Investigations on the mechanical behaviour of structural parts of PCRV as a basis for specific HTR design criteria

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1 SCOPE OF RESEARCH WORKS AND BASIC CONSIDERATIONS

In the course of improved development of nuclear power plants of the HTR type in the Federal Republic of Germany, the criteria for design of HTR components are elaborated or actualized according to the present state of science and technology within a research activity carried out by a couple of competent institutions and subsidized by the Federal Minister for Research and Technology, see Fachkreis "HTR-Auslegungskriterien" (1986). As a substantial part of this work, design criteria for Prestressed Concrete Reactor Vessels (PCRV) for the plant category of 500 MWe are treated, too. In order to provide a thorough basis for laying down actual design criteria, the authors' firm is carrying out some additional research work, by which several selected safety related aspects shall be investigated in more detail. This work is also subsidized by the Federal Minister for Research and Technology.

PCRVs consist of a couple of components, each of which fulfills separate functions:

- The prestressed concrete structure (in the following: PCS) carries the load due to the primary coolant pressure keeping specified deformations and provides the necessary radiation protection.
- Core liner and penetration liners enclose the primary cooling gas performing as impermeable membrane supported by the PCS and fixed to it by anchors.
- Closures provide a leaktight boundary to penetrations and carry pressure forces, too.
- The heat protection system, consisting of insulation and vessel cooling system, protects the PCS against too high temperatures.

Notwithstanding these different functions, these systems have to act together in order to guarantee a safe inclusion of the primary coolant. For that reason, the research project section "PCRV design criteria" covers all these components in a co-operation as close as possible. This contribution, however, is focussed on topics concerning predominantly the PCS, and furthermore only some special aspects investigated so far within the research program, which is still going on.

As for any prestressed or reinforced concrete structure, the design for PCS has to fulfill the requirements of satisfying serviceability and satisfying load carrying capacity. In order to ascertain serviceability, mainly crack widths have to be controlled and deformations of the structure have to be limited - the latter being more important here than elsewhere

Table 1. Permissible compressive stresses in concrete.

Load categories	Permissible compressive stresses in concrete			
	Field stresses		Local stresses	
Construction *)	$\beta_r/2,0$	$\leqq 1,2\ \beta_c$	$\beta_r/1,65$	$\leqq 1,45\ \beta_c$
Commissioning	$\beta_r/1,9$		$\beta_r/1,6$	
Pressure test	$\beta_r/1,85$		$\beta_r/1,55$	
Normal service conditions	$\beta_r/2,1$		$\beta_r/1,75$	
Upset service conditions	$\beta_r/2,0$		$\beta_r/1,65$	
Event category 3 accidents	$\beta_r/1,7$	$\leqq 1,5\ \beta_c$	$\beta_r/1,4$	$\leqq 1,8\ \beta_c$
Event category 4 accidents	$\beta_r/1,2$		$\beta_r/1,1$	**)

β_r Multiaxial concrete strength - in case reduced due to temperature - at age of loading, at most 90 days.

β_c Uniaxial compressive strength - in case reduced due to temperature - at age of loading, at most 90 days.

*) If design loads cannot be exceeded or in case of short time load, field stresses up to $\beta_r/1,8$ and local stresses up to $\beta_r/1,5$ are permissible.

**) Local stresses need not be established, if admissible with respect to PCRV safety demands.

due to the close interaction with plant machinery. Hereby the existing temperatures - stationary or transitional - are of great influence. The safe load carrying capacity is established by an ultimate load analysis demonstrating the behaviour of the structure subjected to theoretical loads exceeding the operational level by a defined degree (safety factor). Definition of the safety factor depends among others on how realistically the overload behaviour is analyzed and on the kind of load assumptions as well. In order to provide a basis for defining these conditions, a couple of investigations are carried out within the research program, some special points of which are presented here according to the present state of work.

Whereas ultimate load behaviour of the PCS as a whole should be analyzed by continuum calculations including non-linear material behaviour, cracking and other types of failure, which is necessary because of the significant stress redistributions during increasing load and on the other hand feasable with tolerable effort, establishing the local load carrying capacity in the same way would be unreasonable. This can be substituted by analyzing the mechanical behaviour under service load conditions and establishing a sufficient distance between existing states of stress and corresponding material strengths. Table 1 gives a survey on permissible compressive stresses of concrete. As shown in this table, this procedure is also valid for stress states under accident loads, particularly because only local zones are affected in most cases. (The permissible field stresses

should not be exceeded in order to provide a satisfying operational behaviour.) In this field, investigations on some special aspects are presented, firstly concerning eventual temperature limitations, secondly dealing with typical accident conditions.

