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EFFECTIVENESS OF CURRENT AND ALTERNATIVE HELMET MATERIALS IN THE PREVENTION OF HEAD AND NECK INJURIES AS MEASURED BY BIOMECHANICAL PARAMETERS

by

Donald Friedman and Keith D. Friedman

Liability Research Group, Santa Barbara, CA. U.S.A.

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Head and neck impacts in motorcycle accidents remain a significant problem for helmeted riders and result in over 400 severe injuries and fatalities annually. Helmeted head impacts in other accidents contribute countless more.

OUR IMPRESSION IS THAT LITTLE HAS BEEN DONE IN THE PAST FIFTEEN YEARS TO ENSURE THAT HELMETS PROVIDE THE LEVEL OF HEAD/NECK PROTECTION NEEDED TO PRECLUDE CRITICAL INJURY IN FORESEEABLE, AND RELATIVELY MINOR, IMPACTS.

Therefore, the purpose of this paper is to:

1) examine the effectiveness of current and alternative materials in preventing the occurrence of critical injuries to the neck during a head impact, and

2) identify modifications in helmet design and current testing standards which would significantly improve the level of protection provided against critical injury in a helmeted head impact.

These studies suggest that if the alternative materials and helmet design approaches identified in this paper were implemented, in conjunction with revised testing procedures, as many as 250 critical quadriplegic injuries to helmeted accident victims could be saved annually in the U.S.

Three study elements are the basis for this paper.

The first element was an extensive literature review which identified typical helmet characteristics, injury stastics,

statistics, and the historical development of minimum helmet testing standards.

The second element was a series of eight detailed case studies involving head/neck injuries associated with impacts to helmets of various types. These cases were analyzed by CVS/ATB-3D computer simulations of the accident circumstances using helmeted dummies and measured liner force/deflection characteristics.

The third element was a study of potential countermeasures in which the effectiveness of alternative materials in reducing critical biomechanical injury measures was evaluated. The study included consideration of current test procedures and identified directions for development of more representative test conditions which would better reflect the environment in which the helmet is intended to reduce injuries resulting from impacts with the head.

The following material was selected to highlight what was done, and what we found particularly interesting.

The review of references showed, among other things, that:

1. helmet standards test impact attenuation with a helmet and headform only, yet real world impacts involve head/neck/torso interaction.

2. materials generally used in helmet liners are rate sensitive.

3. liner is generally a homogeneous material.

4. variations in force-deflection properties can vary with shell type.

5. numerous impact configurations occur which can be categorized.

6. the solution to the various problems inherent in the head/neck protection problem may very well be addressed by solutions specifically developed to deal with each individually.

The case studies showed that:

1. compression neck injuries occur as a result of helmet impact with a surface in such a way that the torso loads the helmet through the neck.

2. many such impacts are not simply a perpendicular impact of an aligned head, neck and torso, but rather involve significant angularity of the head, neck, and torso relative to the contact surface.

3. frictional effects are important for impacts of this sort.

4. a single impact is generally responsible for the neck compression injury.

The countermeasure study showed that:

1. alternative materials can provide force-limiting liners.

2. Risk of Neck injuries in low angle impacts can be significantly reduced through the use of appropriate shell and liner characteristics without affecting the ability to pass existing standards.

3. Practical testing methods and devices are available by which to establish angle impact standards for helmets.

For the purposes of the study, the range of alternative characteristics shown below were considered.

