Formulation Of New Fireproof Boom Designs

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Formulation of New Fireproof Boom Designs

Abstract

New concepts and material combinations are needed if in-situ burning is to reach its full potential as an effective tool in spill remediation. Previous testing had shown that existing fire boom technology had too many shortcomings in the areas of material options and boom configurations. This project had two objectives: to identify new material options for use in fire boom products and to conceptualize boom configurations that could exploit these new material options to achieve improvements in performance, handling and durability.

The program began with a review of existing fire boom products. The intent was to validate the project premise as well as develop insight to the design strategy reflected in each product. The review was based on published literature, patent searches, discussions with several boom manufacturers and discussions with potential end-users. The survey findings were then used to formulate a product specification document, structured to address a broad range of factors that must be considered during the course of product development. The topics included operational considerations, functional requirements, performance requirements and manufacturing considerations. The process first sought to establish a list of desirable attributes and then to associate these characteristics with specific features of existing products. Concepts were then developed and evaluated; evaluation of the better ideas included a thermal analysis to establish projections of the geometry, buoyancy and surface temperatures for various material combinations. Also, the various strategies for management of the heat load were tested and the concepts were refined.

The findings revealed that the evolution of commercial products is not complete. The products currently on the market must undergo additional refinement before in-situ burning can progress to full effectiveness as a cleanup tool. The reasons are many, but essentially involve performance limitations in three critical areas: durability, seaworthiness, and transportability. With these conditions in mind, Southwest Research Institute developed two design approaches. The primary difference between the approaches resides in the management of the heat load. One involves the use of supplemental cooling (as delivered via a water distribution plenum) to limit exterior surface temperatures; the other involves the use of ceramic fibers and conductive materials to limit interior temperatures. Otherwise, both approaches rely on inflatable flotation chambers so as to improve seaworthiness and reduce transport requirements.

1.0 Executive Summary

1.1 Introduction

This report summarizes the work performed to develop improvements in fire boom technology. The project had two objectives: to identify new material options for use in fire boom products and to conceptualize boom configurations that could exploit these new material options to achieve improvements in performance, handling and durability. Previous testing had shown that existing systems simply had too many shortcoming in these areas. Consequently, new concepts and material combinations were needed if in-situ burning was to reach its full potential as an effective tool in spill remediation.

Given the cited objectives, the program scope did not include a comprehensive review of the environmental issues associated with in-situ burning. Environmental concerns were addressed only to the point needed to ensure that the candidate materials would not contribute to or compound the environmental problem. This constraint to the program scope allowed the project team to focus entirely on the process of burning crude at sea and the many engineering challenges it presents.

The program began with a review of existing fire boom products. The intent was to validate the project premise as well as develop insight to the design strategy reflected in each product. The review was based on published literature, patent searches, discussions with several boom manufacturers and discussions with the Marine Spill Response Corporation (MSRC) and the Texas General Land Office (TGLO) - both representing the perspectives of the end-users.

The survey findings were then used to formulate a product specification document. The document was structured to address a broad range of factors that must be considered during the course of product development. The topics included operational considerations, functional requirements, performance requirements and manufacturing considerations. The process first sought to establish a list of desirable attributes and then to associate these characteristics with specific features of existing products. In other words, we wanted to understand why certain features worked and to use that insight to develop concepts. Concepts were next developed and evaluated. Evaluation of the better ideas included a thermal analysis to establish projections of the geometry, buoyancy and surface temperatures for various material combinations. It was during this segment of the program that the various strategies for management of the heat load were tested and concepts refined. While seaworthiness was a major concern, the concepts were not subjected to any formal analysis to establish heave or roll behavior.

1.2 Conclusions

Our review of fire boom technology revealed that the evolution of commercial products is not complete. The commercial products currently on the market must undergo additional refinement before in-situ burning will be able to reach its full potential as an effective remediation tool. The reasons are many, but essentially involve performance limitations in three critical areas:

- **Durability:** Commercial booms have not demonstrated the ability to survive repeated collection/burn cycles at sea without major rework. Considering the facilities required to inspect and/or recondition a boom at sea, rework between cycles is not a practical option. Booms must survive repeated collect/burn cycles to keep the logistics of the clean-up under control, or alternately the booms must be cheap so that they may be consider "disposable" and packaged so that an adequate supply can be made available at the spill site.

- **Seaworthiness**: The towing and sea-keeping performance of the commercial products must be improved. Even though the manufacturers may advertise as having ocean booms, the product(s) have not demonstrated the ability to collect and contain spilled oil at conditions that are likely to prevail on the open sea.

- **Transportability**: Few commercial units are available in configurations that are suited to quick response. As a consequence, the time required to get the fireproof boom from its storage location to the spill site may limit the spill candidates for in-situ burning to costal areas, which will not only complicate the public relations aspect, but also reduce the margin for error.

With these conditions in mind, Southwest Research Institute (SwRI) developed two design approaches. Each approach addresses the above areas and affords mechanisms for improving performance relative to existing products. The primary difference between the approaches resides in the management of the heat load. One involves the use of supplemental cooling (as delivered via a water distribution plenum) to *limit exterior surface temperatures*; the other involves the use of ceramic fibers and conductive materials to *limit interior temperatures*. Otherwise, both approaches rely on inflatable flotation chambers so as to improve seaworthiness and reduce transport requirements.

1.3 Recommendations

The users, regulators and public (as the ultimate benefactor of in-situ burning) should continue efforts to promote improvements in boom technology. Continuation will not only allow the evaluation of novel ideas, but will also provide the users with a mechanism for applying subtle pressure on the manufacturers to improve their products, or risk losing market share. Furthermore, without a vested interest in a specific product or component part, the users are free to pursue or abandon approaches that don't work.

With regard to the current initiative to improve boom performance, the program is ready for the next step, one devoted to refinement of selected concepts to the point that design documentation is sufficient to support the production of hardware.

Continuation should involve the following:

- The seaworthiness of the selected fire boom concepts should be investigated using analytical methods. The analyses should focus on the dynamic behavior and structural loading as a function of sea state, towing conditions, and thermal treatment.

- Unlike metals, the thermal performance of fiber-based materials are sensitive to a host of variables to include bulk density, fiber orientation and moisture. Accordingly, a materials testing effort is needed to more fully characterize the thermal properties of textiles and blankets. The effort would require the acquisition of materials needed to produce representative *cross-sections* of the viable configurations. These specimens would then be subjected to thermal testing to quantify properties, establish service temperatures, and to validate/refine the thermal model(s).

- Ultimately, the viable concepts are those that not only meet the performance requirements, but can be produced at a reasonable cost - one that is affordable to the customer and allows profit for the manufacturer. Thus, each concept and variation thereof should be reviewed to establish a preliminary assessment of its manufacturability and a construction protocol that is consistent with the materials and the design strategy. Once this step has been completed, then the concept would be ready for prototyping and large-scale testing.

- Finally, the modelling methods can also be applied to existing boom designs. Such an exercise would provide numerous benefits to include a validation/refinement mechanism for the methodology, a screening method for products prior to purchase and/or testing, and a means to evaluate the consequence of specific design decisions.

2.0 Summary Of Findings

2.1 The Market

The history of in-situ burning of spilled crude extends back into the late 1960's. The idea of using a towed boom to collect the oil and sustain the combustion process, however, did not emerge as a product until the 1980's. During this period, several different concepts were developed and tested. These test efforts suggested that a properly designed boom should survive the rigors of open sea burning and led to the introduction of several fireproof booms to the commercial market. It is important to note that the evolution of the products occurred in the absence of any recognized standards for establishing product performance or quantification of critical properties.

While the preponderance of test data supported in-situ burning as a viable option for the remediation of spilled crude, regulatory policy regarding spill response remained fragmented. Only after the *Exxon Valdez* experience did government agencies begin to develop a comprehensive spill response policy which could accommodate in-situ burning as a real option. Even then, public perceptions and concerns over emissions and air quality kept the market for fire boom products well below that needed to generate a reasonable return on investment. Consequently, the manufacturers had little incentive to improve their designs. Products sales were simply not sufficient for companies to justify continual investment of the capital resources needed to sustain an aggressive development program.

In 1993, several events took place that altered the situation:

- The MSRC response system was formerly activated.
- Agencies with spill over-sight initiated meetings to discuss technologies and the coordination of resources.
- Test experience from staged burns at sea revealed that the results did not correlate with pool burn experience. The at-sea conditions combined to take a heavier toll on a boom than observed in a the typical pool burn.
- State and federal agencies began to move forward with policy that would extend the authority to approve in-situ burning as a response option to selected regions.

Collectively, these events stirred activity with both the users and manufacturers of fire boom.

At the users' level, there was concern for the durability of products already purchased as well as indecision regarding pending purchases that were needed to fulfill the obligations associated with the "pre-approval" action of the government. In other words, those regions with pre-approval for burning were expected to have the ability to conduct the burn should a valid situation develop.

The uncertainty of the users was due in part to the absence of an accepted method by which products could be compared. There are no standards that clearly define acceptable performance nor translate performance criteria into critical system properties. Fortunately, the F20 Standard's Committee of the American Society for Testing and Materials (ASTM) is making progress with a document that will specify minimum performance criteria and thereby provide a standard basis for rating and comparing products.

In the manufacturing sector, the activity has been largely confined to those companies in the spill containment business, but without a fireproof boom as part of their product line. These organizations have been busy validating their design(s) and positioning themselves for an expected surge in the demand for fireproof booms.

2.2 Status of Commercial Products

At the current time, there are at least 6 companies with a line of fireproof booms. Not all companies, however, manufacture their product, relying instead on specialty shops for assembly. The companies and the respective product trade names are summarized in Table 2.1.

Table 2.1 Fire Boom Vendor Matrix

Company	Product Trade Name	Construction		Class (1)
		Flotation	Barrier	
Applied Fabrics Orchard Park, NY	PyroBoom	Metal Chamber (Spherical)	Fibrefrax & PVC	Group 1
Gamlen Industries Marcel, France	Fireguard	Metal Chamber (Rectangular)	Asbestos & PVC	Group 1
AB Sandvik Sandviken, Sweden	Sandvik Steel Barrier (SSB)	Metal Chamber (Cylindrical)	Stainless Steel	Group 1
KepnerPlastics Fabricators, Torrance, CA	Sea Curtain FireGuard	Air Chamber (Cylindrical)	Thermotex & Coated Polyester	Group 2
3M St. Paul, MN (Licensed to American Marine Cocoa, FL)	Fire Boom (American Fireboom)	Ceramic Foam (Cylindrical)	Nextel & PVC	Group 2
Oil Stop Harvey, LA	Auto Boom - Fire Model	Air Chamber (Cylindrical)	Details Not Disclosed	Group 2

(1) A Group 1 designation denotes a product constructed primarily of metals.
A Group 2 designation denotes a product constructed primarily from refractory fibers.

These products represent two distinct design approaches for protecting/preserving the flotation system. The products in the first group (i.e., the PyroBoom, the Fire Guard HD, and the SSB) derive their fire resistance by virtue of the *metals* used in the construction; those in the second group (the Firegard, Auto Boom and Fire Boom) derive their fire resistance from the use of *refractory fibers* that are based on silica or alumina. Additional details on the individual products are provided in Appendix A.

For the metal booms, it is important to note that the mere use of metal does not ensure a successful product. The more durable products have been those that have used the high conductance of the material in a "heat management" strategy - one that renders a physical configuration that can efficiently reject heat, thereby keeping temperatures in check. One metal boom company indicated that it is upgrading its strategy to include the use of water sprays. By so doing, the company can relax the design constraints dictated by conduction, and consider other configurations that permit improvements in seaworthiness, ease of deployment, durability, etc.

The test history for current commercial products revealed that all have exhibited signs of physical distress that would limited their availability during an operation. For example, the metals used for structural purposes are prone to rapid fatigue and corrosion at elevated service temperatures; the fiber systems become friable and disintegrate with flexure. As a consequence, major refurbishment could be required at the completion of each collect/burn cycle.

The process of reworking a boom once its has been subjected to a burn cycle is not envisioned as a simple procedure. Not only will the thermal protection systems will be soaked with water and coated with tar-like residues, but the weakened state of the exterior boom elements will make removal from the water a difficult, time consuming operation under the best of conditions.

Despite the history, there are elements of fire boom testing that suggest that the obstacles are not insurmountable. For example, the technical literature contains evidence that certain material systems exhibited characteristics that could lead to improvements in boom performance. These characteristics include:

- the production of char layers, comprised of residue from the burned crude and/or boom surface material(s), that enhance containment and provide additional thermal protection of the boom interior,

- the presence of heat conduction paths and materials that promote the distribution and rapid transfer of heat to submerged surfaces, and

- the ability to cool heated surfaces through the evaporation of water adsorbed (or wicked) from the ocean.

As far as we could determine, none of the existing fireproof booms incorporate design features that intentionally exploit these observations.

2.3 Customer Needs and Expectations

In light of the visibility and attention that oil spills create, the marine industry has become well-educated on various response options. Furthermore, industry personnel have intently monitored fire boom testing and have commissioned their own evaluations. As a result, the users can speak to their needs with creditability and conviction. Thus, the general consensus of the users was that the evolution of fire booms is not complete and improvements are well within the state-of-state. When asked about areas in need of improvement, the users were able to make specific recommendations:

- **Improved Durability**: Devise material systems that will allow the product to be used repeatedly over the duration of the spill and require the minimum of refurbishment in between collect/burn cycles. In other words, once a boom is deployed into the water, its availability to the spill task force should be 100%. Furthermore, options for re-use and/or reconditioning of boom elements should be considered, provided the salvage process does not adversely impact the life cycle cost.

- **Facilitate Deployment:** The boom and its stowage and deployment systems must be contrived to permit rapid response. The effectiveness of in-situ burning is directly related to the speed at which the systems can be dispatched and put into operation - the faster the response, the better the result.

- **Reduce the Life Cycle Cost**: The initial cost of a boom is not as important as its life cycle cost. Customers are willing to pay premium prices for a product that will survive the life of the spill and have some salvage value or re-use potential as compared to a similarly priced product that does not last and becomes a major component of the recovered waste.

- **Training Support**: Ultimately, the response to an emergency will depend not only upon the packaging of the system, but also upon the training of the crew charged with deploying the system. Accordingly, the users expressed a need for a product that can be used for training. This training system need not be an actual fireproof boom, but should closely replicate the handling and towing characteristics of the real device.

2.4 Materials Technology

The survey of materials technology revealed that the near-term options for fireproof booms are limited. The findings are summarized below:

- For high flexure applications, the choices for "hot side" materials are limited to fabrics or blankets made from inorganic fiber and/or metallic wire.

- The inorganic fibers options range from the alumina/silica based systems to the silicon carbide/boron systems. Depending upon the producer and physical presentation, the alumina/silica family of fibers have service temperatures ranging from 1800°F to 2300°F. The silicon carbide/boron fibers, on the other hand, have service temperatures up to 3000°F, but are not readily available in commercial forms.

- Because of the heat and corrosion, metal options (for both wire or sheet) are limited to the stainless steels (having high concentrations of nickel or molybdenum) or to certain alloys of aluminum and copper.

- Coating technology may represent the best hope for increasing the operating range of "hot side" materials. The coatings essential reduce the reactivity of the substrate material. Areas of promise include char-producing coatings (intumescents) and the use of surface passivation by advanced diffusion or vapor deposition processes.

- The intumescent products currently available do not produce coatings that could reliably endure the marine environment. Most are friable, foam-like layers, having little compressive strength.

- While additional research would be needed to verify and refine the hypothesis, there is evidence to suggest that the crude oil itself could be used as a major constituent in an intumescent process that occurs as the oil is burned, thus providing a thermal barrier that is both durable and self generating.

Suffice it to say that the materials survey did not yield a high-tech solution nor did it undermined the project objectives. Instead, the results indicated that the better concepts would be those that could supplant the material limitations by exploiting the naturally occurring processes and conditions. Several such mechanisms were revealed in the fire boom test history summarized in Section 3.3.

2.5 Concept Development Strategy

Using the information collected during the survey process, a product "wish list" or profile was synthesized. The elements represent a concept development strategy that seeks to achieve greater flexibility in the use of in-situ burning as a part of a spill response plan. An overview of the strategy is presented below.

- **Reuse:** To improve the life cycle cost, the boom should be designed to permit reuse - provided the combination of in-service exposure and subsequent storage do not promote deterioration in the boom handling or performance characteristics. The parts of the system that are most amenable to reuse would include those not directly exposed to the heat and the sea water, i.e., the interior elements of the boom. Furthermore, the interior elements are more easily designed to be impervious to water thereby reducing the possibility of damage while stored. To incorporate these attributes, the boom should be designed so that the outer thermal layer(s) can be removed and replaced. The approach not only permits complete re-use of the flotation system, but also supports the concept of a special "training" blanket. The training blanket would be designed to survive the rigors of training, but would reduce costs by not involving the use of fire resistant materials. When exercises have been completed, the training blanket would be removed and the thermal blanket installed.