2 INVESTIGATIONS ON TEMPERATURE LIMITS

Within the design of PCRV, an important problem is how to fix the level of temperatures in the concrete walls. Thus, the question, if specification of a range of admissible temperatures in the PCS would be possible resp. necessary, forms an essential part of the basic works for specific HTR design criteria, too. This problem has been investigated from two aspects.

First, the serviceability of concrete, reinforcing steel and prestressing steel has been investigated thereupon, if variations of the material properties themselves with increasing temperatures need establishing limits. On this behalf, the ranges of the relevant material properties in dependence on temperature have been drawn from the literature - for example Schneider (1982) - and estimated with respect to the demands on PCS materials. As a result, no definite material dependent limits could be stated.

Secondly, it has been assessed at which level temperatures would be limited by the fact that temperature related stresses in a PCS exceed the limits of also temperature related permissible stresses. Calculation of stresses in the PCS under varying temperatures basically has been carried out in a simplified way by computing stresses due to prestressing, internal pressure and temperature for a certain temperature and assessing the stresses at other temperatures by means of system dependent conversion factors for the portion of stress due to temperature. The state of stress just at the bound of permissible temperature dependent stress determined the maximum possible temperature. This has been undertaken for stationary and transient temperatures as well.

As an example for this procedure, an investigation for transient temperatures shall be explained more detailed. The states of stress in the standtube area of the PCRV of the THTR nuclear power plant Schmehausen during operation including the stresses due to the steady-state temperatures have been chosen as initial conditions. These states of stress have been superimposed by stresses caused by non-stationary temperatures, which had been calculated with regard to the temperature dependence of the material properties - especially transitional concrete creep - for the difference between the considered transient temperature and the steady-state initial condition. Because on one hand there is no total restraint, but on the other hand also additional restraint e.g. due to steel liners of penetrations can occur, the level of these transient temperature stresses could not be easily assessed. Simplified but exactly enough, it has been assumed however that the system dependent stresses because of a certain temperature difference always have the same ratio to the stress because of the same temperature difference under total restraint. These ratios have been calculated from some special cases analyzed earlier for the THTR-PCRV. Thus, first the transient temperature stresses under total restraint had to be calculated starting from steady-state operation temperature, see Fig. 1. Subsequently, these were modified with respect to the existing restraint conditions by use of the system dependent conversion factors and finally superimposed to the operational stresses and compared with the multiaxial compressive strength of concrete.

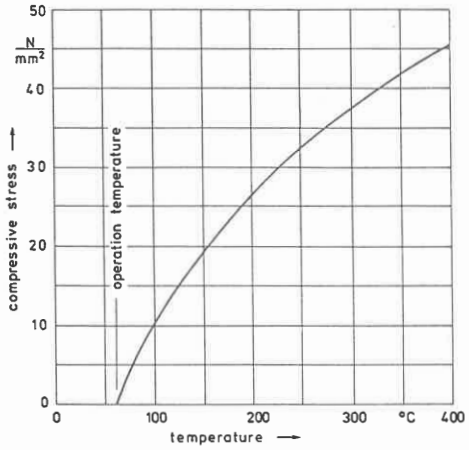

Figure 1. Transient temperature stresses in biaxial stress condition under total restraint.

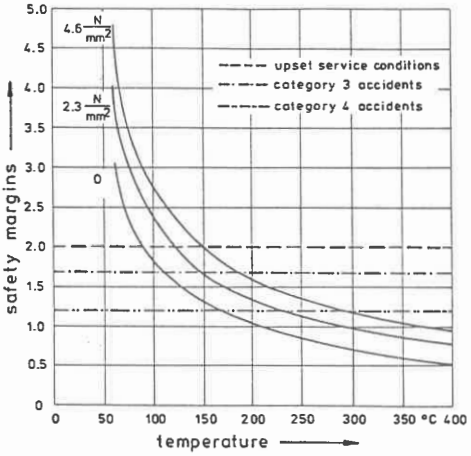

Figure 2. Safety margins in the shut-down rod area of the THTR under different internal pressures.

The resulting curves of the safety margins for different internal pressures representing the third principal stress at the highest loaded inner surface of the standtube area are delineated in Figure 2. The points of intersection of these curves with the levels of the required safety margins (see Table 1) indicate the admissible temperatures of each load category in PCRVs of a conception comparable to the THTR-PCRV (uniaxial compressive strength at room temperature 42 N/mm^2, calcitic concrete).

These results, of course, cannot be generalized, since they depend on the design characteristics of the PCRV type considered. Thus, further investigations are presently in hand for other concretes (cylinder strength 51 N/mm^2, basalt and gravel concrete) and other PCRV dimensions (HTR 500). However, the results shown give a first idea that temperatures at any scenario usually used for PCRV design are lower than corresponding temperature limits.

