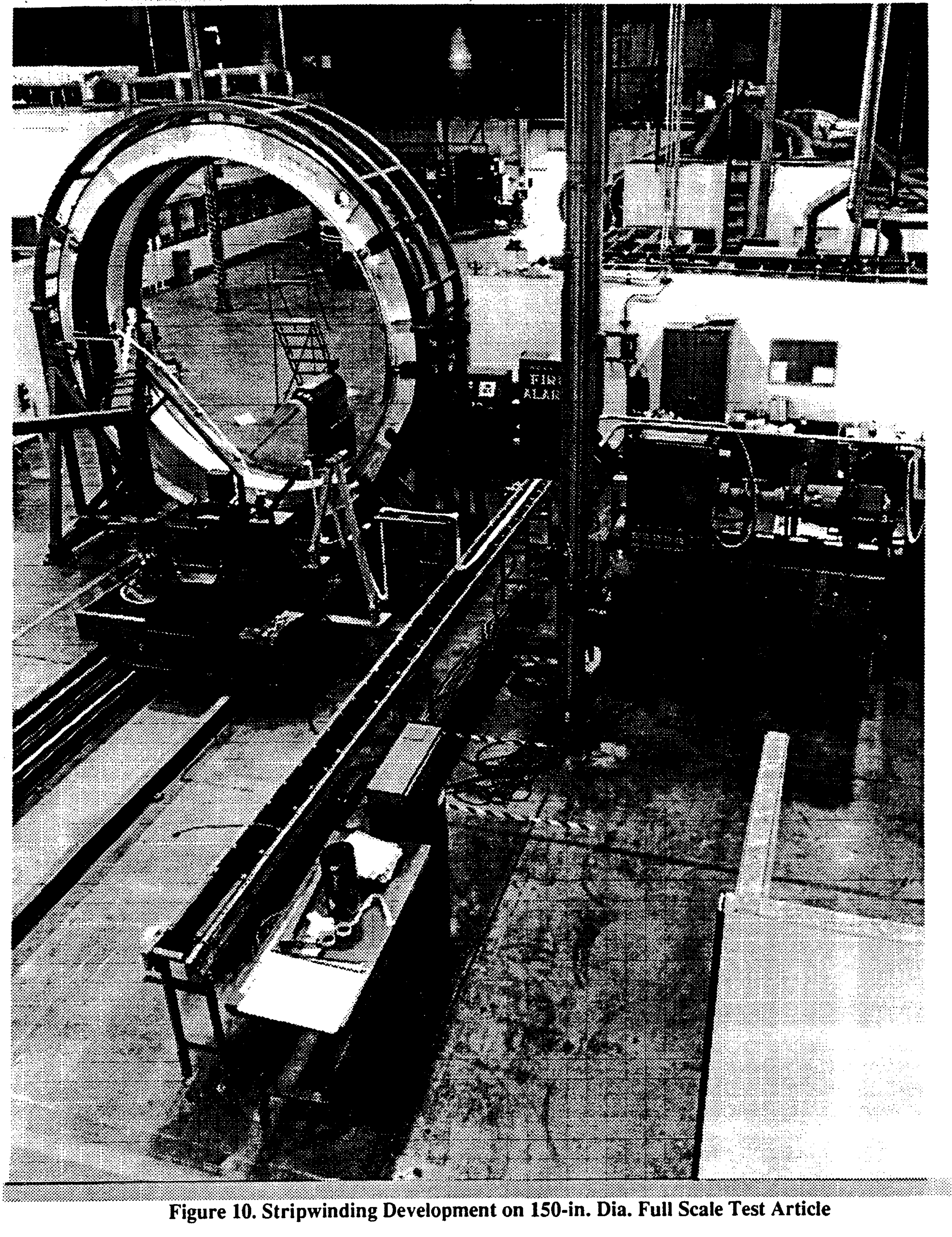


Figure 10. Stripwinding Development on 150-in. Dia. Full Scale Test Article

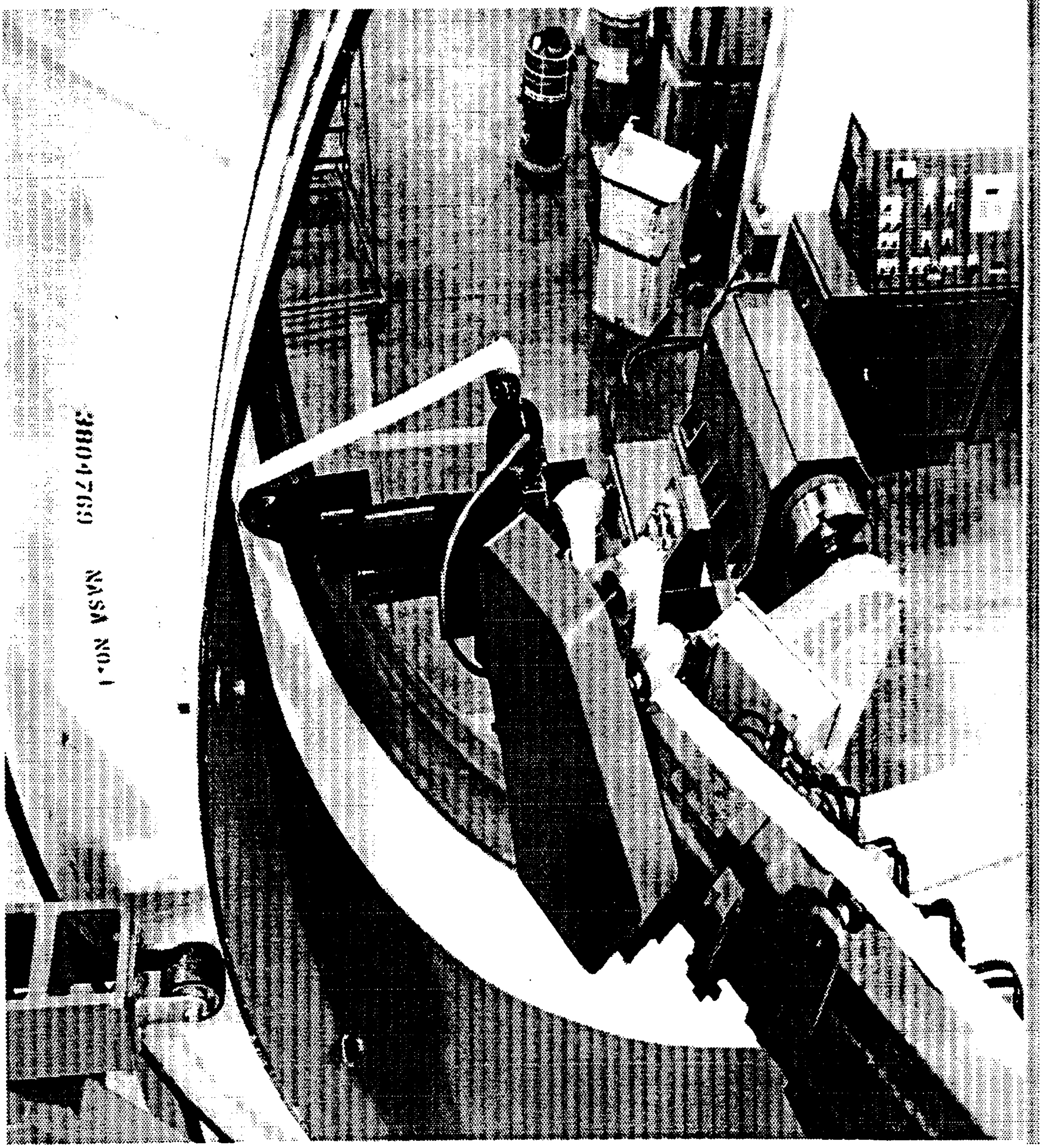


Figure 11. Insulation Strip Application on Inner Diameter of Motor Case

Total Quality Management. Total Quality Management (TQM) philosophy was at work in all aspects of design, test matrix generation, equipment specifications, tooling requirements, process development and Stripwinding Pilot Plant activities. The TQM Team, also known as the Product Development Team (PDT) consisted of members from Design, Analysis, Materials, Manufacturing, Quality, Lockheed Systems Engineering and Integration (SE&I) and NASA Project Office. The TQM team met regularly for brainstorming and planning. There were Technical Interchange Meetings (TIM) with the customer, NASA, to maintain current reporting of the design and manufacturing developmental progress.

TQM development guidelines were established prior to activation of the Stripwinder Pilot Plant (SWPP). All aspects of the Stripwinding pr ocess were delineated using Cause and Effect Analysis (CEA) diagrams. The critical steps in the Stripwinding process are (1) Acceptable Strip Preparation, and (2) Acceptable Strip Application to the Product. CEA diagrams for the critical steps considered Process, Machines, Material, Environment and People. Considered topics were further broken down to include any variables determined by PDT members to have any consequence on the SWPP process. Over 100 variables were included in the final CEA diagrams causing many iterations from the original inputs.