- **Transportability**: To reduce the time required to get the boom into the water, the storage and transport configurations of the boom must be optimized. The lighter and more compact the stowed system, the greater its mobility and the greater the options with regard to modes for transporting the boom to the spill site. For these reasons, a system that can be collapsed and spooled onto a reel or compressed and folded onto a pallet was considered more desirable than a boom with rigid flotation elements.

- **Seaworthiness:** To permit burn operations at higher sea states and wind speeds, the construction scheme should minimize weight and maximize the displaced volume so that the reserve buoyancy to weight ratio is as high as possible without jeopardizing the boom's ability to withstand prolonged exposure to extreme heat and towing loads. For these reasons, a boom having air-filled chambers of circular cross-section are considered more advantageous as compared to non-circular sections with straight edges.

- **Thermal Management**: To adequately protect the boom structure, one of two thermal management schemes should be used. One is a passive approach, involving a specialized materials and arrangements that can survive exposure to the heat by virtue of their physical properties (i.e., strength and stability at elevated service temperatures). The passive approach should not require ancillary support once the boom is placed in the water. The other scheme is an active approach, involving the use of more conventional materials and supported with supplemental cooling delivered from a towing vessel. In both cases, the boom's outer layer would be comprised of a refractory material wherein the fibers are loosely bound so that maximum wicking can occur. Furthermore, these outer fiber layers would be intermixed with layers of wire mesh - with the mesh providing a multiplicity of functions to include

  - re-distribution of the heat load over a larger portion of the boom's surface - some of which is submerged and thereby providing a heat rejection path to the water,

  - protection and containment of the insulating fibers,

  - transmission/distribution of external surface loads into the towing line(s) and

- a deposition surface on which char products can attach and accumulate to form an insulating barrier.

When considered collectively, these attributes suggest that a given design approach is actually a compromise of factors, all of which are ranked in a hierarchy. If the ranking of these factors is changed, the design will change as well. For example, the active cooling approach (by virtue of the coolant's ability to absorb and transport heat from the boom) inherently expands the choice of construction materials with attendant advantages involving boom cost, weight, etc. The approach, however, becomes vulnerable in the sense that even a momentary loss or reduction in coolant could seriously reduce the longevity of the product. On the other hand, a passively designed system would not be so "operationally" sensitive because the materials can tolerate elevated temperatures. In comparison, however, these materials would likely be more expensive and less tolerant of mechanical loading than the conventional materials.

2.6 Concept Descriptions

Application of the strategy summarized above produced two concepts, each having several variations as shown in Figures 2.1 through 2.4. The concept illustrated in Figures 2.1 and 2.2 represents the passive approach to thermal management. The concept embodied in Figures 2.3 and 2.4 represents the active approach. The salient features of the thermal barriers and the flotation systems follow.

2.6.1 Thermal Barrier

For the passive approach, the idea is to *limit the temperature rise of internal materials* by using only those heat transfer modes that are intrinsic to the situation. In this regard, the key objective of the passive approach is to use the ocean as a heat sink. As shown in Figure 2.1, the concept involves a pressurized flotation chamber, covered with a saddle-shaped thermal barrier. The thermal barrier is comprised of an outer insulating layer backed-up with a conductive layer. The insulating layer of the stack-up is terminated at the water line, thereby exposing the conductive layer to the water. Thus, as the flame-generated heat reaches the interlayer, it is transferred to the water by conduction.

Figure 2.2 represents a variation of the passive concept wherein multiple conductive layers are interspaced between thinner insulating layers. The conductive layers converge at the water line to form a thicker lay-up, which then continues downward into the water. Other features of the passive approach are summarized as follows:

- A wire mesh sheathing is used to protect the exterior of the thermal blanket as well as aid in the distribution of heat over the exterior surface.

- Both materials in the stack-up are available to adsorb water, which could help in reducing interior temperatures. Wicking, however, is not the primary method of temperature control.

- Theoretically, the insulating material could be either a textile or blanket made from one of several commercial refractory fibers, as all have similar thermal properties. However, the conductive layer must have a thermal conductivity on par with aluminum.

For the active approach, the idea is to *use supplemental cooling to reduce exterior surface temperatures*. The supplemental cooling would be supported by systems on-board the towing vessels and delivered along a conduit(s) that is rigged with the towing line. Likewise, the boom is constructed with passageways that distribute the cooling medium. For conceptual purposes, water was considered to be the primary coolant medium. Air, however, could also be used to augment temperature control by its introduction into the flotation chambers.

In operation, water flow would begin prior to pool ignition and continue for the duration of the burn. Depending upon the configuration, water would flow down the exterior surface of the boom (see Figure 2.3) or flow from the "bottom up" as achieved by a water jacket (see Figure 2.4).

A comparison of the physical characteristics, based on an 18-inch flotation unit, for both concepts relative to commercial booms is presented in Table 2.2. Furthermore, the values presented are engineering estimates as derived from simplified analysis. More elaborate analysis and testing will be needed to validate the values.

Table 2.2 Comparison of Concepts to Commercial Products

Characteristic	SwRI Active	SwRI Passive	MSRC Boom Tests[3]	3M	Kepner	Oil Stop	Applied Fabrics
Flotation	Air Chamber	Air Chamber	Air Chamber	Ceramic Foam Log	Air Chamber	Air Chamber	Metal Sphere
Dia.[1] (in.)	18	18	31	18			
Thermal Barrier Construction	Ceramic Fiber w/ wire mesh	Ceramic Fiber w/ wire mesh		Nextel w/ SST Mesh	Thermotex		Fibrefrax
Thermal Barrier Thickness (in.)	3	3					
Boom Weight (dry), lb/ft	11.2	14.6		15.3			9
Reserve Bouyancy[2]: Weight	7.54:1	6.4:1	20:1	4.7:1			2.5:1
Freeboard (in.)	14.1	14	31	15	15	18	12
Draft (in.)	24	24	38	28	26	25	18

1 Max. finished diameter of boom (flotation with blanket)

2 SwRI numbers include allowance for "soaked" textiles assumed to be 20% sea water (by volume)

3 Recommended criteria from three phases of MSRC boom tests (MSRC Technical Report Series 95-003)

2.6.2 Flotation System

Both concepts are based on a circular flotation chamber, pressurized with air. The air flotation permits a design that minimizes weight, maximizes buoyancy, and can be collapsed to facilitate storage and/or spooled to facilitate deployment. In addition, the flotation system is amenable to the use of circulatory schemes where by the chambers are continually purged to reduce heat build-up and control pressure/volume variations between collect/burn cycles.