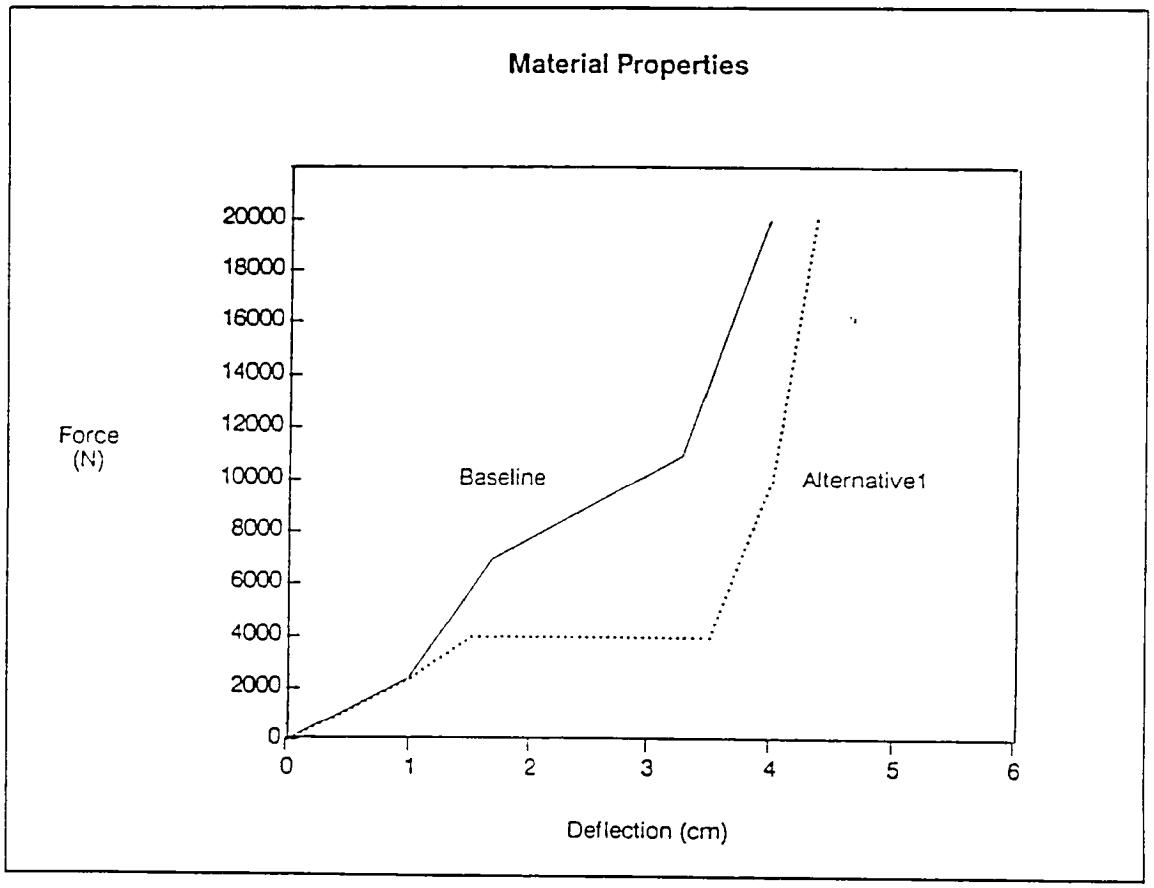
Example Alternate Characteristics	
Shell	**Liner**
- Fiberglass	- Styrofoam
- Polycarbonate	- Polystyrene
- Kevlar	- Polyurethane
- Composites	- Hexcell

Various factors were considered important for the alternative helmet characteristic to compare with a baseline such as shown in the following chart:

Selected factors
- Shell Stiffness
- Liner Force/ Deflection Properties
- Liner Energy Absorption
- Rate Sensitivity
- Shell Frictional Properties

To illustrate how performance comparisons can be made, two helmets are characterized. The baseline helmet has a Polycarbonate Shell and a Polystyrene liner, and the Alternate has a Composite Shell and Hexcell liner. To eliminate confusion associated with the effects of shell-contact surface friction the same coefficient of friction (0.1) was used for both helmets so as not to obscure the effect of the liner/shell properties.

The force deflection properties used for the two helmets are shown in this chart, with the important distinction being that the baseline has a ramping force-deflection characteristic, while the alternative has a force limited property.