Insulation Supplier Qualification. The insulation supplier qualification plan is shown in **Figure 12.** The plan originally intended to qualify three suppliers. But due to programmatic changes, two rubber compounders were qualified to produce the insulation. The suppliers are Burke Rubber Co. and RM Engineering. The dual sources permitted competitive pricing and ensured continuous delivery of the insulation material.

D & V Plan. The overall Development and Verification (D & V) logic is given in **Figure 13.** This plan provided the roadmap for case insulation design and fabrication checkout. The highlights of the D & V plan included optimization of the Aerojet-developed insulation formulation, 12-in and 48-in. dia. subscale motor testing for insulation supplier qualification and erosion data for thickness sizing, insulation stripwinding process development and full-scale development and qualification motor testing. The subscale D & V tasks are near completion. The next major tasks are the full scale Development Motor (DM) activities, which will be done at Iuka.

Conclusion. Aerojet's strategic IR&D planning for a high performance nonasbestos insulation before a major program competition had partly contributed to the winning of the ASRM program. After ASRM contract award, the insulation material was optimized by Taguchi design of experiment to support full scale motor development.

All critical insulation joints have been designed with chamber pressure assisting the sealing of the insulation joint interfaces. Although the steel case joint o-rings are designated as the primary sealing mechanism, they actually will serve as back-up to the effective pressure-assisted insulation joint seal.

The automated stripwinding pilot plant has been established in Sacramento as part of the insulation process development tasks. This new process development has demonstrated Aerojet's capability to stripwind insulation to an inner diameter of a motor case chamber. This was a first for Aerojet and thus enabled Aerojet to match or exceed the capability of its primary competitors in this critical area.