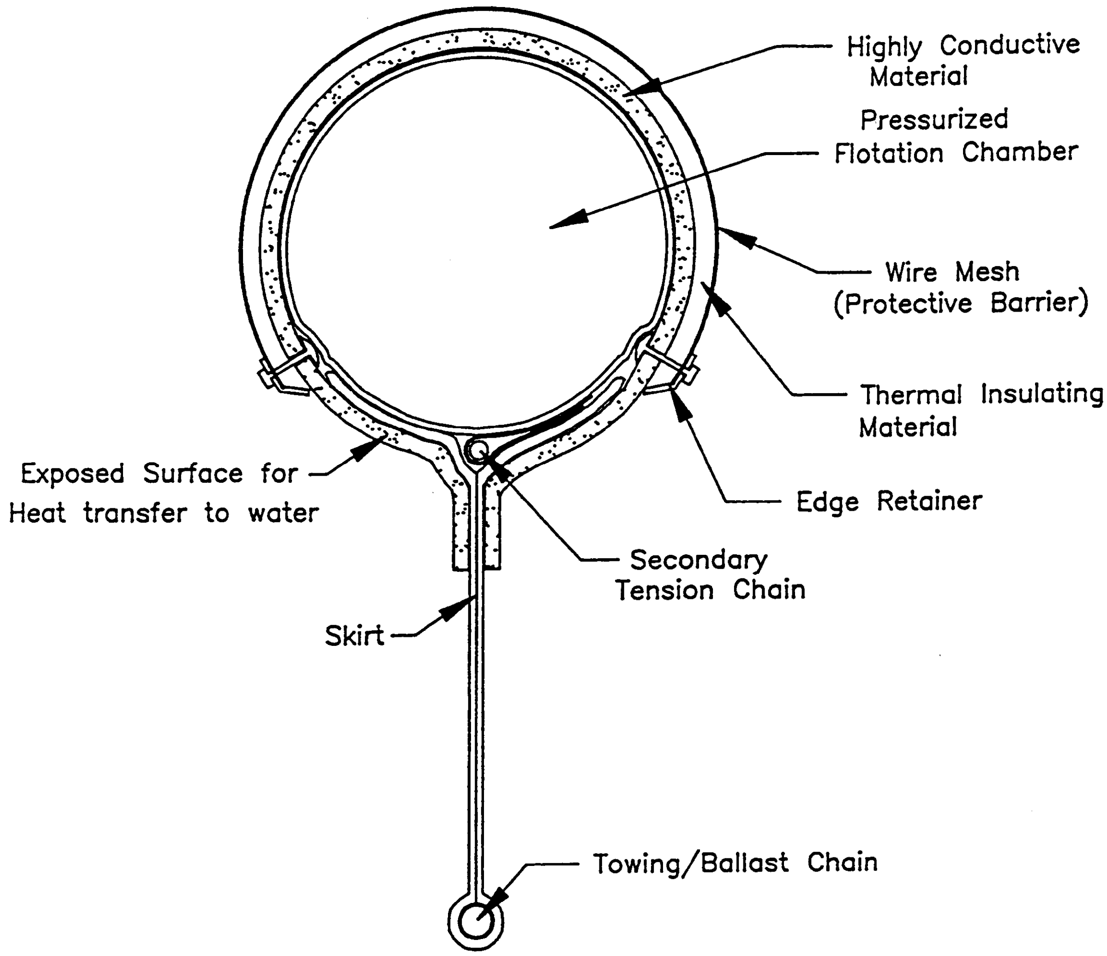

Figure 2.1 *Passively Cooled - Single Layer Blanket/Mesh System*

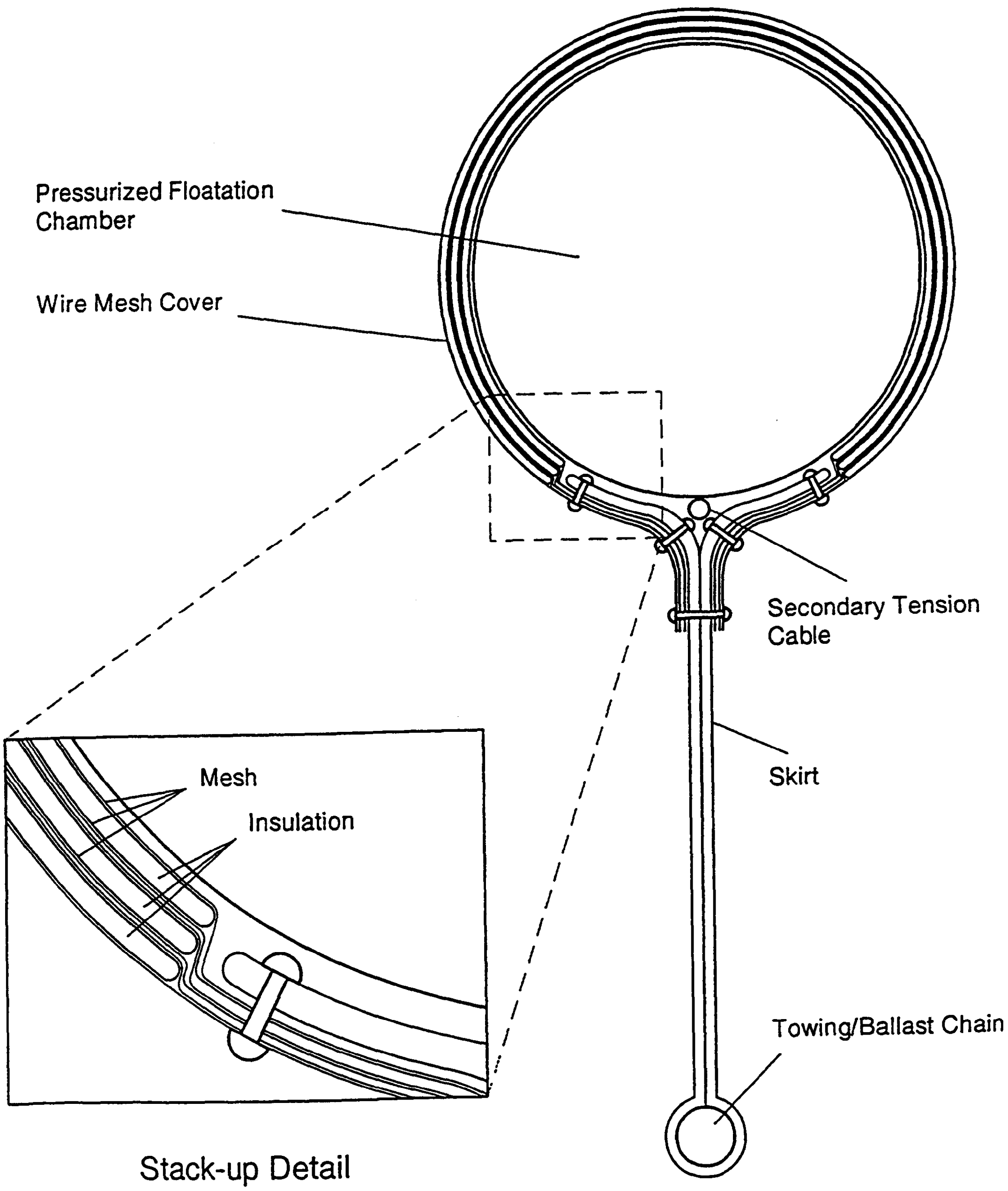

Figure 2.2 *Passively Cooled - Distributed Textile/Mesh System*

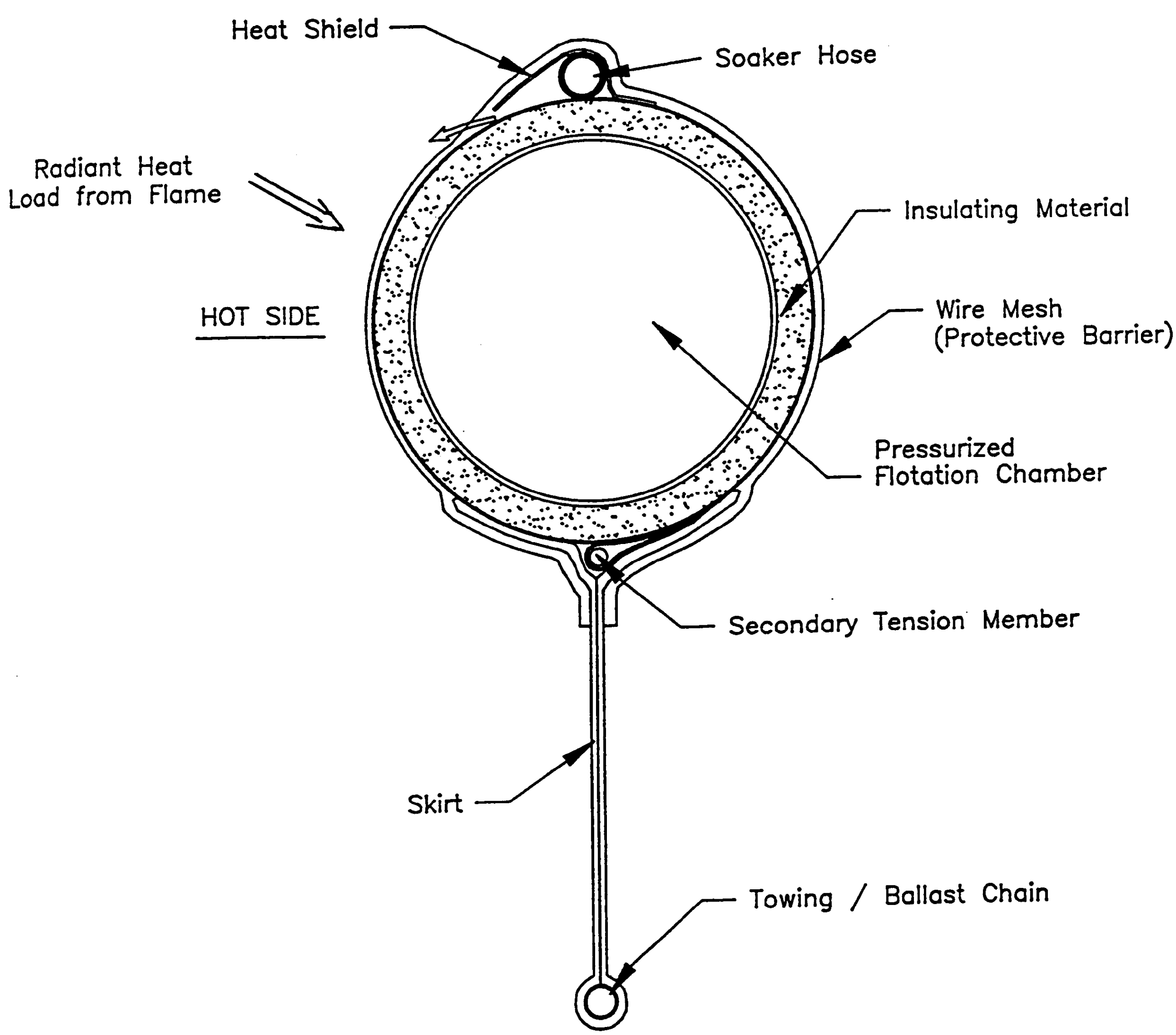

Figure 2.3 *Actively Cooled - Top Introduction of Coolant, Trickle Down*

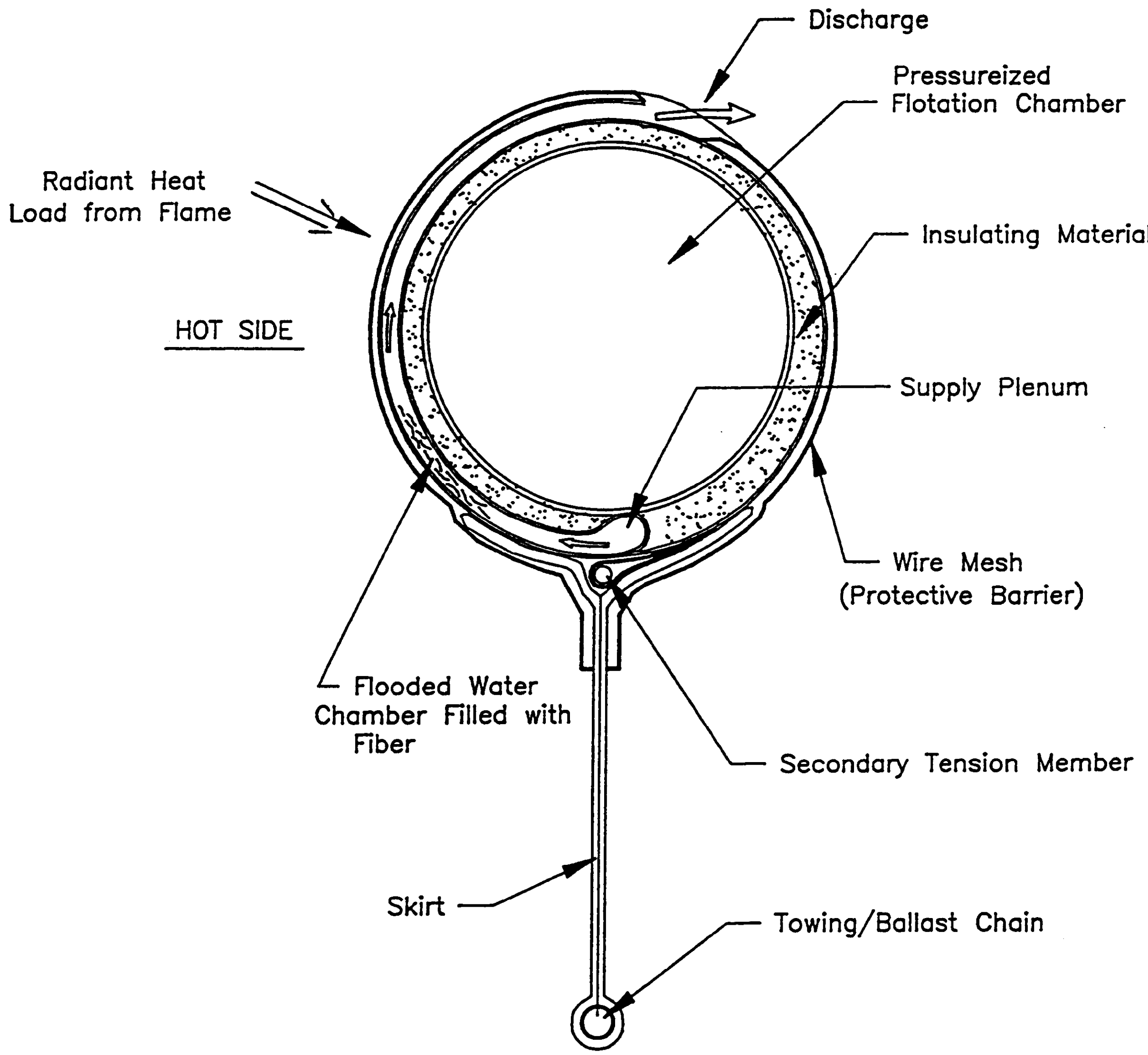

Figure 2.4 *Actively Cooled - Bottom Introduction of Coolant, Top Discharge*

3.0 Detailed Discussion

3.1 Overview of the Concept Development Process

Our approach was to assemble a multi-disciplinary team of engineers and scientist. Then, through a comprehensive process of brainstorming and consensus building, contrive several fire boom designs that would overcome operational and performance limitations. The concept development process was performed not in a single step, but represented the culmination of several preparatory steps that were needed to ensure the effectiveness of the effort. Each step is briefly summarized below.

The first stage involved a review of the technical literature associated with fire boom development and testing. The intent was to provide the design team with a historical record of fire boom evolution and experience. The intent was to compile a comprehensive record of fire boom evolution and test experience that could be used to "jump start" the design team. The challenge was to provide information that would help frame the physical and operational constraints, but would not stifle creative inquiry.

The second stage involved an extended discussion with boom manufacturers and users. From the manufacturers, we sought additional insight to boom construction and design strategies; from the users, we sought insight to spill mitigation, i.e., identification of parameters important to defining the appropriate response to a spill as well as the operational requirements and expectations that the users have for fireproof booms.

The third step was to synthesize the information into a product specification that expressed the essence of what the boom had to do - i.e., the functional requirements, the operational constraints and the performance objectives. Furthermore, it was important that this information be presented in a format that the design team could use in the process of evaluating different concepts.

In the final step, the team evaluated the findings and developed concepts. The actual process involved three brainstorming sessions wherein the design group was isolated and free to discuss design issues and options for extended periods. After the sessions, the more promising concepts were subjected to additional scrutiny. The objective was to quantify basic characteristics of each concept so that it could be compared with commercial systems.

3.2 Survey of Literature and Patents

A detailed survey was performed to identify the relevant literature on in-situ burning of spilled oil. The ORBIT system was used to search Compendex, NTIS, Enviroline, Environmental Bibliography, Pollution Abstracts, and Water Resources Abstracts. Key words, such as fire boom, fire, situ burning, oil spill, Coast Guard, and MSRC were used in various combinations with other descriptors to generate a manageable list of papers.

In total, 296 citations met the search criteria. The abstracts of these works were reviewed to determine which would be the most useful to our effort. Where the content of the abstract suggested that further review was warranted, the complete document was ordered. A total of 48 documents were ordered. A bibliography of these papers is included as Appendix B.

From review of these documents, a good understanding of the technical issues and the history of fire boom design was obtained. By reviewing previous designs, the problem of reinventing the wheel was avoided. A patent search was also conducted to determine which designs had a patent history. The results of that search are shown in Appendix C.

After the literature on fire booms had been reviewed, a collection of the more meaningful papers was created. These papers were "The Development and Testing of a Fireproof Boom" by Ian A. Buist, "In-situ Burning of Spilled Oil", by Alan A. Allen, "An Effective Low-Cost Fireproof Boom" by K. M. Meikle, and "Alaska Clean Seas Test and Evaluation of Fire Containment Boom" by Alan A. Allen. While these papers encompassed only a small portion of the research performed on fire booms, they provided insight into the theory of in-situ burning and characterized some of the more successful fire boom design efforts. For these reasons, this collection of literature was provided to each member of the design team.

3.3 Review of Commercial Products

Early in the program, project personnel visited with three companies that sell fire booms. These companies were 3M, Oil-Stop, and Kepner Plastics. The project team also meet with American Marine, which builds both the 3M and Oil-Stop products. A short discussion of these products follows in the text below.

3.3.1 3M Fire Boom Design

The design of the 3M Fire Boom evolved during the mid to late 1980's. By 1990, the 3M product had become the most "tested" product available for the in-situ burning of spilled oil. Today, the situation remains unchanged. Supplemented with the recent experience of the NOBE burn in September 1993, the 3M boom has no rival that can match the accumulated testing and open sea experience.

The 3M personnel were not willing to disclose how much boom they had sold. They did reveal that the boom was assembled by American Marine, with 3M providing the basic materials. They also indicated that 3M had no plans for the continued development/refinement of the boom. Engineering efforts are confined to minor adjustments in material specification as opposed to radical changes in design that could lead to reduced cost and/or weight. The single adjustment mentioned in the materials area was associated with the stainless steel encasement mesh, which failed during the NOBE burn. Otherwise, 3M did not plan any further work until a clear government policy emerges and "sufficient" sales had been made to offset their development costs.

The discussion of the boom design details did not extend beyond the basic features illustrated in the 3M product literature and summarized below.

- The flotation core for each boom element is actually comprised of several shorter, columnar segments of "ceramic" foam. The short segments of foam are stacked end to end and sleeved with a stainless steel "sock" to ultimately form a standard flotation unit, approximately seven feet long.

- The foam is produced under a proprietary process involving volcanic ash and select oxides. While the resulting product is capable of withstanding temperatures on the order of 2100°F, it cannot handle the thermal stress induced by wave splash. As a consequence, the core material is often broken into many smaller pieces. There is no significant loss in flotation, however, as the particles are confined by the wire mesh.

- The foam material has a density of 10 to 12 pounds per cubic foot. As such, the core makes up a major part of the boom weight, approaching 80 percent of the total weight for an 18-inch boom.

- Each boom unit terminates with a metal "clip". This clip has been the subject of extensive development as it must transfer tensional load into the NEXTEL fabric and wire mesh and also serve as a coupling mechanism between elements. The system is based around a captive tongue and groove configuration with shear pins providing a mechanical lock once the two pieces are aligned. The coupling has no flexibility; all movement of the boom in response to wave action must come from the limited flexibility of the "stacked" flotation core and the fabric/mesh transition area between the core and the end clip.

The 3M personnel noted that while the NOBE test conditions were relatively mild, the results of the testing produced several unexpected results. First, the burn produced and sustained surface temperatures that were higher (in magnitude) than observed in previous tests. Secondly, the peak temperatures were observed at higher positions on the boom surface than previously observed. These revelations, in addition to the extensive handling of the boom prior to the burn, were used to explain the failure experienced with at least one boom segment. Accordingly, 3M was considering a change in the stainless steel mesh, switching from the 309 currently used, to a stainless that had better stability and corrosion resistance at elevated temperatures.

With regard to product attributes, 3M believes that the longevity of a fireproof boom will be directly related to the cost and weight. In other words, the more durable the product, the more it will cost and weigh. With regard to reuse, 3M stated the windward surface of a fire boom will typically accumulate an asphaltic-type residue which will complicate or preclude reuse. At best, one could contrive a boom in which the inner parts are reusable with an outer shell that is disposable.

3.3.2 Kepner Fire Boom

The Kepner Fire Boom, FireGard®, is a fire-resistant boom constructed of a high temperature refractory fabric cover installed over a self-inflating flotation chamber. The self-inflation aspect accrues from the shape change of an internal helical wound spring as the boom is deployed. The ballast material and tension member is a high-strength chain. The boom can withstand operating temperatures from -40°F to 2,300°F. If any of the outer refractory materials become damaged they can easily be replaced. The advertised operating freeboard is approximately 85% of the float diameter.

The boom weighs approximately 5 lbs/ft in 12-in. diameter sections, providing much easier handling as compared to other fire booms. The FireGard boom is quickly and easily deployed from a reel. The boom requires some manual assistance to assure proper compaction and winding back onto the reel during recovery.

The boom has not performed well in simulated burns. For example, during a test burn in Mobile in 1992, the flotation material interior to the boom ignited a few minutes into the burn with subsequent loss of freeboard. While Kepner states that the problem has been corrected, no data was available to verify the claim.

3.3.3 Oil Stop Fire Boom

Like the Kepner product, the Oil Stop boom relies on captive air chambers for flotation. The chambers (formed from a coated fabric) are protected by a thermal blanket which is supposedly free to wick water during a burn. The resulting construction is collapsible, and stored on a spool to facilitate handling and deployment. The spooling capability in conjunction with the use of a remotely controlled boat make it possible for one man to deploy the system at speeds up to 200 feet per minute, not including time to inflate the boom sections.

The flotation chambers are discrete and approximately ten feet in length. This aspect protects the boom from progressive flooding should an individual segment be punctured during operations. Inflation of each chamber is accomplished by a high volume, low pressure blower that is manually attached to a "fill" port as the boom pays off the reel.

Because of its construction, the manufacturer claims that the system can be produced with buoyancy to weight ratios on the order of 35 to 1. The product literature, however, is noticeably devoid of any detailed information on construction, weight, or buoyancy.

Oil Stop claims to have conducted 20 test burns in the last two years. In all cases, the boom was purported to have endured the fire and was even reusable after some events. Neither the conditions of these burns nor the test data, however, were made available. For these reasons, serious questions remain as to the efficacy and durability of the product.

3.3.4 Other Systems Reviewed

We also communicated with Applied Fabric Technologies and AB Sandvik. Both companies are in the process of introducing new fireproof systems. Applied Fabric Technologies is marketing a product under the *PyroBoom* trade mark. The PyroBoom is based on an earlier design developed by Globe International and known as the *GlobeBoom*. Similarly, AB Sandvik is retrofitting an existing product for water sprays to control surface temperatures.

3.4 Product Requirements and Specifications

As product requirements and design relationships were identified, the relevant information was "earmarked" for inclusion into a specification-type document. These fragments were blended together to produce the preliminary boom specification included as Appendix D.

The document was prepared to address three critical needs associated with the concept development process:

- The specification served as a training resource for the design team members and provided a common starting point or baseline from which discussions were launched. It included an introductory statement to clarify the project scope and then provided a summary of the product requirements as expressed in three areas: functional, operational and performance.

- The document provided quantification of boundary conditions and performance criteria where possible. By so doing, the design team was given a sense of scale or perspective to the physical aspects of the problem.

- Finally, the document provided a foundation from which the detailed design specifications could evolve. This would also ensure that the precepts, assumptions, etc. used in developing the concepts would be available for examination at any time. These elements are represented by logic diagram shown in Figure 3.1.

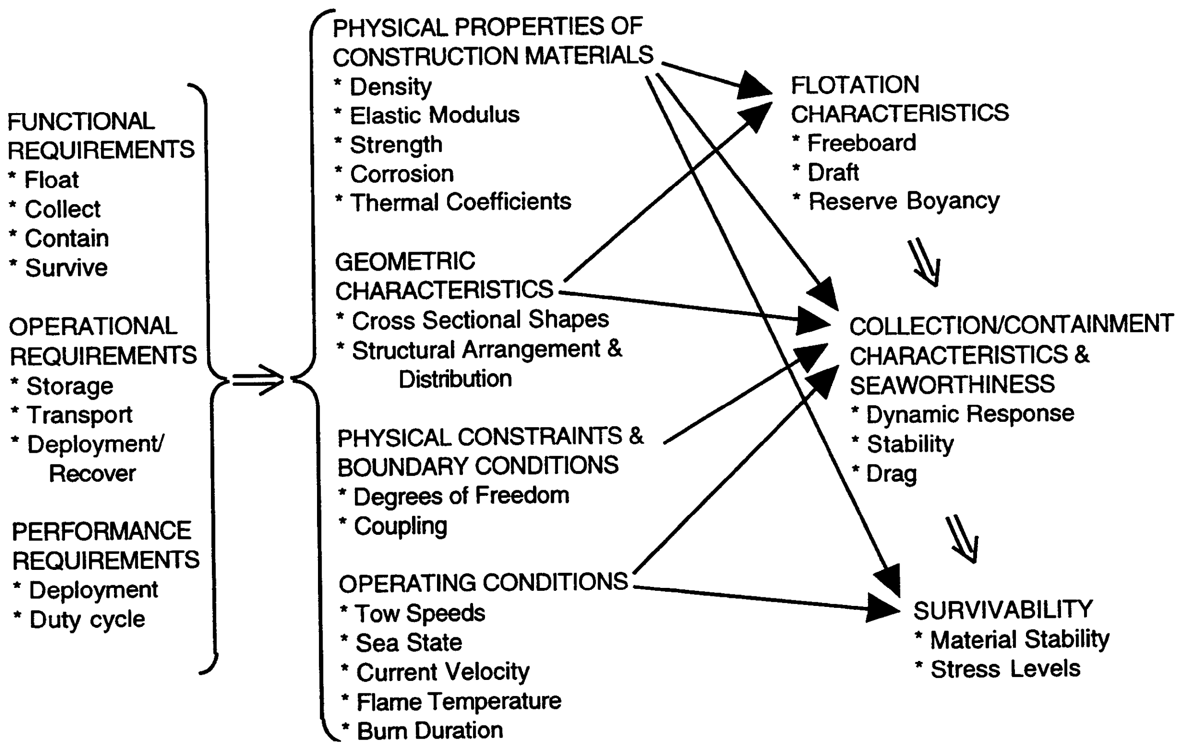

Figure 3.1 Relationship of Requirements to Design Parameters

3.5 Development of Concepts

The concept development process was a cooperative effort, involving the exchange of ideas within a focus group of experts. The personnel selected for the design team were identified by searching the Institute's computerized database of personnel relative to the technical skill areas thought important to the topic of fire boom design. The skill matrix included dynamics of floating structures, heat transfer and thermodynamics, materials, coatings and advanced composites, corrosion, combustion of liquid pools and fire technology. By using the computer, we were not only able to identify personnel for each key area, but several that had an over-lap in other areas. As such, each person represented a technical resource that permitted a wide range of topics to be discussed with confidence. Three sessions, each approximately four hours in duration, were conducted. The minutes of these meetings are included as Appendix E.