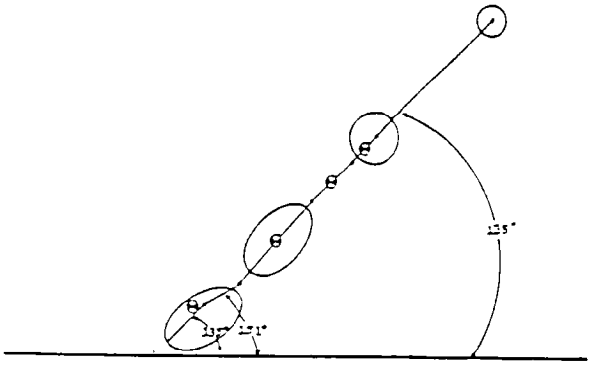
The MVMA 2-D program and Hybrid III dummy characteristics were then used for testing the two helmets in various impact configurations. First, the helmets and dummy heads were drop tested onto flat plates with impact velocities corresponding to FMVSS 218 and the Snell 1990 first-impact standards. Both helmets passed these elements of the respective standards.

Next, various realistic impact angle and velocity conditions were selected to be consistent with the ability of helmets to provide protection to the head and neck in the presence of torso augmentation. The tests were conducted by impacting the two helmets, in conjunction with the Hybrid III head, neck and thorax onto a ground like surface as shown below.

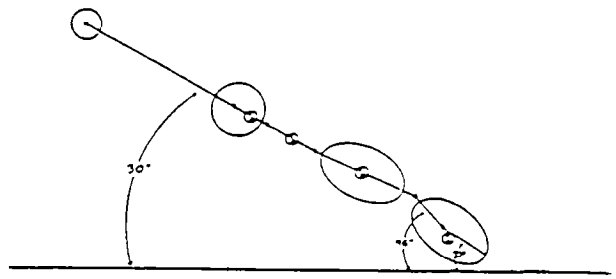
Torso Augmentation Impact Test Matrix

	Impact Condition		
	1	2	3
Impact Angle (deg)	135	30	45
Vx (m/s)	-4.23	4.77	4.0
Vz (m/s)	4.23	4.57	4.0

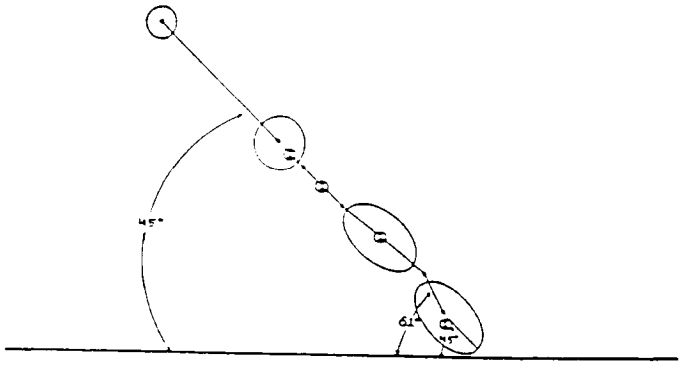
Thus, Condition 1 represents a face and chest up type impact, while Condition 2 and 3 represent a face and chest down type impact at 30 and 45 degree's respectively as shown below.



Test Condition 1



Test Condition 2



Test Condition 3

In all cases the head accelerations were well below the requirements of the various standards. But as shown below the Alternative 1, force limited helmet alone, provides axial neck compression loadings below the 4000 newton GM criteria for a significant probability of AIS 5 neck injury.

Neck Compression Results

Helmet	Impact Condition 1	Impact Condition 2	Impact Condition 3
Baseline	3025 N	4827 N	5857 N
Alternative 1	1867 N	2686 N	3385 N

To examine the effect of friction, the frictional characteristics were changed for each of the helmets. The effect of increasing friction at these impact angles serves to exacerbate the risk of neck injury as shown below, but the force limited Alternative 1, even at 0.5 ground-helmet friction, is only slightly above the injury criteria limit.

Effect of Friction on Neck Compression (Test Condition 2)

Helmet	Ground-Helmet Friction .1	Ground-Helmet Friction .3	Ground-Helmet Friction .5
Baseline	4827 N	6081 N	7412 N
Alternative 1	2686 N	3335 N	4313 N

SUMMARY - The most important observations and findings were:

1. The ability to mitigate the risk of compression neck injury is a function of impact angle, velocity vector, rotation, orientation, coupling, friction, etc.