3 LOCAL EFFECTS OF ACCIDENTS

Effects of accidents in coherence with transient heat up of the inside of walls and penetrations of a PCRV may eventually influence the design of PCRV top caps. A former contribution to SMiRT (Schimmelpfennig and Schnellenbach 1981) dealt with such typical effects of accidents, in most cases caused by malfunction or failure of the liner cooling system. At that time, first results from temperature calculations using the PCRV of the THTR nuclear power plant Schmehausen as an example had been presented. The experiences gained from structural analyses of the representatively investigated system parts of the PCRV, as the research project went on, have proved that disturbed zones in the top cap, above all the standtube area characterized by numerous lined penetrations with short distance, are most of all stressed by accident loads. This fact becomes apparent in considerable non-linear material behaviour in parts of the standtube area during heat up and minor local exceeding of admissible stresses in concrete. For presenting the order of magnitude of the arising stresses, Figure 3 shows the temperatures and resulting radial stresses

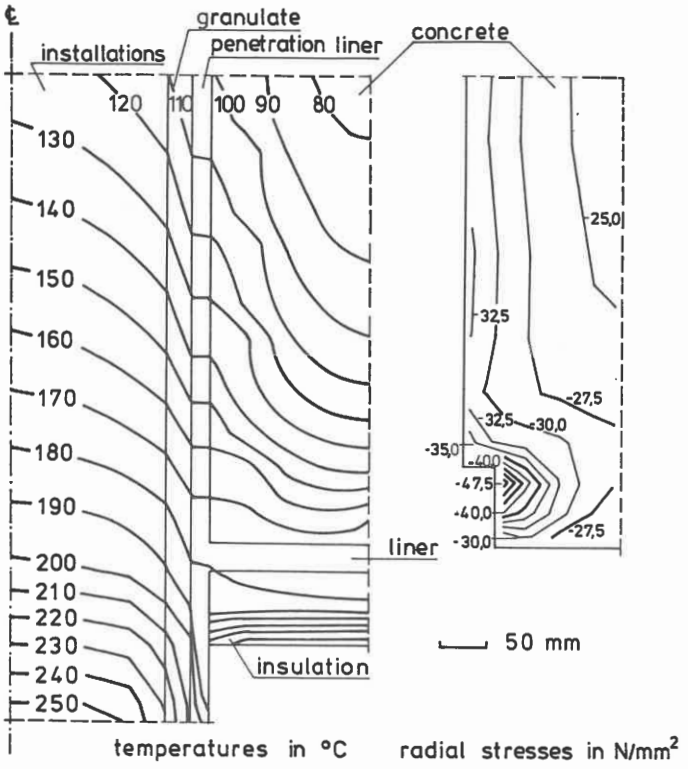

Figure 3. Isolines of temperatures and radial concrete stresses for detail of shut-down rod area during typical category 4 accident.

in the liner adjacent concrete area of a standtube. Accordingly the intended further research works have to consider that on one hand the stresses in the THTR-PCS during the defined event sequences with five hours time for attempts at repairing before shutdown of the reactor come up to the admissible stress limits, but on the other hand longer periods until required shutdown of the reactor are aspired to. Hence, the investigations aim at determining by which variation of geometric resp. material parameters these desired longer periods could be realized yielding an even higher safety.

4 INVESTIGATIONS ON ULTIMATE LOAD BEHAVIOUR

4.1 Preliminary remarks

Ultimate load behaviour of the cylindrical part of PCSs is governed by stress-strain behaviour and strength of the prestressing tendons, the concrete being more or less only used for transferring by compression forces due to cavity pressure to the tendons. Structural behaviour of these regions including crack propagation can be analyzed without any problem and needs no further research.

More difficulties arise with the overload behaviour of the top caps, particularly if the sections that have to withstand substantial shear forces

are diminished by penetrations for heat exchanging components. In the past, the safety factor for these regions was set higher than for the cylindrical part. In case it can be shown that calculation methods available today allow a reliable ultimate load analysis for such top caps, too, a certain reduction of this elevated safety factor could be discussed. Or, based on detailed calculations of that kind under variation of main design parameters (slab thickness, diameter and number of penetrations), simplified but safe methods for establishing the ultimate load could be derived.

Especially for the standtube area, simplified methods are reasonable, since discrete modelling of each shut-down rod tube would obviously be too expensive, and idealizing assumptions inducing a fictitious homogeneous substitute material - as well known for service load conditions - appear to be possible.

These are - among others - main objects of the present research activities, the actual state of which will be outlined in the following.