At the end of the brainstorming sessions, the team had produced two basic concepts: one based on a passive approach wherein ceramic-based materials were selected and arranged in such a manner that the boom would survive exposure through prudent management of thermal characteristics and heat flow paths. The other was based on the use of more conventional materials, supported with active cooling so that service temperatures are not exceeded.

3.5.1 Material Options

Initial plans were to search the literature for composites and high temperature ceramic materials that could withstand surface temperatures up to 2000°F. After the initial design group discussions, however, it was clear that conventional metals would have an important role to play in any design. Accordingly, the scope was expanded to include nonferrous metals as well as the stainless and coated steels.

As shown in Table 3.1, several sources of commercial textiles and insulating blankets were found that could meet the temperature requirement. The majority of the high temperature textiles are composed of Silica (SiO_2) with varying amounts of Alumina (Al_2O_3), Zirconia (ZrO_2) and Boria (B_2O_3). The actual chemical compositions of various commercial products are tabulated in Table 3.2. In the case of Kao-Tex 2200 and Nextel 312, the textiles are continuous ceramic filaments consisting primarily of Alumina-Boria-Silica. These materials provide a slightly higher service temperature, but suffer for the low resistance to abrasion. To improve their resistance to abrasion, many of the products (i.e., Fibrefrax L-144, Fibersil, and Kao-Tex 2000) are available with alloy wires interwoven with the fiber to form a reinforced fabric.

The high temperature blankets are primarily Silica and Alumina, with varying amounts of Zirconia. Blankets consist of a random, three-dimensional interlocking of the ceramic filaments. They do not have the abrasion resistance of the textiles but typically have a continuous use temperature 200-400°F higher than the textiles. The blanket densities and thickness can be varied to suit the need. Likewise, the external face sheets are commonly aluminized. This feature could prove useful as a shield in reducing the radiant heat load on the interior portion of the boom.

Table 3.1 Summary of Commercial Ceramic Textiles and Blanket Products

		High Temperature Textiles and Blankets		
Textile Name/Company	**Continuous Limit (°F)**	**Weight or Density**	**Thermal conductivity, K (btu•in)/(hr•ft^2•F), Temp °F**	**Specific Heat, Cp BTU/(lb•F), Temp °F**
Vertex, Amatex	1600	22 oz/yd^2	0.362, Room Temp.	not available
Fibersil, Carborondum	1800	32 oz/yd^2	2.58, 2000°F	0.28, n/a
Sandtex, Cooperheat	1800	18-36 oz/yd^2	not available	not available
Refrasil, 3M	1800	35 oz/yd^2	1.5, 1600°F	0.290, 1600°F
Ultisil, Ametek	2000	36 oz/yd^2	2.4, 2000F	not available
Fibrefrax (L-144), Carb	2000	1.5 kg/lin.m	2.4, 2000F	0.28, n/a
ZetexPlus, Newtex	2000	8.5-60 oz/yd^2	1.5, 2000F	not available
Nextel 312 (AF-62), 3M	2200	29.5 oz/yd^2	not available	not available
Nextel 440 (BF-30), 3M	2500	not available	not available	not available
Kao-Tex 2000, Th. Ceramics	2000	not available	not available	not available
Kao-Tex 2200, Th. Ceramics	2200	6-30 oz/yd^2	not available	not available
Kao-Tex 2500, Th. Ceramics	2500	11,14, 20 oz/yd^2	not available	not available
HYTEX 2600, Mid-Mountain	2550	not available	not available	not available
Blanket Name/Company	**Continuous Limit (°F)**	**Weight or Density**	**Thermal conductivity, K (btu•in)/(hr•ft^2•F), Temp °F**	**Specific Heat, Cp BTU/(lb•F), Temp °F**
Kaowool Blanket S, Th. Ceramics	2000	64 to 128 kg/m^3	not available	not available
Cerachem Blanket, Th. Ceramics	2400	96 to 128 kg/m^3	1.45 to 2.2 @1600 F	not available
Durablanket S, Carborundum	2300	64 to 128 kg/m^3	0.2@100°F to 2.4@1800°F	0.27, 2000F
Durablanket 2600, Carborundum	2600	64 to 128 kg/m^3	0.2@100°F to 2.4@1800°F	0.27, 2000F
		Other Low Temperature Materials		
Material Name/Company	**Continuous Limit (°F)**	**Weight or Density**	**Thermal conductivity, K (btu•in)/(hr•ft^2•F), Temp °F**	**Specific Heat, Cp BTU/(lb•F), Temp °F**
Thermoglass (e-glass), Amatex	700	8.5-20.5 oz/yd^2	not available	not available
Kevlar, Du Pont	450	3-12 lb/yd^2/in. Thickness	not available	0.2, RTn/a

Table 3.2 Chemical Composition of Commercial Ceramic Fibers Products

Material Name	Silica	Titania	Alumina	Boaia	Zirconia	Other	Comments
Vertex	Chemical Makeup Unknown						
Fibersil	Chemical Makeup Unknown						
Sandtex	98%		0.20%	0.10%		1.70%	Leached E-glass
Refrasil	97.9%	0.55%	0.29%	0.41%		0.80%	Leached E-glass
Ultisil	>96%					<4%	Leached E-glass
Fibrefrax (L-144)	52%	1.50%	40%		5%	1.50%	Wire Insert
ZetexPlus	Silica yarn completely encapsulated with delaminated vermiculite binder						Wire Insert
Nextel 310 (AF-62)	24%		62%	14%			
Nextel 440 (BF-30)	28%		70%	2%			
Kao-Tex 2000	53%		47%				
Kao-Tex 2200	24%		62%	14%			
Kao-Tex 2500	28%		70%	2%			
HYTEX 2600			99.5%beta				
Cerachem Blanket	50%		35%		15%	trace	
Durablanket S	52%	1.50%	40%		5%	1.50%	
Durablanket 2600	53.50%		30.50%		16^		
Kaowool Blanket S	53%		45%			2%	
Thermoglass (E-glass)	54%		11%	10%		21% CaO, 4% other	E-grade Fiberglass
Kevlar	An organic fiber of the aramid class						

To improve the strength and durability of the thermal blanket, as well as distribute heat, several metal alloys were considered for use (as a wire mesh) between the outer insulation and the interior flotation core in the boom. To be suitable for use as wire mesh, the candidate materials had to possess good oxidation resistance, reasonable stress rupture strength at 1800°F, and be immune or highly resistant to chloride-induced pitting, crevice corrosion, and stress corrosion cracking (SCC).

Alloys with good oxidation resistance typically will have high concentrations of Chromium and other elements, such as Aluminum, that form protective oxides. Materials with high chloride resistance typically will be Fe-Cr-Ni alloys with high concentrations of Nickel and Molybdenum. The Nickel imparts the SSC resistance, and the Molybdenum enhances the material's resistance to pitting and crevice corrosion. Stress rupture strength will depend upon a variety of factors.

Type 310 stainless steel (25Cr-20Ni) has excellent oxidation resistance, its stress rupture strength is acceptable (about 1.5 ksi at 1800°F at 100 hours), and it is available as wire. However, Type 310 contains no Mo and is susceptible to chloride-induced pitting, cracking, and crevice corrosion. Consequently, it would be a poor choice for use in an insulated fire boom. Conversely, Inconel Alloy 625 (58Ni-22Cr-9Mo) has excellent oxidation resistance, good stress rupture properties (4.5 ksi at 1800°F at 100 hours). Further, the 625 is essentially immune to chloride-induced corrosion problems, and it is available as wire. Inconel 617 (44.5Ni-23Cr-9Mo) is available as wire, is highly resistant to chlorides, and has even higher stress rupture strength (6 ksi at 1200°F at 100 hours). Inconel 690 (58Ni-29Cr) has acceptable stress rupture and oxidation resistance, it is available as wire, and its Ni content is high enough to make it essentially immune to stress corrosion cracking in chlorides. However, the absence of Mo in Inconel 690 indicates that it may be susceptible to pitting and crevice corrosion in chlorides.

Other materials that may be acceptable are Inconel 25-6Mo (25Ni-20Cr-6.5 Mo) and similar alloys such as AL-6X, that contain 6% Mo, and Incoloy 825 (42Ni-22Cr-3Mo). These alloys have excellent resistance to chloride corrosion, but stress rupture or oxidation properties were not readily available. Similarly, Hastelloy Alloys C-276 and C-22 have excellent chloride resistance, but oxidation and stress rupture resistance were not readily available. While no stress rupture data are given in Inco literature for Incoloy 825, it does have good high temperature tensile strength (10.9 ksi at 1800°F), so it likely has acceptable stress rupture properties. Incoloy 825 has the advantage of being less expensive than the other alloys listed here.

Finally, the copper alloys (particularly the naval brass, the phosphor bronze and the low Silicon bronze compositions) offer exceptional corrosion resistance and thermal properties. These aspects combine to make the copper alloys viable materials where heat conduction is more important than strength. Potential applications include wire mesh lay-ups with fire resistance textile.

3.5.2 Thermal Analysis

To complete the assessment, each concept was evaluated and refined using a simplified heat transfer model. The analysis provided the means to evaluate the ability of a given thermal treatment to control surface and interior temperatures to values within the service envelops of the materials. Furthermore, because of its reliance on the geometry of the boom and the mass of the construction materials, the analysis also provided a way to evaluate the consequence of the thermal treatment on boom behavior in the water as deduced from buoyancy and center of mass, for example.

In the beginning, the thermal analysis was structured to include the transient response of the boom's surface. The major assumptions associated with the model were that the radiant heat load from the flame was on the order of 20 kilowatts per square meter and that the boom's surface was at a uniform temperature. With these assumptions, the analysis indicated that the surface temperature of a typical thermal blanket could easily reach a steady state value of 3500 F within five minutes of initiating a burn cycle. Further, as the insulation thickness was increased, the surface temperature would increase as shown in Figure 3.2.

Since the thermal response was so fast in relation to the 1 to 2 hour burn times envisioned, the model was re-configured for steady state conditions. The model involved three layers - an outer insulating layer, a conductive layer, and an inner insulating layer next to the air flotation chamber. To make the results conservative, the outer layer was assumed to have a uniform temperature of 2000°F. The conductive layer was modelled as a series of lumped mass elements wherein each element absorbed heat radially and circumferentially and rejected heat to the interior (radially) and circumferentially.

As its output, the model predicted the temperature at selected radial positions within the thermal barrier. Figure 3.3 illustrates a case result for different boundary conditions assumed to exist at the outer surface of the flotation chamber. Additional details and assumptions are documented in Appendix F.

To evaluate the effects of supplemental cooling, the model was modified to account for the reduced heat load on the interior that accrues from the evaporation of the coolant on the exterior surface. The influence of coolant flow on surface temperature is shown in Figure 3.4.

It should be noted that the results predicted by the model are based on numerous assumptions to simplify the mathematics. As such, the results serve only as "first order" approximations. They do, however, provide insight to the synergistic effects of materials and construction on thermal performance.