2. While both baseline and alternative helmets pass the elements of the Standards tested, it is clear that the angled impacts with a frictional surface representative of roadways are more indicative of the ability of a helmet to reduce the risk of compression neck injuries.

3. The liner and shell properties can clearly reduce the risk of neck injury in low severity impacts.

4. The rate sensitivity of some liner materials can produce a more hostile environment for the neck than necessary.

5. A helmet with a force limited liner at the top of the helmet, can provide significantly better protection against compression neck injuries than the typical baseline liner.

6. Our work, and the work of others, make clear that the current Standards do not ensure that the head/neck protection technologically available is provided to all helmet users.

7. Directionally optimized material properties can provide the head/neck protection necessary to eliminate many unnecessary critical injuries.

8. Partial body angled impacts can be used to ensure that improved head/neck protection is provided.

CONCLUSIONS

The purpose of FMVSS 218 is to reduce deaths and injuries to motorcyclists and other motor vehicle users resulting from head impacts. It's clear that neck injuries occur as a result of head impacts, yet the current test conditions do not ensure that adequate head/neck protection is provided even in relatively minor impacts.

In fact, the Standards focus attention on one result of a head impact - head injury, while ignoring another result - neck injury. Small changes in test Standards will ensure that many catastrophic neck injuries never ruin the life of an unsuspecting helmet wearer. The fact that manufacturers have not voluntarily provided such protection uniformly, points out that revisions in the Standards need to be accomplished to ensure that all users are protected fully.

As pointed out long ago, the solution to the head impact problem is a set of solutions. These solutions have been, and continue to be, identified on a problem by problem basis, and added to the overall protection concept.

At this point, it's time to add directionally optimized material properties and partial body angled impacts to the overall performance evaluation of helmets. These additions to the design process may even facilitate the development of new head/neck protection approaches.

References

"Accident Facts," 1990 edition, National Safety Council.

Bowman, Schneider, Rohr, Mohan, "Simulation of the Head and Neck Impact Responses for Helmeted and Unhelmeted Motorcyclists," SAE 811029.

Careme, L.M.M., "Collision Dynamics and Injury Causation in Motorcycle Accidents," SAE 900745.

Fatal Accident Reporting System (FARS) 1989, National Highway Traffic Safety Administration (draft).

Federal Motor Vehicle Safety Standard (FMVSS) No. 218.

FMVSS 218, "Laboratory Procedure for Motorcycle Helmet Testing: TP-218-02."

Hirsch, Arthur, ed. Caveness & Walker, "Current Problems in Head Protection," University of Chicago, Head Injury Conference Proceedings.

Hodgson, V., Thomas, L., "The Biomechanics of Neck Injury from Direct Impact to the Head: Experimental Findings," Head and Neck Injury Criteria: A Consensus Workshop. DOT-HS 806-434.

"Human Tolerance to Impact Conditions as Related to Motor Vehicle Design -- SAE J885," SAE Information Report, April 1980.

Kingsbury, H., Herrick, Wayne C., Mohan, D., "High and Low Rate Force-Deformation Characteristics of Motorcycle Helmets," SAE 790324.

Kingsbury, H., Rohr, P., "Structural Characteristics of Motorcycle Helmets," SAE 810372.

Langwieder, K., "Collision Characteristics and Injuries to Motorcyclists and Moped Drivers," SAE 770920.

Muller, Andreas, "Evaluation of the Costs and Benefits of Motorcycle Helmet Laws," AJPH Vol. 70, No. 6. June 1980.

"National Accident Sampling System (NASS) 1986," National Traffic Safety Administration, DOT-HS-807-296.

Newman, James, "On the Use of the Head Injury Criterion (HIC) in Protective Headgear Evaluation," SAE 751162.

Ouellet, J., "Appropriate and Inappropriate Strategies for Injury Reduction in Motorcycle Accidents," SAE 900747.