ASRM Case Insulation Design and Development

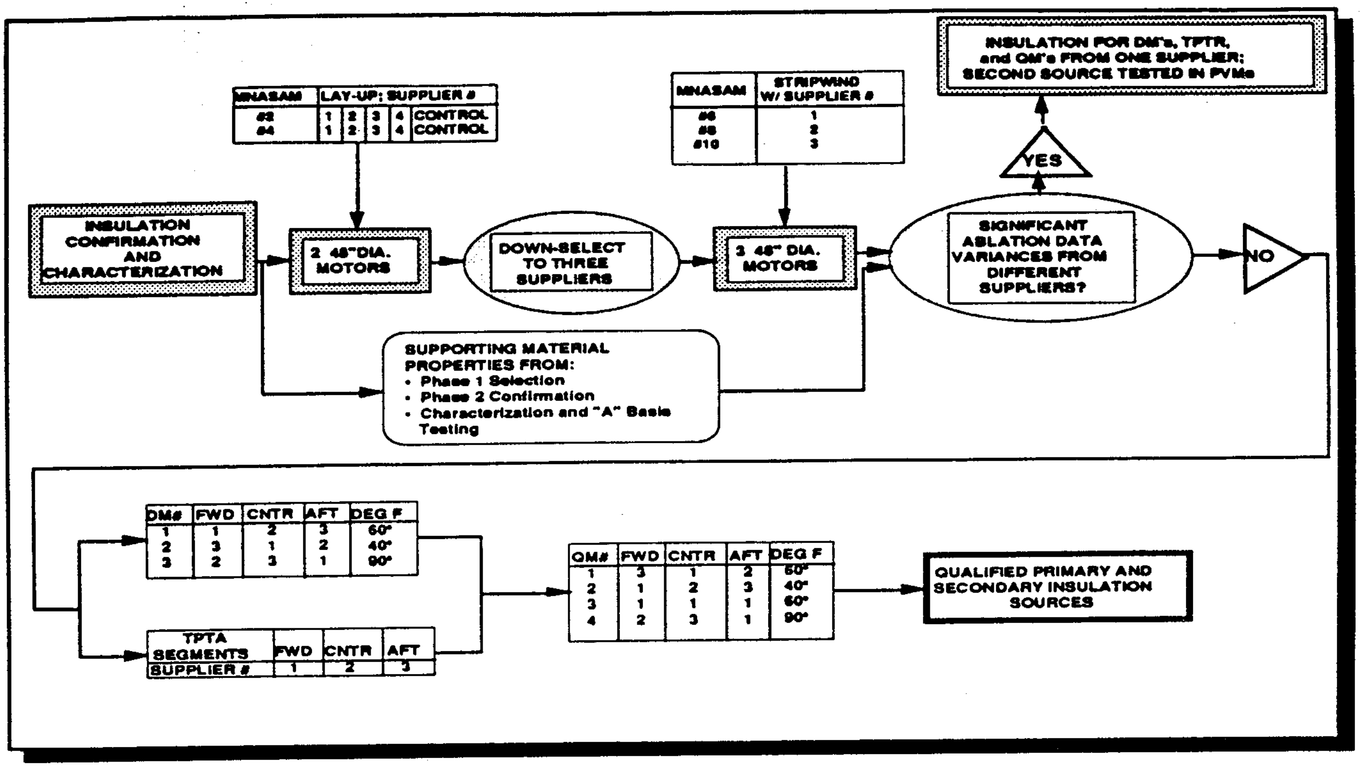


Figure 12. Insulation Suppliers Qualification Logic

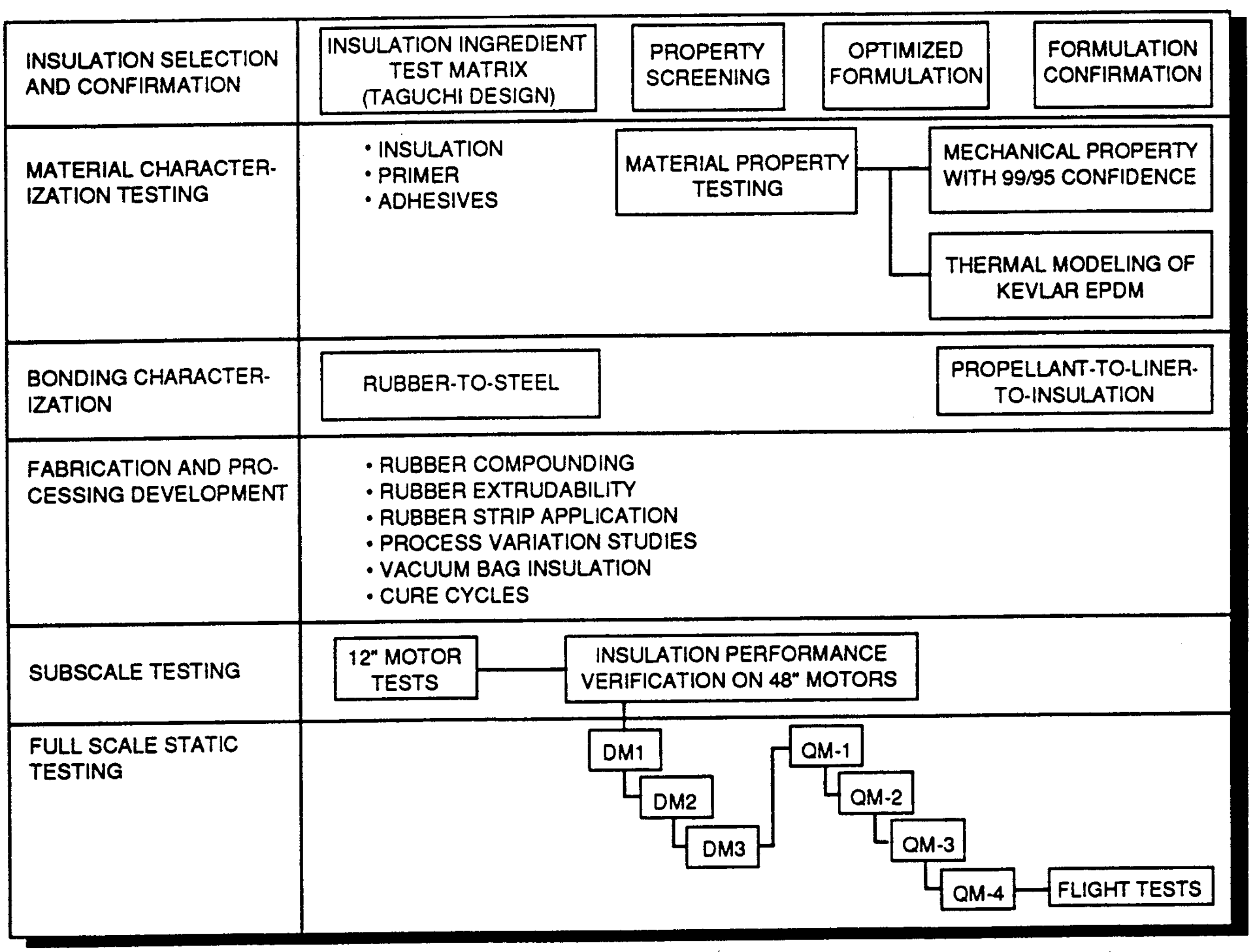


Figure 13. Insulation Development and Verification Overview