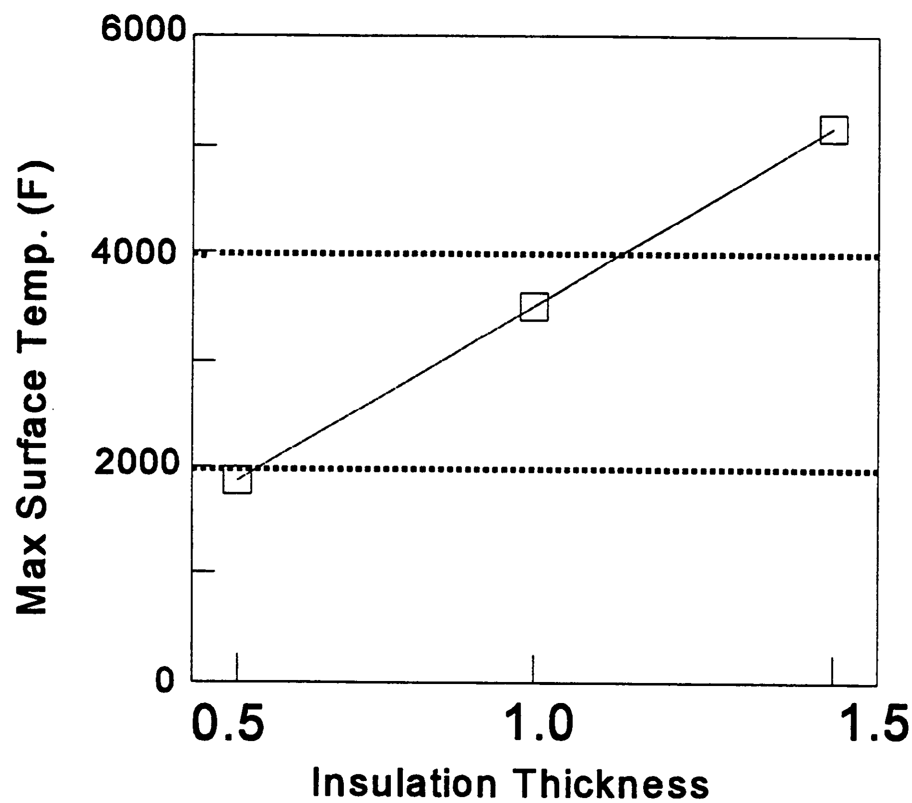

***Figure 3.2** Boom Surface Temperature as a Function of Insulation Thickness*

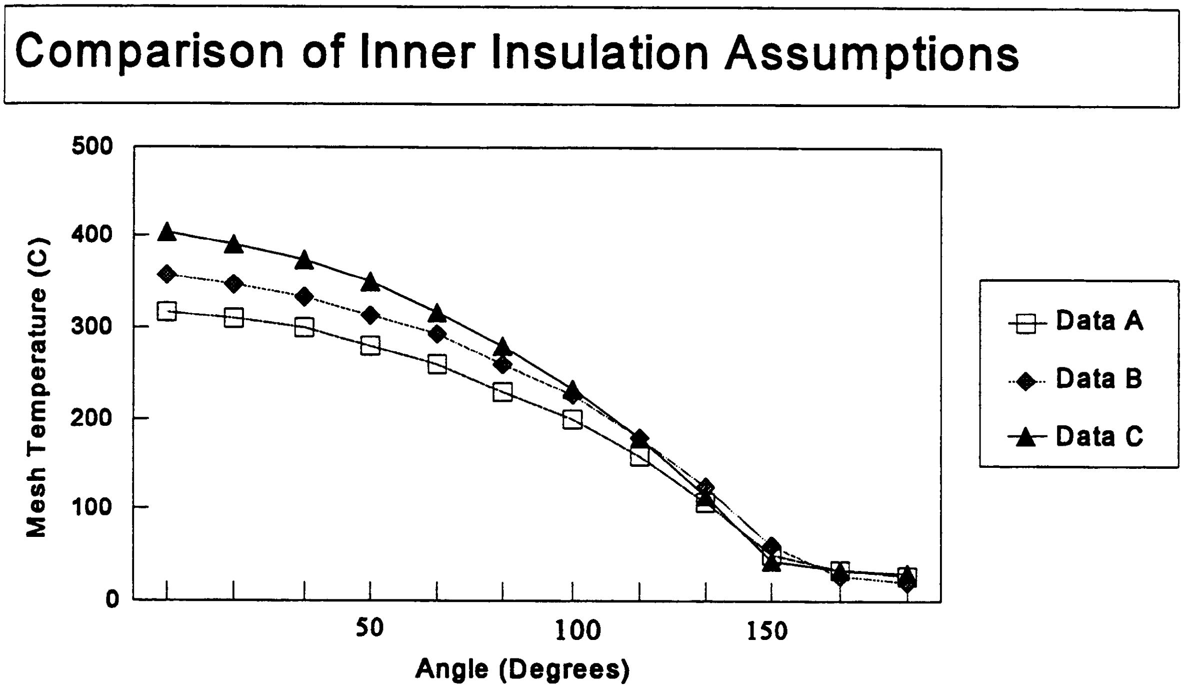

Figure 3.3 Temperature Distribution

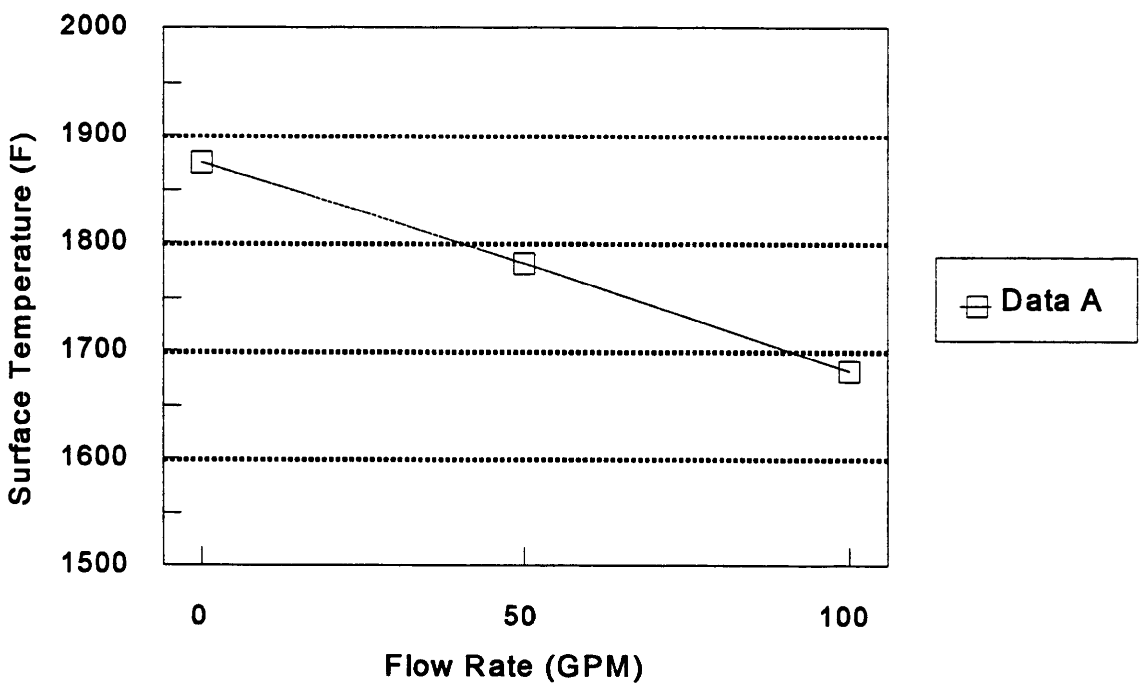

Figure 3.4 Boom Surface Temperature as a Function of Coolant Flow

Appendix A

Characteristics Of Commercial Fireproof Booms

Table A.1 Characteristics of Commercial Fireproof Booms

Manufacturer	Kepner Plastics	Applied Fabrics	Ab Sandvik	3M	Oil Stop
Boom Type	Curtain, self-inflating	Fence	Fence	Curtain, fire containment	
Model	FireGard BTIP 1823 FG	Pyroboom 30	SSB-800 Steel Barrier	18" flotation by 24" skirt	
Cost $ US/m ($/ft)	Inquire	Inquire	Inquire	Inquire	
Freeboard mm (in)	381 (15)	300 (12)	266 (11)	381 (15)	460 (18)
Draft mm (in)	660 (26)	400 (18)	533 (23)	711 (28)	640 (25)
Boom Height mm (in)	1.041 (41)	760 (30)	800 (34)	1,092 (43)	
Standard Length m (ft)	31 (100)	15 (50)	2 (6.5)	15 (50)	15 (50)
End Connectors	Bolted plates		Bolt-joint	Quick	
Skirt Material	Urethane/PVC coated polyester	PVC coated fabric	Stainless steel	Reinforced PVC	
Sail Material	Thermotex hi-temp fabric	Silicone coated Fibrefrax	Stainless steel	PVC/steel mesh/Nextel	
Flotation	Air Chamber	Metal Sphere	Metal Cylinder	Ceramic Foam Cylinder	Air Chamber
Flo. Member Length m (ft)	9.7 (6.5)			1.8 (6)	
Weight kg/m (lb/ft)		14 (9)	9.5 (6.4)	23.1 (15.3)	
Res. Buoyancy kg/m (lb/ft)				108 (72.6)	
Reserve Buoyancy/Weight		2.5:1		4.7:1	
Waterline Beam mm (in)				373 (15)	
Vertical CG mm (in)				368 (14)	
Ballast Material	H. T. chain	chain or lead	None	10 mm (3/8 in) galvanized chain	
Ballast Weight kg/m (lb/ft)				2.8 (1.9)	3.6 (2.4)
Tension Member (1)/Strength (1)N (lb)				Chain 47,000 (10,600)	
Tension Member (2)/Strength (2)N (lb)				Fabric 234,000 (52,000)	
Tension Member (3)/Strength (3)N (lb)				Connector 61,000 (13,700)	
Total Strength N (lbs)					
Fabric Tensile Strength N/50 mm (lbs/in)		9000 (1000)			
Fabric Tear Stren. N (lb)		230 (500)		675 (150)	

Appendix B

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Appendix C

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Appendix D

Fireproof Boom Specifications
(Preliminary)

1.0 SCOPE

Our objective is to provide the customer with a better fireproof boom design than is currently available - one that will expand and enhance the customer's remediation options. In-situ burning of spill crude using a fireproof boom is one of several methods the sponsor would like to have in his "inventory". We have not been asked to address the air quality issues nor have we been asked to develop other approaches to spill remediation. As such, our scope is limited to fireproof boom designs and the application of technologies that may lead to improved boom performance.

2.0 BACKGROUND

The following material has been extracted and synthesized from several sources. We recognize that it is not complete, and that it is missing quantitative detail in several areas. Where quantitative data is provided, the numbers represent "best estimates" and are subject to refinement as additional information becomes available. This expression of general requirements, however, serves as a starting point. It is our hope that the specifications will evolve into a comprehensive statement during the course of the brainstorming sessions.

2.1 Customer Evaluation Criteria

Response time is critical. The sooner systems can be on the site of a spill and made operational, the better. We're talking hours instead of days. A favorable response time would 6 to 18 hours. The effectiveness of systems (in terms of treatment) is better, costs are lower, and environmental impact is minimized.

Cost is a relative parameter. The customer is willing to pay a high unit price, but expects a proportional benefit in terms of product performance. For example, benefits that would offset a higher cost include:

- Greater durability and longevity of the product. Current products can costs $300 per foot and may not last more than 5 or 6 hours before failing.
- A greater range in the conditions of use (such as the ability to conduct operations at a sea state 5, a reduction in "the time to station" as a consequence of a smaller transport cube, etc.)

2.2 Summary of Minimum Operational Requirements

2.2.1 System Definition

At a minimum, an acceptable fire-boom shall consists of 500 feet of boom with all required connectors, towing chains, bridles.

2.2.2 Storage

The fire-boom should be constructed from materials that can withstand prolonged storage under coastal conditions. Furthermore, since the system may be used to train personnel, it should be tolerant of repeated handling and re-packing for storage (e.g., stored on a reel) under field conditions.

2.2.3 Transportability

The fire boom components should be packaged in configurations that facilitate their transport from the storage location to the deployment site. As such, containers, reels, or pallets should not exceed the standard "shipping cube", which is specified as follows:

Maximum Length:	25 ft
Maximum Height:	7 ft
Maximum Width:	7 ft
Maximum Weight:	10,000 lbs

While it is desirable that the fire-boom be packaged for minimum volume, it is not necessary that the entire system fit into a single container. Multiple modules are acceptable.

2.2.4 Deployment and Recovery

The fire boom should be easily deployed and recovered via means that are typically available on sea-going work boats. Any specialized hardware needed to support the deployment should be included as part of the stowed system.

The deployment process may include introduction of the boom into the water at shore facilities with single-ended towage to the spill site at speeds up to 10 knots; post-spill retrieval may follow the reverse process, but at reduced speed.

2.2.5 Compatibility

Since the fire boom may be used in "series" with conventional containment booms, provisions must be made to permit the mechanical connection of adjoining segments.

2.3 Summary of Functional Requirements

The product must be able to perform the functions summarized below:

* Float on the water surface during all phases of the operation which include deployment, collection, burning and the eventual removal of hardware from the spill site.
* Collect spilled crude when towed from both ends (catenary configuration) at speeds up to 1.5 knots.
* Contain the collected crude with minimum leakage underneath, through or over the structure
* Survive the operating conditions - which are summarized as follows:

  - Sea water environment: submergence and splash, (continuous and intermittent),
  - Water temperatures down to 32°F,
  - Flame temperatures on the order of 2500°F,
  - Wind velocity up to 20 knots,
  - Significant wave heights up to 7 feet

2.4 Summary of Performance Requirements

2.4.1 Transport, Deployment, and Retrieval

Once the decision to use in-situ burning has been made, the system must arrive on the site within 12 hours or within the window-of-opportunity for in-situ burning, which ever is smaller. Once delivered to the spill site, the boom must be designed so collection operations can begin within 1 hour. The boom should be designed so it can be retrieved within 1 hour.

2.4.2 Duty Cycle

The boom should, as a minimum, withstand 12 cycles of collection and burn. This duty cycle is based on the following parameters:

collection time:	2 hours
burn time:	1 hour
cycles per shift:	3
shifts per day:	2

Also, the boom should withstand 8 hours of continuous collection and burn.

2.4.3 Containment Efficiency

Loss rates from boom systems is, in general, a factor that may significantly reduce the effectiveness of an in-situ burn operation. A fire-resistant boom should fulfill the same operational criteria for first loss and gross loss as regular booms. The freeboard, draft and reserve buoyancy of the fire-boom should be optimized to meet general boom operational conditions and reduce crude loss as a result of

a) splash over,
b) drainage, or
c) entrainment

Appendix E

Minutes of Design Group Meetings

Minutes of the

First Fireboom Design Meeting

May 5, 1994

The first Fireboom Design Meeting was called to order by Co-Principal Investigators Martin Bartlett and Jim Burkes at approximately 9:07 a.m. in the Main Southwest Research Institute Cafeteria Dining Room 1 (One). Requested attendees were Martin Bartlett, Jim Burkes, P.A. Cox, Dan Benac, Stuart Schwab, Steve Green, Paul Watson, Wayne Biediger, Lemoyne Boyer, Tom Ryan, and Diane Shipton. All attended except Mr. Dan Benac and Steve Green. Mr. Fred Lyle was chosen as a replacement for Mr. Dan Benac. No replacement had been chosen for Mr. Steve Green.

Agenda and project information packets were distributed prior to the first meeting to give chosen participants an opportunity to become familiar with project objectives. Participants were chosen based on their expertise in a particular field or discipline related to the project design requirements. Attendees were Martin Bartlett (High Temperature Materials) Jim Burkes (Mechanical Design), P.A. Cox (Structural Dynamics), Stuart Schwab (Chemist, Advanced Organic High Temperature Materials), Paul Watson (Manufacturing and Fabrication to Assembly and Joining of Materials), Mr. Wayne Biediger (CADD/CAM Mechanical Design & Drawings), Lemoyne Boyer (Thermal Heat Transfer/Fire Resistance and Oil spills Thermal Radiation), Tom Ryan (Combustion Fuel Behavior and Marine Oceanic), Fred Lyle (Material Sciences and Corrosion), and Diane Shipton (Secretary and Data Support). A brief introduction was given by Mr. Martin Bartlett, which included an introduction to the three current existing fireboom products and their problems as well as identification of the project sponsors. The "Rules" were handed out to each participant detailing what each person could expect to happen before,during, and after each meeting. A copy of "The Rules" is enclosed as Attachment 1.

At approximately 9:38 a.m. Martin Bartlett introduced Jim Burkes (Co-Principal Investigator) and turned the meeting over to him for the actual project overview. Jim stressed that it was very important for each one to understand the process of the effects of oil spills on the environment and how oil spills are affected by the environment. The objective of the fireboom is to 1) collect, 2) contain, and 3) create an environment to burn the oil from the spill. This involves knowing how oil behaves in waves, how it is influenced by the winds and the boom itself, and the structural behavior of the boom (to avoid gaps between the water and the boom). It also involves identifying the problems created or occurring as a result of the previous information (i.e.; oil passes over and under the boom; oil must reach 3 millimeter thickness to ensure continued burning).

Combustion discussions began with Mr. Tom Ryan contributing information as to how the oil films behave on water, especially in higher seas. The physics and combustion problems were identified: the requirement of 3 (three) millimeters of thickness must be maintained; amount of heat loss depends on the temperature of the water, and how much water the oil will take on. He stated that the oil produces a sooty film which could be a problem to the structures operation, radiating temperatures depend where on the boom the oil is located, and also brought to everyone's attention that some burning actually takes place on the boom. Materials used must consider the wettability, radiating heat transfer (reflective characteristics), and the fact that 50% of the boom must be below water to have a good heat sink. He stated it would be a good idea to get a more in depth look at the water/oil chemistry when determining the best material to be used for the boom. We also should get more accurate temperatures rather than just accepting what is published. Lemoyne Boyer stated that he thought the published temperatures were acceptable based on his studies performed at Fire Tech. Tom Ryan asked if some minimal amount of testing could be performed here at the Institute? It was determined that funding would not allow for a lot of testing. Lemoyne stated as for heat transfer, the designs call for thin layers of non-flammable material. He noted that we needed to take a closer look at what we are actually protecting. We have a sooty flame and (depending on temperature) cold blocks of radiation; radiation is necessary to induce heat transfer to protect the boom. The temperature also depends on where the fire is on the boom (i.e.; in middle, less intensive because less oxygen). Maybe we could look at using steel as material. It is heavy, but is good as a heat sink. Jim Burkes interjects that we need to protect the floatation device and specifically the connections to the tows from the sooty residue that may cause possible malfunction.

Lemoyne relates that a study was done in the Fire Tech Division to determine how to best protect safes. They used 1/2" steel plate and burned at temperatures <= 1900 degrees Fahrenheit. Steel corrodes and warps, but was affected minimally by the fire. It was noted that maybe you don't need to protect from fire, but from corrosion, when using steel material. It was noted that maybe a ceramic fiber should be used for fire protection to the boom (if not using steel) because of its thermal conductivity. Jim Burkes noted that duration was a key factor because no matter how good an insulator the material is, the interior is going to get hot. Stuart Schwab states that ceramic fabrics are very fragile, and they coat them with PVC to make them durable for storage. PVC is quite toxic when it burns and may put off unacceptable fumes. He said they may not care out on the ocean, but people breathing this air may be quite concerned.

The discussion turned to pool burns and what effect towing had on the burn. It was determined that where the burning was in relation to the boom, would determine the intensity of the fire. At the apex would be the greatest degree of heat. Tom Ryan asked if it was absolutely necessary to tow the boom while burning. Could it be towed away and left to burn while using another boom to collect more? Then you would need more than one boom, would have storage problems, and too much weight on the ship. Martin interjects that the process is currently gather - pull away - ignite and burn - go back - collect - pull away - ignite and burn, etc., a continuous cycle. Tom Ryan reiterated that one of the design issues would have to be the materials buoyancy, but also its ability to be partially submerged.

At this point Jim Burkes said we needed to discuss the environmental issues first, so that we could better understand the effects of the high seas and wind to maximize the heat transfer from the boom. Tom Ryan said the literature was unclear regarding the pool burns whether there was actual relative motion between the surface and the boom? He said if you look at the photograph provided in the literature it is very clear that there is a motion. It is obvious that the towing of the boom has an affect on the collection and combustion, so probably when towing into the wind, the oil would indeed gather mostly at the apex. This would also affect the burning of the oil. This brings up the question of whether we may want two different boom systems: one where you can pull in a circle, light it and burn on its own, or do you always have to tow and burn off? Martin says these spills normally sheen at about 12-24 hours where it is no longer combustible and so you must tow to keep adequate thickness for combustion. thickness. Martin says this was done with the Valdez spill and 99% of the oil was burned off using this method. Stuart Schwab asked what was the actual requirement of sea state to be addressed on this project, because previously in the literature, it had been mentioned that this boom needed to be able to withstand a sea state of 5. Viewgraphs identifying the different levels of sea state with a brief description of each were shown by Jim. Stuart noted that this sea state was almost gale proportions, so durability was of most importance. Martin introduced the World Catalog of Oil Spill Response Products, which each would have access to as needed.

Wind effects depend on the sea state at the time. Sea state is always different, and can change rapidly, so you must take this into consideration when determining design. Jim notes that sea state of 4 is equal to 17-21 knots, and above 5 is a gale wind and almost impossible to perform a burn of any kind. The *period of the wave* is very important to determining the needs of the design also. The primary waves are uniform waves; the secondary, or "chop" waves, create the major containment problem. These waves could be more of a structural design problem. Jim Burkes asked who could discuss wave motion? Stuart Schwab and Tom Ryan both responded positively. Ryan relates his experience with wave heights during his stint in the Marines. On a lifeboat and 3 foot waves, it became impossible to get back on the boat. With the boom we are talking about bobbing also, which can cause problems. With bobbing during sea state 5, the problem would be how to dampen the boom so that it would not have to be under water most of the time. Ryan raises the question regarding design again, whether the boom should be in sections or rigid? If rigid, then the boom would have lots of gaps which leads to greater amounts of lost oil. Look closer at how the design will affect the film and its collection. What about the temperature of the sea water? Ryan says temperature of sea water is usually between 30 - 80 degrees Fahrenheit. Schwab says the swells of the water are not bad, but the "chops" are bad. The chops will be in the direction of the wind and could even be caused by the design of the boom itself. He also stated that as he understood, white caps form with wind at 12 knots. Ryan states that from the designing aspect (simple view), a sections design would be best. This idea is based on the fact that not all parts of the boom will be experiencing the same forces as others at the same time. With this in mind, if all of the boom had the same floatation capabilities at the same time, then it would not be a good design. Lemoyne Boyer brought up the need for more free board, that is unless the boom was designed to be less sensitive to the wind. It was determined that storage would be a problem; they want a reelable system; and, want reusability with minor updates. P.A. Cox asks, "What now are the critical issues, so that we can rank them by means of importance?"