Schaper, D., Grandel, J., "Motorcycle Collisions with Passenger Cars -- Analysis of Impact Mechanism, Kinematics, and Effectiveness of Full Face Safety Helmets," SAE 850094.

Snively, George, Chichester, C., "Evaluation and Design Criterial of Protective Headgear," The Fifth Stapp Automotive Crash and Field Demonstration.

Snively, S., Becker, E., "Helmet Head Protection State of teh Art and Future Directions," 6(2):11-20, J. Head Trauma Rehabilitation, 1991.

"Specifications for Protective Headgear for Vehicular Users," American National Standards Institute, Inc.

"1990 Standard for Protective Headgear," Snell Memorial Foundation 1990.

Tsongos, Nicholas G., "Head and Neck Injury Causation in Motorcycle Accidents," SAE 900745.

DISCUSSION

PAPER: **The Effectiveness of Current and Alternate Helmet Materials in the Prevention of Head & Neck Injuries as Measured by Biomechanical Parameters**

SPEAKER: Don Friedman, Liability Research

QUESTION: King Liu, University of Iowa

After listening to your talk I still don't know what kind of study you undertook. Was it an experimental study or a theoretical study?

A: It was both. I have done a number of litigation cases associated with helmets, football helmets, motorcycle helmets, and in those circumstances our efforts have been to reproduce the injury that results. One of the big effects we find are axial-neck compression injuries--fractures of the cervical spine--and those are the result of the natural course of these accidents and that the reason that the neck compression injuries seem to occur, in many cases-not in all cases but in many cases, is that helmet characteristics are essentially a ram-function. They're not a force-limited function so that you get a high force as a result of some reasonable amount of energy associated with torso augmentation. If you visualize the solution that we're talking about as cutting off the liner in the top of the helmet and inserting a piece of Hex-L in that location and leaving the rest of the helmet alone, then you might see that for given levels of energy the torso augmentation can be limited in terms of producing a neck load which is in the tolerable region of less than about 4,000 Newtons.

Q: During phase I of the contact impact that you have just now described, the force is coming in through the contact impact of the helmeted head and this torso augmentation, as you call it, occurs only during phase 2. Which is the torso has had time now to move to load the head so now if you are talking about protection during phase I, how would your alternative design be any different when compared to, for example, protection against phase 2, if there is a phase 2?

A: Usually the neck compression injury is a phase 2 injury because it's a compression of the neck between the torso and the head.

Q: But the whole thing is predicated on, for example you give the characteristics of Hybrid 3 which is at least 3 to 5 times stiffer than the cadaver neck.

A: Yes, I understand that but that's not the limitation of the study. The study makes clear, and we have used other dummy configurations, that whatever criteria you have for the neck-axial compression injury measure that it is possible to, up to a certain velocity, adjust the force deflection properties at the top of the helmet such as to limit, within the energy considerations that are involved, the compression force on the neck. And it may be that, if

you want to run the analysis with a different characterization of the dummy, you have to use the injury measure associated with that dummy. I happen to have the injury measures that are thought of as appropriate for the Hybrid 3 dummy.

Q: I still don't understand whether this is a modeling study or whether this is an experimental study because I don't know where one ends and the other begins.

A: The data is real world data although there are also a variety of laboratory data that has been used from the point of view of determining what the force deflection properties of current helmets are; those data were published by a fellow I think by the name of Kingsbury in 1979 and in 1981 and used by Bruce Bowman in 1981. So the helmet characteristics are measurements of the existing helmets and the case work is associated with real world accidents that have occurred. And the alternative is a counter-measure associated with analytically comparing the actual accident that has occurred with the injury measure and force deflection properties of the current helmets and saying, "O.K. what can you do in this particular accident to change force deflection properties at the top of the helmet to reduce axial neck compression?" That's what we did, that what we characterized; we characterized it in several ways that I haven't discussed here but, as an example, just visualize putting Hex-L on the top of the helmet and when the neck loading in a normal impact with a normal helmet gets to 5000 or 6000 Newtons, I'm saying that if you substitute the Hex-L that you're going to be able to limit that neck loading to 2500 or 3000 Newtons and that's the point I'm trying to make; that a directionally sensitive liner, which is force-limited, can limit neck loads.

Q: Arthur Hirsch, Chi Associates

What do you precisely mean by directional optimization of the material? I can't see it in the context of your hemispherical type of structure. How do you accomplish this?

A: In the paper, I wasn't trying to characterize the directional characteristics which are optimized in other than the top of the head that produces axial neck loading. But if you wanted to visualize it you would think of making a non-homogeneous liner that has different and optimized force deflection properties for characteristics associated with head strikes in that direction.

Q: In other words they would be perpendicular to the shell at every point?

A: Right now it's foam, and if you visualize different kinds of foam in different areas of the helmet you could think of directionally optimizing the helmet for strikes in various directions.

Q: There's no foam material which has the characteristics you're pointing out, which have a uniform compression under a uniform load. So that the only thing you could use is some

kind of composite structure and I can't envision anything like that to put into a helmet. You're talking about a honeycomb type material which you could put on top of your head for some top load but how would that work on the sides?

A: I wouldn't know how to optimize on the sides, we didn't study that question but if you want to consider that. There is a material, it's called NOMEX, a nylon based honeycomb which is capable of being distributed over the entire surface of the inside of the helmet. The question is what is the right force deflection property for that area of the helmet and I'm not dealing with that; I'm merely suggesting that axial compression loading in helmets can be mitigated by changing the force deflection properties of the top of the helmet.

Q: Guy Nusholtz, Chrysler

I, like King Liu, have problems understanding what you're doing, however I'm assuming it's a theoretical study and you've taken some force deflection characteristics based on past research. Is that correct?

A: The baseline helmets are based on a large number of samples of current helmet materials, yes.

Q: And you had a single curve that you were using as the force deflection, as an example and that was what you were using in you model and when you changed directions, you used that same force deflection curve...

A: I didn't change directions, I merely compared that helmet in that circumstance with a helmet which had an alternative material in that direction such as the equivalent of Hex-L. There are three conditions in which there is a Hybrid 3 dummy and it is configured as face-down configuration, one face-up configuration, going into the ground at something like a 45° angle. Those are the base line conditions that we are considering. And in one case the dummy has the characteristics of the current helmet on it and in the other cases, the dummy has the characteristics of the equivalent of Hex-L or a force-limiting kind of helmet material. And what you saw was the result which indicates that you can cut, taking those three samples you can take hundreds more, that you can cut the neck axial compression forces from what they otherwise are in the standard helmet substantially by the use of some force-limiting material between the surface that is contacting and the head.

Q: In your stylization the force limiting come up, go over flat, and then come straight up. Now if you happen to choose the energy of the impact appropriately in a honeycomb and the Hex-L material, what you can do is come along that force deflection. You won't absorb much energy but when you reach that endpoint, all the sudden the force is going to go way up. In those types of cases the polystyrene will show up to be a much better type of response.

A: It turns out not to be the case, that is, if you put that same amount of energy into the polystyrene then you get very high neck loadings. I'm trying to be clear that it's not that I characterized it at 3000 Newton force limiting, it may be but you can't use such an idealized curve that's going to have some value which is other than an essentially straight line force deflection property,but which has energy absorption capabilities at constant force level or near-constant force level for some portion of the definition.

Q: So, if you compress the load, then all of the sudden when it reaches that endpoint, where it rises straight up, you might get 50 or 60 times the force load and none of that is going to show up on the neck.

A: Why is that?

Q: Once you run up that steep wall, using very little energy and Hex-L, once you come to the bottom, that's it--you've got to run up a steep wall.

A: Well, you've used up a lot of that energy.

Q: If you just come past, using polystyrene, you have greater dynamic range because you're force deflection is ramped up and you can absorb much more energy using polystyrene than you can with the Hex-L at that load limiting.... so if you choose the Hex-L and you choose the energy, you'll come up to that wall and you'll hit that wall and end up with huge forces on the top of the head. And therefore, you're claim is that none of those show up on the neck.