Jim Burkes states the sponsor will be willing to pay a higher cost for a product that has a higher burn life or even reusability (ability to store wet without later problems). Response time is critical (6 to 18 hours is acceptable). Cost is a relative factor. Effectiveness of the system is also very important (lowers cost & environmental impact is lessened). What the trade-offs are is very relevant to what they will be willing to pay for, and want. Jim refers to his viewgraphs again. Look at the buoyancy to weight ratio. The objective of this boom is to float, collect/contain the oil, and burn/survive. Lets look at the operating conditions/requirements again. Requirements are:

Functional Requirements:

- Minimum 500 feet of boom with connectors, towing chains, bridles, etc.
- Boom materials must be able to withstand prolonged storage (corrosive conditions).

- Maximum shipping/storage measurements: Length 25 ft., Height 7 ft., Width 7 ft., Weight 10,000 lbs.
- Easily deployed and recovered, if necessary.
- Coupling capabilities.
- Floatable on water surface to collect spilled crude when towed from both ends at speeds of 1 knot.

Operating Conditions:

- Sea water environment, submergence, and splash.
- Water temperatures down to 30 degrees Fahrenheit.
- Flame temperatures on the order of 2,500 degrees Fahrenheit.
- Wind velocity up to 20 knots.
- Wave heights of up to 5 feet.
- Survive the *period of the wave*; per Tom Ryan there are mathematical formulas available for assistance.
- Freeboard, draft, and reserve buoyancy of the boom should be optimized to reduce crude oil loss due to wash , top blowover, or entrainment.

Jim Burkes stated that a burn usually lasts about 2 (two) hours and ideally you should get 2 to 3 burns per boom. They want to burn for 24 to 48 hours because if you only burn for 2 hours, then 12 to 24 booms would be needed for each job. This would obviously cause storage and transportation problems. Tom Ryan says in view of that, let's go back and discuss the possibilities of a biodegradable system, such as the environmentally safe foam. Boom sprayed with foam would collect, contain, and burn the spillage totally out; then, just reel in the boom. There would be no waste to collect and dispose of, no reusability, nor storage issues to address.

All agreed the oil was not reusable. It would not be cost effective and the volatile components would be gone, leaving it just an oily goo. Besides, if it would be attempted to salvage the crude, the time involved to separate the crude from other components (i.e., water) would be extensive.

As for types of materials: Schwab stated the ceramic would be environmentally benign, if it was sunk, it would be okay. Need to look into this some more. Paul Watson brought up "ablative materials". Many people did not understand what that was exactly, so Paul was asked to give more detail. It is a material originally developed in the NASA Space Program. As this material burns it creates a barrier to protect it from heat (it forms a film of protection between it and the fire). Maybe a spray-on-ship silicone-impregnated material could be used, which is an excellent insulator. Temperature would be a problem with the silicon materials. Jim stated it may not be a problem if there was a "boom-let,"or heat pipe to release heat just enough to maintain an acceptable temperature. Another note from Jim was that it must be puncture resistant. It was now 10:23 a.m. and time for a break for snacks, etc..

At 10:32 a.m. the meeting commenced with Martin reminding us of the top priorities for the sponsor. Our main priority was to submit our two best designs presented as a proposal. Both Ryan and Schwab presented ideas to Jim and Martin during the break. They will be discussed in more detail later.

Martin presented us with a breakdown of what kind of work we are hoping for after this Phase I, which is to submit our two best, feasible designs. Phase II would be to actually build, test, and ensure the ideas will work. Phase III is to actually work with a fabricating company to build the unit.

Discussion of the fireboom specifications (included in the packet) from the sponsor ensued. As stated before, the sponsor is willing to increase cost with improvements. Their main objectives they want are: 1) durability, 2) more longevity for life of the system, 3) minimum residue to dispose of, 4) storage - for training purposes, easily deployable or maybe just build a "For Training Unit" only that will not need to be burn worthy, and 5) must be complete in its own right or have all items needed already on the boat.

On a scale of 1 (least important) to 10 (most important) the following factors were rated:

FACTOR	LEVEL OF IMPORTANCE
Cost	#3
Durability (Ruggedness for Man-Handling)	#8
Reusability (2nd Spill)	#1
Reusability (Salvageability)	#3
Storage	#7
Ease of Deployment	#8
Reelable	#5

Once these factors were categorized by level of importance, the serious discussions about design problems commenced. The major factors were determined to be temperature, sea state 4 - 5, towing at 1 knot, corrosive environment (salt & sand), minimum life of 36 to 48 hours, collection efforts must be 95%, and high buoyancy ratios. It was pointed out that buoyancy ratios are determined by the operating conditions, weight issues, types of couplings used between joints, and their stiffness.

With open sea conditions in mind, we need to develop the highest containment method. This appears to be a structural dynamics issue. It was also noted that the more of the boom that is consistently above water, the more wind problems and effects will exist. It was also noted that you must keep up the tension in the towing devices so enough oil can be kept to maintain the flame for burning. Ryan stated also that we could use a combination of rigid and flexible parts to the boom. All agreed that it must be attached several places top and bottom. If attached just at the lower level, then oil will go over the top during the tow; if attached at top only, then oil would go under bottom.

Watson suggested that maybe we could tow at a faster speed to make collection and burn processes faster. It was determined that the towing force would go up to the point that it would jeopardize the entire operation. Schwab reminded everyone that the boat would also possibly sustain damage because with the increased boat speed, the pounding of the water on the boats exterior will increase accordingly.

Jim asked the group if they felt they were where they wanted to be as far as information for design? It was determined by Tom Ryan that we needed more information on what would be a good metal to use in a design? Paul Watson volunteered that Envarol could be the answer. It has aluminum which was good for corrosion, but is not fire resistant. Burkes says maybe the heat release unit would be useful in this instance. What about stainless steel? What would be a comfortable temperature at which to use stainless steel? Per Fred Lyle and Paul Watson 1200-1500 degrees Fahrenheit would be acceptable. Jim said we need to be very careful with temperature, so the attention turned back to the combustion discussions. Radiation is a very important part of the heat transfer mechanism. He wants to make sure about the temperatures.

Are we looking at 2300 degrees or are they more like 3,000 degrees. Does anyone have a feel for the temperature issue because Jim does not think that anyone else in the industry actually knows for sure. All others have done are some tank tests and pool burns, and in a few instances performed full scale tests actually out on the sea. Only one involved using instrumentation and it was found was that the pool burns and tank burns don't scale regarding temperature. Temperatures in the real world are considerably higher. Tests on ground have run for days with no ill effects on the material, so they put them on a ship thinking they have a good design, only to find they last only an hour. It is obvious that there is something more that needs to be figured into the formula or something that is biasing the test results. He thinks that as we get more into the design concept we need to put a number to the temperature.

Under ease of deployment we need to discuss how the boom we design could possibly be deployed? Lemoyne suggested a small crane on the boat could lift it up and drop it in the water. Maybe a helicopter drop off would be better, that way it would not take up storage space on the boat. Also weight would not figure as heavily into the overall design. With the helicopter drop-off, it could possibly be designed so that is could already be containing the oil before the tow boats get to the site. This could possibly minimize even more the environmental effects of a spill. A 12 hour response time may be acceptable. Keep in mind that 10 knots is the maximum speed when towing the boom to the site, and 25 knots for the boat without tow, with the helicopter drop off.

It was noted that in certain circumstances durability was more important than ease of deployment. If one boom is available then durability is more important, but if we can use multiple booms then ease of deployment is more important. If the helicopter drop off is used then durability once again becomes more important. At 11:41 p.m., lunch was served.

At 12:17 p.m. we commenced to discuss the different design concepts that had been addressed earlier and tried to categorize them. The first step was to discuss types of metallic materials. The question was asked, are metallics a thermal barrier or just structural? P.A. Cox says he believes they are structural. With most of the boom under water- there is no problem, but what about above water exposed area? If using for this area above water, we must use a coating for protection. For thermal coatings there are ablative (uses out-gassing), intumescent (foams and provides char to protect for lengthy burn), and TBC - Y+Zr, Si-C, & Si-N (brittle, bulky, and will slow down burn). If we go back to a furnace in back of the boom, we would not have to worry about materials used. One thing to remember is that the thermal shock will be high. Tom Ryan insists that temperature range must be known before making a determination of need. It is believed that thermal flame temperature is between 2400-2500 degrees Fahrenheit. The maximum that 3M had was 1850 degrees Fahrenheit (1000 Centigrade) per Martin.

The first design sketch presented was from Tom Ryan. It is an under water type labelled the *Semi-Submersible Upright Screen*. Most of it will be put under water for protection. Per Lemoyne, almost all are partially under the water with cable connections at top and bottom. Designs also have a cable ballast at the bottom. Ryan recommended a fine wire mesh screen.

Lemoyne added the idea that we needed to use high freeboard; otherwise oil will roll over the top of the boom. How high must the barrier be? Ten Feet? It must be at least 5 feet because of the 5 foot waves. It was suggested that maybe we could put the barrier in front and in back, and freeboard would not have to be as high. It was asked what about colder temperature areas where there may be ice? *Semi-Submersible Upright & Flat Screen* could be the answer. This is an off-water burn boom (low temp body; low mass high temp freeboard) type.

The next design concept was the *Semi-Submersible Vane*. It is a pop-in or hinge boom. It is neutrally buoyant, but would survive a fire. The problem with this may be how to deploy it?

Maybe for *passive cooling* we could make it conductive to throw off heat, or use wicking. Possibly a round blanket of some material to wick up the water, or an aluminum nitrate fiber for a heat pipe to conduct the heat down could be used. Maybe *active cooling* with a power system is the answer. What about sprinklers on the top? It would be porous enough to not burn. If we made it double-hulled, we could pump water and blow air. This would have air/water annular separate compartments made from stainless mesh. When it burns the goo or tar will cling to everything. One problem may be if boiling of the seawater occurs, then there will be salts to contend with. This type would require more manpower, so operational and training costs would go up. What about punctures? We would have two separate pipes, each being an independently operated 20 foot section. If one section went down then we are not dead-in-the-water. Water is cheap to use. Paul Watson suggested using sensors to control water flow. That would jump us into a higher technical arena. So maybe we would need a certain amount of water always flowing.

A boom design under the *Others* category was the *Incinerator Concept*. This would be a furnace type made of a thick burning material or a honeycomb material. Note that the temperature limits are driven by the material used. If using a porous material it would help with the decrease of oil loss (porosity and surface tension are important factors). Jim Burkes added that if using the honeycomb material the oil would be more viscous, get trapped, and would burn on top. Maybe it could be like a floating rug (cotton). Tow speed and size would control the burn. Tom Ryan said if using a rigid structure maybe a propylene material should be considered. Jim Burkes said possibly a phenolic-based material would be appropriate. The oil would rise to the top inside and burn. Should it be flexible or rigid, a fabric or steel mesh? Once again we are brought to the question, "Is there any money for testing?" Jim states there is little money available for testing. P.A. Cox asked ,"What data do we already have regarding floating material that we could use?

Barge Burner is another type of *Other* boom. This burner (holder) would be towed behind the boom. The boom would actually collect the oil and in some way pump it into the holder/burner for the burn. A *Channel Burner* was suggested by Jim Burkes. It could possibly be a long and narrow burning trough, which could be used as a collector and burner at the same time. Fred Lyle suggested *Burning Logs*. They could rotate or roll, and would not burn so quickly. The problem with these is that they could only be used for 1 (One) cycle, and how would you connect them if need be? How would you get them to the site if not on ship already? Tom Ryan gave us our last suggestion of a *Push-Rather-Than-Tow* boom. Why have to tow? And what about submersibles? Maybe steam tubes to propel from the burn. It would be like a burning version of a skimmer.

At approximately 1:37 p.m. Jim Burkes stated that since we had presented today all our ideas and concepts regarding the boom, what should our goals for our next (second) meeting be? We should review ideas and concepts presented and expand on them, or unanimously reject them by looking at the pros and cons of each based on the requirements and desires of the sponsor. Any new idea that may be conceived since our first meeting should be introduced. We need to narrow the list down to our best ideas. In order to accomplish this, we will need more complete concepts, and more in depth evaluations to insure all elements of the specification are met.

As for our third meeting we should be actually creating boom designs. There is one person that manufactures successful boom designs for two competing fireboom company's. We thought of maybe bringing him in as a consultant to advise us on the feasibility of our designs. Tom Ryan suggested using a matting .85 density made of a hydrophilic material with a hydrophobic material coating. This would make it oliophobic where it would only absorb the oil. It was also suggested that we needed to address the buoyancy system. Martin says that 3M uses a proprietary volcanic ash material. Could it be perlite?

At this point Martin brought up the question about whether we thought anyone was missing from the team or maybe an area that may not be covered by the current team? Diane Shipton suggested Isam El-Shaffey from Division 07 because he has an oceanographic background and could maybe provide more insight regarding wave motion modelling.

The meeting was adjourned at 2:05 p.m. The next meeting was scheduled for May 11, 1994 at the same time (9:00 a.m - 2:00 p.m.) and place (Dining Room 1) in the cafeteria. Meals will be catered.

Minutes of the Second Fireboom Design Meeting

May 11, 1994

The second Fireboom Design Meeting was called to order by Co-Principal Investigators Martin Bartlett and Jim Burkes at approximately 9:12 a.m. in the Main Southwest Research Institute Cafeteria Dining Room 1 (One). Attendees were Martin Bartlett, Jim Burkes, P.A. Cox, Stuart Schwab, Paul Watson, Wayne Biediger, Lemoyne Boyer, Fred Lyle, Tom Ryan, and Diane Shipton.

The first order of business was to request any changes to the minutes for the first Fireboom Design Meeting held May 5, 1994. Since the minutes were not available to most people until the day before this second meeting, many had not reviewed the minutes in great detail. Stuart Schwab did request that his expertise be updated to read "(Chemist, High Temperature Materials expertise)." Tom Ryan requested that we re-word a sentence that started on the very last line of page two: "We have a sooty flame and"... to continue at that point to read, "...(depending on temperature) since soot increases the radiated heat transfer to the boom." All were requested to review the first minutes more closely and E-mail any requested changes. It was also determined that Steve Green would not be replaced because the expertise of the present group was sufficient to cover the area that Steve Green would have been responsible for addressing.

Hard copies of the first minutes were distributed to members as they requested as well as the Second Meeting Agenda. After a few moments given to review the Meeting Agenda, Martin Bartlett presented a brief overview of the first meeting and what had been accomplished. At this point Jim Burkes introduced the expectations of what was hoped to come from this second meeting. We first would want to identify all the possible material options available to us that would meet the sponsor's requirements of being lightweight, durable, and thermally stable. The discussions would then turn to identifying the best-suited materials, and then on to structural designs. Once all the old/new structural designs were identified, we would determine the pros and cons of each design. Jim stated that we need to look at this as setting up a tool kit with all the materials and structures which meet the known requirements.

At this point the discussions began to concentrate on identifying the material options available to us. P.A. Cox suggested we look more closely at the silicate foams. The foams are porous and durable up to 1,000 degrees Centigrade. These foams are also lightweight, easy to handle, and are not too costly. He thought maybe the foam could be sprayed on a mesh at the spill site, or maybe a continuous foaming as the boom is reeled out. Stuart Schwab says the curing time is too long, and since foaming is a physical instead of a chemical reaction, if it does not cure, then the water contact would just dissolve the material. He said Ultramet is the company that makes a low density product (SiC Foam) compared to the volcanic ash material of 3M. Fred Lyle recommended we look at a glass foam product similar to obsidian. Ryan suggested maybe a product made floatable with asbestos.

Fred Lyle brought the discussion back to metals. The SS310 has a high chrome/moly content and is great for temperatures from 1800-2000 degrees Fahrenheit. The negative attributes of SS310 are that it is twice as heavy as ceramics and highly sensitive to contact with sea water. The SS608, because of its high nickel content, is the better metal based on its resistance to cracking and pitting when it comes in contact with sea water. The weight factor was brought up. It was noted by Jim and Martin that one of the problems with the 3M structure is that it was too heavy, thus, it has a poor buoyancy/weight. We also need to be reminded that the 3M product is too costly, but costliness should not be stressed as much right now. Because of the possible trade-offs, cost is not as big a factor as the others. Carbon-carbon was suggested. Stuart Schwab stated carbon-carbon is a buoyant material, but it would disintegrate at about 600 degrees centigrade. It would need a coating of some kind to protect it. They have been working on the same coatings for many years for the Shuttle and still had nothing better than they had at first.

Refractory metals were suggested - especially Titanium. It was said they are very dense and would sink. If coated then the material would be buoyant; however, then it burns too quickly (at 1800°F it can survive, but not at higher temperatures).