A: No, if you choose those energy levels that will show up, you will get large forces at the neck. You bottom the helmet, bottom the Hex-L or polystyrene, at that point the forces rise exponentially. The fact that the kinds of velocity impacts that are being tested by the standards and that seem representative of the contact velocities that we see in the actual accidents is 5 m/sec, or something like that, the energy doesn't exceed the value that's necessary to bottom either the Hex-L and the energy with respect to the conventional helmet, has by that time, exceeded the capabilities of the neck to deal with an axial compression, based on the way that one has characterized neck compression loading, which is that at about 4000 Newtons, you will start to see axial compressions.

Q: That response is based on the dummy model?

A: No.

Q: Why not?

A: Because we've considered a variety of alternative configurations for the dummy. The dummy doesn't have to go in with an aligned torso and head, neck. You can think of it as if you were seated in the car; your mass is not aligned with respect to your neck, so you have lower torso augmentation. All these things have been considered.

Q: You're still dealing with a dummy in each case and the three situations you are talking about are still in close enough range so you still have the problem that the type of phenomenon that you're looking at is in a range that may not be applicable to an actual person.

A: I can't argue with that-that's the caveat I gave you at the beginning; I don't decide what the engineering criteria are.

Q: James McElhenie, Duke University

I have built helmets out of NOMEX and paper-based Hex-L and other things of that sort. If you squeeze these materials, including polystyrene, between two flat plates, you do get the nice, load-limiting characteristic. There are some other structures that will give you that also. The problem in the helmet, however, is that you're not squeezing this material between two flat plates, instead you're squeezing it between two curved surfaces. And what happens is as you compress the material, you pick up more and more area, and these materials display the same stiffening characteristics in a real helmet as the materials currently used. If you could devise some geometrical scheme whereby you could get load limiting with curved surfaces penetrating fairly deeply into the foam, then I think your calculations give you the right answer. But I would say, practically speaking, it can't be done. I have one other comment. And that is that you indicate 4000 serious neck injuries in motorcycle unhelmeted, and 1200 helmeted a year. This seems to be high by factor of five by the studies I have seen. My understanding is that, across the board, there are about 10,000 serious neck injuries in the country per year and the majority of those are in automobiles, and motorcycles run about 5% to 7% of those, so we're looking at somewhat under 1000 a year.

A: You don't want to add the figures in the slides up. My understanding is that the numbers are very weak, that is, there are not very well established. I think that it is clear that there are a substantial number of critical neck injuries with helmeted motorcycle riders...

Q: There have been good studies about this, I think the number is about 700 to 1000.

A: I think that's right and that's why I said that I thought that if you could come up with this kind of material, the potential is for reducing about 250 a year.

Q: You see, this is not a material problem. It's a geometric problem. It has to do with a curved surface pushing into a deformable surface and picking up more and more area as it

deforms into the surface and this is inherently a stiffening situation. And I don't know if I have ever heard anybody offer a solution to this problem.

A: With respect to that, I don't think I have, by any means, done any comprehensive research. We have done some helmet characteristics in which we have inserted flat metal plates that can be deformed spherically and those seem to have force limiting characteristics, too. Not nice and even as we see on the chart; in fact, they do have the right characteristics from a head form.

Q: Jim Newman, Biokinetics and Associates, LTD

I just had the pleasure of lecturing this morning at the Biomechanics Trauma Symposium, and I talked about helmets and head protection and I ended my presentation talking about the ultimate helmet, and I didn't know you had already designed it--otherwise I would've given you credit. The fact of the matter is that the kind of so-called force limiting characteristics that you've been proposing does represent an idealized, theoretical, probably impossible case. Now the reason I deduce that is, like James McIlhenie, I, too, built some helmets this week. The first one I build was back in 1975 and I used paper honeycomb. The reason we used paper is because you can actually drape it over a spherical surface somewhat, if you form it properly. It looked really good, but it didn't work for a variety of reasons. I am wondering, at this stage--1991--if you've actually built any helmets that verify this concept Because if you have, I have to go back and rewrite the paper from this morning.