Stuart talked about the use of ceramics fibers/fabrics. It was asked whether the ceramics would take on too much water? Fiberfrax was named as a potential material. An ablative coating would be ideal because then the material would not absorb as much water, and any fiber could be used to wick up the water as needed. Jim asked about the shock resistance and Stuart recommending using a ceramic with an organic binder. Martin asked about the availability and inquired about the cost since it was not readily available off-the-shelf. Stuart said that Philip's Lab may have someone that makes it in bulk. We make it here, but it is too expensive.

As for intumescent "plastics/coatings", when this polymer material decomposes it produces gas. A modified intumescent was mentioned by Stuart Schwab.

From these discussions came a list of usable materials with a brief description of the Pros and Cons:

Materials	Pros & Cons
Silicon/Ceramic Foams	Good thermal barrier, but still fryable above 1000°C; porous and easy to handle, but curing time too long; need closed porosity.
Refractory Metallics (Titanium)	Burns too quickly (1800°F is maximum temperature; Very dense & will sink; Will keep strength, but must have coatings to do so.
Metals (SS310)	Very heavy; with high chrome/moly content, good oxidation resistance; But sensitive to contact with sea water.
Metals (SS608)	Very heavy; High nickel or moly contents makes it resistant to sea water damage; Nickel is very expensive, but moly same benefit and cheaper; difficult to store and handle.
Ceramics	Lightweight; High Temperature withstanding; Neutrally buoyant; Difficult to keep upright in high winds; Easy to sink because will take on water too easily; May be quite expensive unless we can find someone that makes it in bulk.
Intumescent "Plastics"/Coatings	When decomposes, lets off toxic gas;
Polypropelene	A reflective material (like that used in auto window shades); Durable, but can't control heat.
Carbon-carbon	Will disintegrate at 600°C; Coatings will be needed, but no good reliable ones exist; Would be a good buoyant material.

Teflon	Flexible, but too toxic; Flows before it decomposes; If coated with aluminum silicate maybe it would be okay.

Next we discussed possible structural designs, but first we needed to try to get ideas as to why the 3M design failed. The problem identified was that the mesh oxidized and broke. What could have made it break? Possibly the stress and crevices weakened it to the point it was brittle and easily broken. Since the mesh is a major part of their structure design and because 3M used SS310, it probably was from the effects of seawater.

The main structural attributes needed are high-buoyancy, low weight (low water absorption), flexible, durable (shock-resistant, adhesive, and compliant), strong and thermally stable (1800°F-2500°F max). The most important of the attributes are the need for high-buoyancy and low weight. It was asked to discuss the types of structures to possibly use for the boom.

The following structural design concepts were identified with their pros and cons:

FINE MESH SCREEN CONCEPT. This would be a fine mesh screen or sail that traps oil, but lets air pass through it. It has flotation and a skirt for stability. Possible materials would be SSTs and glass/ceramic fabrics. There are three concepts designs under this one category: The upright screen model, the Dual upright & flat screen, and the Pop-out or Hinge Vane. The cons are that with stainless steel, it would twice as heavy as ceramics and still has the burn and disintegration problems. There may be an advantage to having several screens, one in back of the other? If made of glass/ceramic fabrics, floatation would be protected, and it would be much lighter than metals.

TIN CAN CONCEPT (SHELL OIL "SCHWEPPE"): A cylindrical tube floatation device 4-foot in diameter. The can provides the floatation and the tube material provides a barrier for the oil. This item would be difficult to store and the real problem is that it would have to have some kind of a power deployment system, which the sponsor does not want. The sooty flame may cause reliability problems because it could clog the automatic air-sucking system. It was determined that it could be designed so that each can was flat and it would spring open (like a purse) as it was deployed and auto-inflate. It was determined that it may have buoyancy and cooling problems.

BURNING MAT: This design consists of a long mat of material or a honeycomb that wicks only oil, similar to a floating rug. Material used could be Hemp with floatation underneath or maybe nylon with a passively cooled exterior finish. Bouncing and bobbing may be a problem that could cause a major oil loss, but it could probably be weighted in some way to avoid this problem. The burning will cause the continued oil wicking, which is good because no disposal would be needed. Look at the vegetable oil candle where the wick floats. Crude oil has a little different viscosity, but the same principle applies.

INCINERATOR CONCEPT: This design incorporates a barge burner being towed behind the boom. The oil would be somehow pumped into the barge burner. When full, the barge burner would be released and burn internally. The barge burner could also be a long, narrow burning trough that collects and burns while under tow.

BURNING LOG: Similar to the "Burning Mat" concept, this would be a one-time-use concept. The structure could be covered with a material that collects only oil. Since it would burn totally away, there would be no disposal problems. It could be a flexible u-shaped log that could burn unattended or while under tow, which could speed up the collection process. Multiple logs would be needed and you would run into storage problems on the boat.

COMBO AIR/WATER ASPIRATION: The tube could have a tube in the center filled with water and forced-air in a tube surrounding that. If the center was made of a low density foam, it could be surrounded by a tube with forced-water actively cooling the unit. It would have some porous material on the outside. It would be totally collapsible like a plastic bag, so great for storage and handling. The air would have to be continually flowing.

INFLATABLE TUBE DESIGN: We would have a structure with the greatest amount of positive attributes. The primary advantage of this design is the buoyancy, but it is also collapsible (so easily stored if necessary), deployed easily (air is in abundance), and is low in cost. It would incorporate a tube that is filled with air using something as simple as a hair dryer with a blanket on the outside that wicks the oil/water as needed. The only drawback of the tube design would be the possibility of puncture. It was decided that it had good buoyancy, was collapsible and storable, and it had a low cost. The use of low density/rigid foams was brought up. It would need a *Urethane Foam* for the out of water portion of the tube for protection. The foam could be dispersed as the tube came off the reel, then if it was punctured the foam might lessen the air leak preventing a possibility of complete failure. It would be easily stored flat. The following designs were discussed:

1) *Rotating Tubular Element with Evaporative Cooling:* Another inflatable tube structure idea is the Rotating Tubular Element with a water absorbent coating to help protect the tube from the fire. The rotation would also help protect the tube itself.

2) *Non-Rotating Tubular Element with Evaporative Cooling (Wet Blanket):* Another one would be the same as the tube above (like a wet blanket), but it would not rotate. The part of the tube that would be on top would be coated with a material that sucks oil and water as appropriate.

3) *Tubular Element with Intumescent Polymers That Produce a Foam:* What if we had a cylinder that had an internal structure that would be activated to expand when the outer part is leaking? Stuart said this would be another possible approach IF we could keep it cool. We could use a urethane foam involving a two component mixture that when reeled out to sea, the two components could be squashed together and react chemically to produce a foam that could protect the tube in terms of loss of air or would at least slow the leakage. We would definitely have to look at some way to insulate the tube to increase its longevity. The inside layer would be made of a PMR15 with a laminate on the outside of the first layer. The second layer would be the

intumescent polymers layer. The third layer, a sacrificial layer, would be used to wick up the water. It would have a chain ballast for stability. It would be reelable, and may last as long as 2 or 3 days; however, it would NOT be reusable.

4) *Tubular Elements with Oliophylic/Hydrophilic covers/blankets:* An inflatable, non-rotating, tube structure treated with materials to make it shed oil or water, as appropriate.

PITOT TUBE: This could be a water induced passively cooled structure. The only drawback for this design is that it needs to be able to be used whether towing or not; this one is not.

Briefly discussed were some other active cooling concepts, such as Forcing Water Through a Porous Jacket, Forcing Air Through a Tube, Air Curtain, Water Curtain. One design was discussed in more detail and that was the Water Curtain design. It was determined that the wind would keep the structure wet, but not uniformly.

After much discussion it was determined by overall group consensus the *Inflatable Tube Design* seemed to be one of the best. We would have a structure with the greatest amount of positive attributes. The primary advantage of this design being its buoyancy, its collapsibility (so easily stored if necessary) and its easy deployment (air is in abundance). The only drawback of the tube design would be the possibility of puncture, and that has been addressed in the discussions.

Many shapes for the boom were presented, such as balloon shape, round tube shape, two oval shapes, freeboard shape, and diamond shape. It was determined that for a hard-materialed structure, the diamond shape was the best. It was also determined that the oval upright was the best at preventing oil loss because it does not bounce or bob on the water as other designs would.

For the next meeting (May 27th) the plan is for each of you to come up with what you think are some viable and feasible designs with sketches. The group will discuss the pros and cons of each, and together will rank them according to how they solve the problem.

The meeting was adjourned at 1:57 p.m. Next meeting was scheduled for May 27, 1994 at the same time (9:00 a.m - 2:00 p.m.) and place (Dining Room 1) in the cafeteria.

Minutes of the

Third and Final Fireboom Design Meeting

May 27, 1994

The third and final Fireboom Design Meeting was called to order by Co-Principal Investigators Martin Bartlett and Jim Burkes at approximately 9:25 a.m. in the Main Southwest Research Institute Cafeteria Dining Room 2 (Two). Attendees were Martin Bartlett, Jim Burkes, P.A. Cox, Stuart Schwab, Paul Watson, Lemoyne Boyer, Tom Ryan, and Diane Shipton. Fred Lyle and Wayne Biediger were unable to attend.

The first order of business was to review briefly the sketches from the previous Fireboom Design Meeting held May 11, 1994. All were requested to review the minutes more closely and E-mail any requested changes.

Hard copies of the present Meeting Agenda were passed out for review. A list of criteria questions that needed to be addressed for each design was also passed out. After a few moments given to review the Meeting Agenda, Martin Bartlett presented a brief overview of the previous meeting and what had been accomplished. He let everyone in attendance know that we needed to be very focussed for the meeting today, possibly spending a maximum of one hour on each design concept or sketch. The objective was to determine the two best all-around concepts. A new data sheet identifying a High Temperature Blanket material was introduced. It could withstand up to 2000°C and was used in a NASA Technical Brief.

At this point the discussion turned to potential fireboom designs, with Advanced Material Designs being discussed first. It was determined that this design would be reusable if the round-shaped boom was used and was filled with air. If the round design was filled with foam, it would probably have to be a one-shot boom. It was determined that we needed to look at the positioning of the layers - were they correct for this design? Would the freeboard be adequate? What material should be used for insulation? It was determined that the insulation material should be hydrophobic. The reflective layer should be watertight. Aluminum could be used, but it melts at 1200°F so the problem would be how to keep it cool. Stainless Steel (SS) would be better, but it would eventually crinkle and lose its flexibility. What material would be acceptable for high temperature exposure? A silicate product that comes in a roll was suggested. Remember the purpose of the reflective layer is to use a high temperature material on the outside that would reflect the heat, thus reducing the inner temperature. Maybe the reflective layer could be a spray-on type? Maybe that reflective layer could be put on the inside (second layer from the outside). Maybe spray it on the two outermost layers and make sure they are sealed together to keep the water out? It was noted that if the weave was tight enough, the tension would keep the water out, so you would not have to worry about it being sealed.

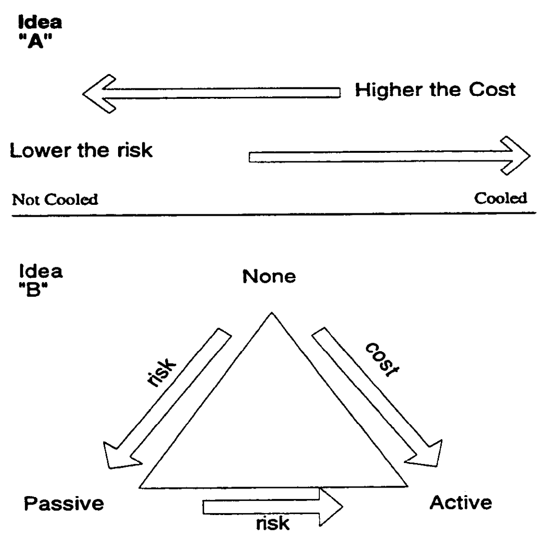
What if the outer fabric was of a wicking material, but the insulating layer was water tight? What fabric would be acceptable? Glass was suggested, but it was believed to be too brittle and fragile. Bonding would be difficult with glass. Also, if the weave was too tight then it would not take on oil, and if too loose it would take on water and sink. It was noted that there needed to be some wicking calculations and heat transfer calculations before any final determinations could be made. A blanket for protection was suggested such as an intumescent ablative material. A question about this protective coating was, would it be able to be replaced? Someone needed to look in a safety equipment catalog to try to identify some material that would be replaceable, which was an intumescent ablative type. Nextel was suggested. It is an alumina silicate (white in color). This material is not reflective and not absorbative. It was suggested that a side meeting with Stuart Schwab to discuss just the use of materials and their availability was necessary.

The blanket style design was discussed and although it would be feasible (especially with the identification of the NASA material that could withstand temperatures of up to 2000°C), it would be difficult to insure its success.

Instead of the cylindrical design, a balloon style was suggested. The balloon style would be less effected by the wave motion. The inner core would have to be saved because it is so expensive. Perhaps we could cut and peel away the outer layer and replace it. The problem would be how to fill it with air. It was suggested that the material have vent holes and if we maintained a constant temperature, the boom would fill with air and be able to maintain itself. A foam was suggested as a material because it would be floatable yet easily stored. It was agreed that whatever design was used, it should be segmented, so that in case of a puncture the whole boom would not be rendered a failure.

Six (6) *Advanced Material designs* were suggested and discussed. A break was taken at 10:40; the meeting continued at 10:55 am with discussions on *Passive Cooling designs*. These designs should be high temperature/wicking types with no intumescents. It was identified that getting a really good "wicker" was a problem. It was determined that there were too many "anti-wicking" problems, so maybe we could identify a material that is just a good wicker and then try to come up with a solution to that materials' wicking problem. A good concept was detailed: initially it was just a good wicking material; then during the combustion process, the oil burns leaving a residue; As it builds up, it forms a coating for protection (making a good insulator). Vaporization would be used for the cooling. There would be a deployability problem as well as a storage problem. Perhaps if a wood particle board/urethane combination were used it would work. It could have a sacrificial PVC layer on the exterior.

Several ideas were brought up as to how to rate the materials and ideas. One idea ("A") was a continuum where all the way to the left was not cooled and as you move to the right it becomes more cooled. The higher on the continuum, the higher the cost, but the lower the risk. The triangle concept (Idea "B") of rating material options was another way that was discussed.



By looking at the triangle, note the *Active, Passive and None* titles. If you follow the continuum from *Passive* cooling to *None* (no cooling), as you get closer to None the cost goes Higher; If you have None (no cooling) and move closer to the Active Cooling, the risk increases. This triangle demonstrates tradeoffs involved in making design decisions. Now just because the cost goes higher (from passive cooling to none) does not mean that the idea is bad because initially it may be a higher cost, but may be less labor intensive. The discussions turned back to the passive cooling design/material options.

A wood veneer with insulation and floatation that rotated was again mentioned. It would be much lighter than other designs, easily transportable, buoyant, and it would not burn through because wet wood will not burn. A Urethane coating was suggested, but it was noted that if the system was impregnated with urethane, it would not be buoyant.

The question arose as to exactly what did 3M use to join layers? They had 50-foot section with 7-foot inner floatation cores tied off with metal strips. So with this in mind, it was suggested that maybe we should use a material that melts, put it in a large amount of layers, and as it melts, it protects itself. It would have an inner core filled with foam or air. That core would be coated with the material that melts as it burns thereby protecting the inner core, and the outside could be replaced, making it reusable.

Back to active cooling, pumping by natural convection was suggested. A 100 - 200 GPM pump can be installed on a boat. Briefly discussed were some other active cooling concepts, such as forced water through a porous jacket or forced air through a tube. It was determined that the wind would keep the structure wet, but not uniformly. There is a center core that you are constantly pumping air and water through at a constant pressure. If the exterior is porous, what about clogging from the residuals? Also, would it last for 48 hours? If not, we would need to know how long it will last, so we would know how many of the units we should have to store onboard the ship. What about weight? If you did not want a material that would weep to protect the exterior, then use a high temperature material like that used on firehoses. Also, the boom must be able to withstand floating debris impacting it, so maybe a thin polyester coating would be useful. Maybe a water release at the top that allows the water to run down would protect the surface. If the water is fed from the bottom, if compromised, then all would be lost, so maybe the top water flow is better.

A passive design that has the same porous/weeping capabilities is possible. The exterior could be a silicone carbide. The next inner layer could be an insulating protection material. All layers should be made more fire-resistant, and should be of a flexible material so that it can be reelable. It was suggested that the project managers would have to look at availability of materials.

The following facts were reiterated: active cooling can not use foam, but passive cooling can use foam (deployed when reeling the boom out); If we just choose to add an intumescent coating to the already existing 3M design, then it would be an improvement; Should use flame retardant materials unless it is a self-destructing design; Fiberfrax with heat gets brittle and rigid (Flame temps of 900°C - 980°C would have to use a quartz fiberglass); Soot reduces the surface temperature; and, We need off-the-shelf materials that are hydrophobic and hydrophilic. It was also agreed that even though the active cooling requires more advanced technologies, it is better than the passive cooling because of its high degree of uncertainty. The advanced material design may still the best all around. The things that still need to be done that may help in the decision process are: 1) A material search for availability, meeting temperature limits that were set, and acceptable cost, and 2) A preliminary thermal analysis.

In closing, each participant was thanked for his participation and expertise. Stuart was agreeable to give Lemoyne Boyer intumescent materials information, so that he can do some minor modeling. The meeting was adjourned at 2:11 pm.

RULES

A group effort based on the use, experience and unique skills of the individual to produce an insight that is beyond that of the individual acting alone.

Each meeting will be under the control of a Facilitator. the Facilitator's function is to ensure that members are allowed to participate without stress, embarrassment or intimidation.

Meeting structured around an Agenda, with each item having a time limit.

Each item will be introduced by the facilitator or someone so designated. The initial comments shall be limited to a short summary of the scope of the topic (boundaries) and the item objective (where we want to be at the end of the discussion).

Round table discussion with individual response limited to 5 minutes.

Facilitator can decide to establish small work groups if there are several issues being discussed simultaneously.

In addition to the Facilitator, there will be a "time keeper," whose function is to monitor total time spent on an agent item as well as the individual allowance given to discussion.

At the end of each session, there will be time allowed to discuss the experience and to identify ways of improving the process. In addition, the agenda for the next meeting will be reviewed and revised as necessary.

Appendix F

Thermal Model Development

APPROXIMATE HEAT TRANSFER MODEL OF OIL BOOM

PROBLEM

Two concepts have been proposed for the oil booms. They both aim at removing heat to keep the boom's component material temperatures within tolerable levels. The first is a passive system that uses an inner metal liner to conduct the heat into the seawater. Radiant heat flows through the insulating blanket to the metal, then flows radially by conduction down to a submerged section of the boom where heat is transferred by natural convection to the seawater. The second concept is an active one, using water pumped over the surface of the boom to cool the surface.

The heat transfer through the boom is actually a complicated three-dimensional, multi-material, multi-phase problem. This is a simplified, approximate model of the boom intended to give some preliminary insight into the impact of the many parameters on the temperatures developed in the materials. A brief discussion of the analysis and its preliminary findings follows.

ANALYSIS

Key Assumptions

- All calculations for an 18" ϕ boom
- $\dot{q}_o$ = constant = 20 kW/m^2
- Neglect heat absorbed by the insulation since $(MCp)_{insulation} \ll (MCp)_{metal}$ for range of cases studied
- Water temperature, Tw = constant = 65°F
- Uniform temperature in mesh
- Cooling water pumped through 1.5 ϕ Pipe along the boom
- Heat absorbed by coolant evaporation is $\eta \dot{m} h_{fg}$
  - η Efficiency
  - $\dot{m}$ Coolant flow rate
  - h_{fg} Water heat of vaporization
- Coolant uniformly distributed over 300-foot section of boom
- Metal mesh heats up about +100°F in calculating convective heat transfer coefficient
- 20% of the volume of insulation is saturated with seawater

PROCEDURES

The approximate heat transfer analysis follows a seven-step procedure.

Step 1. Define the boom layers and materials, and calculate the weights of the components.

- The materials selected for the boom are described in a separate appendix.
- The boom weight is calculated as the sum of its parts. The boom considered have an outer textile covering, an insulating blanket, water piping, water seeping into the boom, a 0.5" chain at the bottom of the skirt, and a feltmelt cylinder.

Boom Weight (per foot of length) $D_o = 18$ in. $D_o = 18$ in.

$$W = W_T + W_B + W_W + W_M + W_C$$

$$W_T = \text{Textile Weight}$$

$$= \pi D_o(1)p$$

$$= \pi(18")(12")\left[\frac{2.25\text{lb}}{\text{yd}^2}\right]\left[\frac{\text{yd}}{36\text{in}}\right]^2$$

$$= 1.18 \text{ lb/ft}$$

$$W_B = \text{Blanket Weight}$$

$$= \pi D_o \Delta(1) \Rightarrow$$

Material	Thickness Δ(in)	Density (kg/m3)			Weight (lb/ft)			Thermal Conductivity (W/mK)		
		A	B	C	A	B	C	A	B	C
Durablankets	0.5	64	96	128	0.78	1.18	1.56	0. 25	0. 31	0. 37
	1				1.56	2.34	3.12			
	1.5				2.34	3.51	4.68			
	2				3.12	4.68	6.24			
		D	E	F	D	E		D	E	F
Cerachem Blanket	0.5	64	96	128	1.18	1.56		0. 21		0. 32
	1				2.34	3.12				
	1.5				3.51	4.68				
	2				4.68	6.24				

W_w = Weight of cooling water + water saturating insulation

- Cooling Water Line (Seawater @ 64 lb/ft³)

ϕ	Weight (lb/ft)
1	0.35
1.5	0.78
2	1.4

- Water in Insulation - Assume 20% saturated

$$W = .2\ p \text{ water } \pi D_o \Delta \frac{12^{11}}{12^3}$$

$\rightarrow$

$= 5.03\Delta$

Δ (in)	Weight (lb/ft)
0.5	2.52
1	5.03
1.5	7.55
2	10.06

W_c = Chain Weight = 2.5 lb/ft (0.5" Chain)

W_m = Weight of Feltmetal

$= \pi (D_o - 2\Delta)\, \Delta_m\, p$ $\quad$ p = 35% of alloy density = (.35)(490 lb/ft³) = 171.5 lb/ft³

Δ	Δm	Weight
0.5	.125/.25/.5	7.95/15.9/31.8
1.0		7.5/15/29.9
1.5		7.0/14.0/28.1
2.0		6.55/13.1/26.2

Note: Δm = Metal Thickness (in.)

Step 2 Determine how the boom floats in the water.

The buoyancy is calculated as the weight of a one-foot length of 1.5 ft. boom filled with seawater (113 lb.) divided by the boom eight. The submerged section of boom is equal to the volume of seawater weighing the same as the boom. The volume is $\frac{W_{Boom}}{\rho_{Water}}$.

Geometrically, for a cylinder of unit depth,the volume is shown as the shaded region. That region may alternatively be defined as the wedge section of angle 2θ ($\frac{2\theta}{360}\pi R^2$) minus the triangular section ($A = R^2 \sin\theta\cos\theta$). The angle from the boom center to the sea surface, θ, may then be calculated from the boom weight. The surface area of the boom above the waterline to that below is

$$\frac{A_{in}}{A_{out}} = \left[\frac{\pi - \theta}{\theta}\right] = \frac{\text{Area of Radiant Heat In}}{\text{Area of Converted Heat Out}}$$

W / 1 (lb/ft)	ΔSubmerged / ΔCross Sections	A In / A Out	θ	Boundary
10	0.156		27	11.31
14			30.6	8.07
15	0.234	4.71	31.5	7.54
16	0.25	4.59	32.2	
17	0.267	4.45	33	
18	0.281	4.37	33.5	
19	0.297	4.26	34.2	
20	0.312	4.17	34.8	5.66
21	0.328	4.08	35.4	
22	0.344	4.0	36.0	
23	0.359	3.92	36.6	
24	0.375	3.85	37.1	
25	0.391	3.77	37.7	4.5

Step 3. Define the input heat flux.

$$\dot{q}_{in} = \frac{(\varepsilon\, \dot{q}_o\, A_{in} - \dot{m}_l\, h_{fg}\eta)}{\Delta_{in}} = \frac{\text{RadiantHeatIn} - \text{HeatLossByEvaporation}}{\text{ExposedArea}}$$

Where:

ε = Surface Etamissivity

[The Textile Covering Is Reflective Assume $\varepsilon \cong 0.9$]

$\dot{q}_{in}$ = Heat flux from fire (20 kW/m2)

$\dot{m}_l$ = Coolant heat flow (lb/sec/ft of boom)

h_{fg} = Heat of vaporization of water (2454 J/kg)

η = Fraction of coolant absorbed (Assume ~ 25%)

$A_{out} = \pi D(1)/(1 + A_{in}/A_{out})$

$A_{in} = (A_{in}/A_{out})(A_{out})$

Step 4. Estimate the convective heat transfer coefficient , h

$\dot{q}_{out} = h\ (T-T_{water})$ [Heat Flow to Seawater]

The natural convection from a heated horizontal cylinder is defined by:

Dimensionless Heat Transfer, Nu = f (Dimensionless Buoyancy Term, Ra)

$$Nu = \frac{hD}{k} = .13\ Ra^{1/3} \qquad \text{for } 10^9 < Ra < 10^{10}$$

$$\text{Rayleigh Nu, } Ra = \frac{g\beta D^3(\Delta T)}{M\alpha}$$

g = Acceleration due to gravity - 32.2 ft/s^2

ß = Coefficient of Thermal Expansion = $.1x10^{-3}R^{-1}$

Evaluated for Water @ 140°F μ = Kinematic Viscosity = $.514x10^{-5}ft^2/s$

α = Thermal diffusivity = $6.02x10^{-3}ft^2/hr$

k = Thermal Conductivity = $.376 \frac{BTU}{hrftF}$

$\Delta T \cong$ 100F

$$Ra = \frac{(32.2ft/s^2)(.1\ x\ 10^{-3R^{-1}})(1.55ff)^3(100R)}{(.514\ x\ 19^{-5})(6.02\ x\ 10^{-3}ft^2/hr)(hr/3600s)}$$

$$Nu = .13\ (1.3\ x\ 10^{11})^{1/S}$$
$$= 650 \quad \text{[At steady state] [Nu = 1 initially]}$$

$$h_\infty = \frac{Nu\ k}{D} = \frac{(650)(.376BTU/hrftF)}{1.5ft} = 163\frac{BTU}{hrft^2F}$$

When starting,

$$h_o = \frac{Nuk}{D} = \frac{(1)(.376)}{1.5} = \frac{.25BTU}{hrft^2F}$$

$$\text{The Average Coefficient, } H_{AV} = \frac{h_o th_{oo}}{2} = 8.16\frac{BTU}{hrft^2F}$$

Step 5. Calculate equilibrium temperature of metal mesh.

At steady state -

Heat In = Heat Out

$$\dot{q}_{in} A_{in} = A_{out} \dot{q}_{out} = A_{out} h_{\infty} (T_{EQ} - Tw)$$

$$T_{EQ} = \frac{A_{in}}{A_{out}} \dot{q}_{in} / h_{\infty} + Tw$$

Step 6. Calculate equilibrium temperature of surface

$$\dot{q}_{in} = \left(\frac{k_{insulation}}{\Delta_{insulation}} \right) (T_{SEQ} - T_{EQ})$$

$$T_{SEQ} = \frac{\dot{q}_{in} \Delta}{k} + T_{EQ} \quad .$$

Step 7. Calculate Transient Temperatures

$$MC_p \frac{\alpha T}{\alpha t} = A_{in} - A_{out} \dot{q}_{out} h_{AV} (T - Tw)$$

Initial Temp, To

$$= A_{in} \dot{q}_{in} - A_{out} h_{AV} (T - Tw)$$

$$T^1 + \frac{A_{out} h_{AV}}{MC_p} T - \left[\frac{A_{in} \dot{q}_{in}}{MC_p} + \frac{A_{out} h_{AV} T_w}{MC_p} \right] = 0$$

$$T = T_{EQ} + (T_O - T_{EQ}) \ \text{EXP} \left[\frac{-A_{out} h_{AV}}{MC_p} t \right]$$

$$T_s = T_{SEQ} + (T_O - T_{SEQ}) \ \text{EXP} \left[\frac{-A_{out} h_{AV}}{MC_p} t \right]$$

Oil Boom Approximate Heat Transfer Analysis

Input Conditions:

20	heat flux from fire (kW/m^2)
65	water temperature (F)
0	coolant flow rate (GPM)
2454	coolant heat of vaporization (J/kg)
1.5	boom diameter (ft)
0.5	insulation thickness (in)
0.125	mesh thickness (in)
14.93	weight per unit length (lb/ft)
0.25	fraction coolant vaporized

Material Properties:

0.9	surface emissivity
0.21	insulation thermal conductivity W/mK
7.95	metal weight (lb/ft)
0.11	mesh specific heat (BTU/lb/F)
64	water density (lb/ft^3)
1.56	insulation weight (lb/ft)
0.27	insulation specific heat (BTU/lb/F)

Calculations:

convective heat transfer coefficient, h -

For a horizontal cylinder, the dimensionless heat transfer, Nu, is a function of the ratio of buoyant to viscous forces, Ra, by Nu = .13 Ra^.33 for 10^9 < Ra < 10^12
Ra = gBD^3 (del T) /n/a
For water at about 140°F, g = 32.2 ft/s^2,
B = coeff of thermal expansion = .0001 R^-1
D = dia = 1.5 ft

a = thermal diffusivity = 6.02E-3 ft^2/hr
n = kinematic viscosity = .514D-5 ft^2/s
k = water thermal conductivity = .376 BTU/hr/ft/F

Initially, del T = 0, so Nu = 1
h = Nu k/D = .2506667 BTU/hr/ft^2/F

At steady state:
del T = metal/water temp difference = 100 F (est)

Ra = 1.3E11, Nu = 650

h = Nu k/D = 163 BTU/hr/ft^2/F

.2332813 ft^2 = area submerged
1.767144 ft^2 = total cross sectional area
.1320103 ratio of submerged to cross sectional areas
qin (W/m^2) = 18000

theta	= 31.4		
Awedge	= 1.233074 ft^2		
At	= 1.000593		
Asub	= .2324811 ft^2	.2332813	
A_{in}/A_{out}	= (pi - theta)/theta=		4.732484

Teq = $A_{in}A_{out}*q_{in}/h + Tw$ = 230.6660F

Tseq = q_{in}*del/k + Teq = 2189.237F

A_{bou} = $A_{total}/(1 + A_{in}/A_{out})$ = .8216333 ft^2
$A_{in}(A_{in}/A_{out})(A_{out})$ = 3.888367 ft^2
exponent = A_{out} * hav/m/cp

FINDINGS

- Calculations were conducted for a boom with the insulation wrapped around the full circumference. The surface temperatures for this configuration were very high, as the boom was unable to readily deposit the heat to the seawater.
- A number of test cases, covering a range of designs for the two concepts, have been considered. A table of the test cases follows.
- For a practical range of boom weights, there is about four or five times as much area exposed to the flame as there is available for convection to the seawater. This trend is shown in the attached figure.
- An insulation thickness greater than 1/2 inch shows surface temperatures greater than 2000F.
- A coolant flow rate of 100 GPM was able to reduce the surface temperature by about 200F. This is shown in the final figure.
- The passive system seems to be a simpler, more effective way of cooling the boom. Refinement of the model and experimental verification are needed.
- The booms heat up and approach a steady state temperature within about five minutes

Problem - Determine the circumferential temperature distribution ion the metal and insulation.

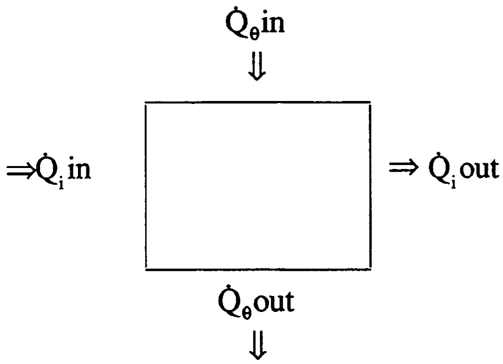
Given - Assume the outer surface temperature is 2000F, and the inside core temperature is 200F.

Approach - Divide the boom into sections (wedges) and estimate the temperature of the metal by an energy balance on each section. Assume steady state behavior and simplify by reducing the analysis to linear coordinates. The analysis:

1) Balances heat flow through each section
2) Balances overall heat flow, in and out of boom

Angle	Insulation Δ_1	Metal Δ_2	Insulation Δ_3
0°			
15°			
30°			
45°			
60°			
75°			
90°			
105°			
120°			
135°			
150°			
165°			
180°			

For each cell of metal,



At Angle θ Metal Temp = T_i
At Angle θ - 15° Metal Temp = T_1 - 1
At Angle θ + 15° Metal Temp = T_i + 1

Energy Balance

Heat In = Heat Out

Heat In Through Insulation + Heat In Through Metal = Heat Out Through Metal + Heat Out Through Insulation

$$\frac{k_i(T_s - T_i)x - \tau}{\Delta_1} + \frac{k_m(T_{im} - T_i)\Delta_2\tau}{X} = \frac{k_m(T_i - T_{im})\Delta_2\tau}{\Delta_3} + \frac{k_i(T_i - T_B)x\tau}{\Delta_3}$$

Where:

k_i = Insulation Thermal Conductivity
k_m = Metal Thermal Conductivity
x = Section Length = $\frac{15°}{360}\,\Pi D$
τ = Unit Length Along Boom
Δ_1 = Outer Insulation Thickness
Δ_2 = Metal Thickness
Δ_3 = Inner Insulation Thickness
T_1 = Surface Temperature
T_B = Backface Temperature
T_i = Metal Temperature

For sections below the waterline (θ >150°)

$$\dot{Q} = hA(T_i - T_w)$$

h = Convective HT coefficient ≅ 925 W/M2K
Tw = Water Temperature ≅ 20°C

Find Temperatures By Trial & Error So $\varepsilon\dot{Q} \approx 0$