A: No, we have not built any helmets that verified the concept in the physical experimentation. We have verified how it would work in a three-dimensional model. We have looked at the question of how the force deflection properties worked in roofs, in roofs of vehicles with the impact from heads.

Q: If I understand correctly, you're saying that if you lower the strength of the material, whatever it is, so that it crushes at a lower force, the forces on the neck are lower.

A: That's right. If you can keep the level higher in the initial portions than it is in the ramped force deflection properties of the conventional, current helmets, then what you can do is get the same energy with the same deflection, but limiting the force.

Q: I don't agree with that. I agree with Guy Neuscholtz; you can't have it both ways, you can't lower the force level and still maintain the same net energy absorption. If you do lower the force level, you're going to run into that wall you talked about and you'll get extraordinarily high forces. If you just trip over the edge of what you expect the impact energy will be, then you will prevent the neck injury, but I'm afraid the man will be dead from a caved-in skull.

A: I must say that what the problem must be is the force level at which the axial compression occurs. Because what you see is 10,000 to 14,000 Newtons as the limiting, even with the current helmets and with 5.5 to 6 meter per second impact, you can see 14,000 newtons in the neck. What I'm saying is that under those same circumstances, maybe idealized, you can maintain the neck loads below 3,000 Newtons.

Q: Arthur Hirsch, Chi Associates, Inc.

I don't agree with Dr. McElhanie. I don't know the details of his or Dr. Newman's helmet experiments using honeycomb material, but I worked with paper honeycomb quite extensively back in the 1950s and 60s. I found it very effective, when loaded dynamically, in providing a uniform force limitation. This is what is necessary if we are to make full use of the crushable space allowed using helmet design, which is in the order of only one inch. You cannot make full use of this distance with material which may, over its full crushing thickness, vary in stiffness from too soft to unacceptably hard.

It is true that honeycomb structures are quite sensitive to off-axis loading. They also may not perform as desired when encapsulated in such a manner as to prevent venting of the compressed cells. The picking up of more and more compressible area as the spherical shell as described by Dr. McElhanie is not necessarily applicable to the helmet. First, the head is not a sphere, but has many surfaces, some of which have no significant curvature. Second, a properly designed helmet should have a shell which is stiff enough to distribute a point loading over a significant area. The molding of the interior cushioning may not be so difficult if the relatively flat skull surfaces are accommodated. Guy Nuscholtz's concern about impact at bottoming, when honeycomb is used, is equally true for foam materials. I congratulate Mr. Friedman for reminding us that honeycomb force limiting characteristics are attractive and that it might make good sense to reconsider them for helmet cushioning design.

Q: James McElhaney, Duke University

I like to take a minute to explain what the situation is. This material is described by the manufacturers as crushing at a certain pressure. Obviously, if you have a square inch of this material, it crushes at a lower load than if you have a square foot. Now, if you put a round head into this material, what happens is, at the contact, which is very low area, you start to crush. You gradually, as you push the head into the material, you pick up larger and larger areas and larger and larger forces to require continue pushing into the material. It becomes a stiffening material at that point. And it is a stiffening material, under these conditions.

A: Yes, I agree with that. But you're saying that somehow it cannot be designed to limit the deformation. The segment that I'm talking about is not a constant thickness segment. Do you realize that? Think of the crown of the helmet being cut off; there's a different length segment in the center than on the edge. One of the other things that occurred to me is that a big solution is to get the neck to bend. When you get the neck to bend in the course

of the force-limiting property, you would have avoided axial compression. And when you deal with the real world orientations of the torso, neck and head, we have mostly the opportunity for there not to be axial compression. We're looking at a very limited case where the alignment of the neck is such that you won't get a axial compression loading. Most of the time you don't, and the reason is that you have an impact that rotates the head so that the axial compression loading doesn't occur.