4.2 Ultimate load behaviour of top caps with large penetrations

Some years ago, the senior author had been involved in extensive investigations on material characteristics affecting the shear compression failure of hick restrained concrete slabs, which were calibrated by a lot of verifying calculations (Schimmelpfennig 1976). These studies were carried out for axisymmetric systems, and there had been no opportunity to extend them to the general three-dimensional case. Today, a couple of computer programs are available that allow taking into account non-linear material behaviour for structures of any geometry based on the finite element method. However, as far as known by the authors no investigations with the special aim as mentioned above have been done up to now with these programs, that means studies establishing the true description of

- crack propagation in regions under shear forces combined with lateral restraint,
- non-linear deformation behaviour under high multiaxial compressive stresses,
- initiation and propagation of crushing in the inclined compression struts.

Such investigations are now in progress within the mentioned research work. As a first basis for verifying calculations, a 1/20 scale model of the THTR-PCRV top cap as published by Lotz and Meerwald (1971) has been chosen, which corresponds to the actual type of structure, see Figure 4. A first trial analysis was performed by use of ADINA program system with its "concrete model". As a great surprise, the very first calculation resulted in an ultimate load level between 190 bar and 200 bar, which fits very well the ultimate load of the test at 196 bar by shear compression failure, see Fig. 5. Crack directions showed a good agreement, too, whereas coincidence of cracked regions appeared to be not as satisfactory.

Of course, it still has to be checked whether this satisfying result is at random or not. For this purpose, among others the possible sensibility against modified boundary conditions (describing the fixing by tendons) or single material parameters has to be analyzed, and other model tests will be re-calculated, too. These works are in hand now. It can be expected that after finishing these investigations well established methods for analyzing ultimate load behaviour of these structural parts of PCRVs will be available.

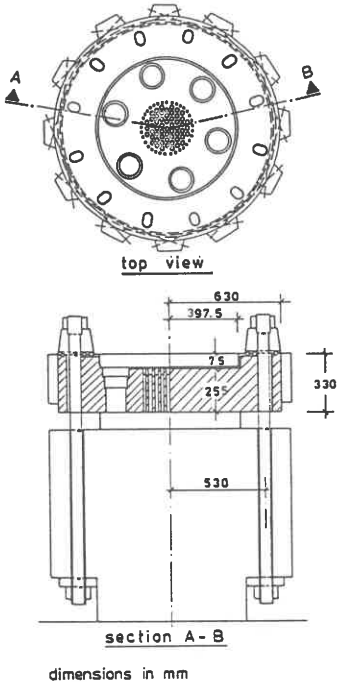

Figure 4. 1/20th scale model of PCRV top cap (Lotz & Meerwald 1971).

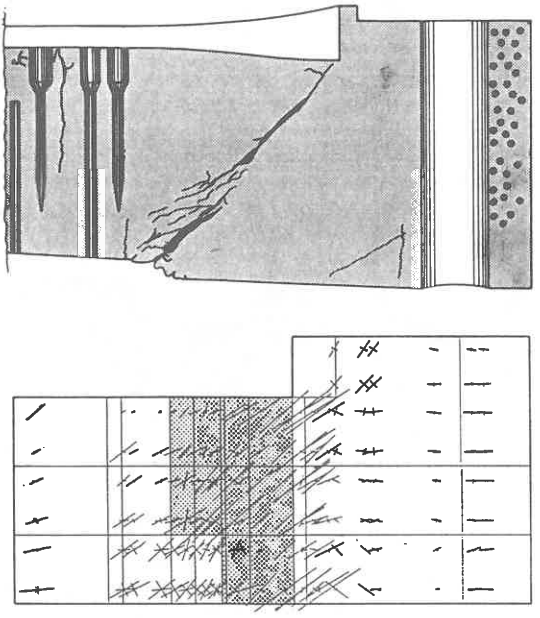

Figure 5. Top cap model after testing and corresponding analysis.

4.3 Treatment of the standtube area in the ultimate load analysis

The analysis of the structural behaviour of the standtube area (characterized by numerous lined penetrations with short distance) requires particular consideration. The effort would be exceptionally high at detailed modelling of the single tubes in ultimate load investigations of a whole top cap or a whole PCS. For that reason, it is meaningful to look for possible simplifications of modelling this area nevertheless affording the highest possible degree of information about the safety of the structure. One starting point for this purpose is given by the regular arrangement of the penetrations on a net of equilateral triangles, see Figure 6. For the range of linear material behaviour, it is possible to refer to the well known method representing the compound system of steel tubes and concrete as fictitious homogeneous substitute (Abdul-Wahab & Harrop 1967), which meets the requirement that under load a model of the fictitious material suffers the same deformations as a real model of tubes and concrete. Utilizing symmetry properties, a hexagonal section with a central tube is thought to be cut from the standtube area. Comparing calculations being in good agreement of results have shown that it is permissible to neglect the wedges and only to consider the circular slab within the hexagon. In that case, the load of the lateral single tube section and the marginal stress of the whole circular standtube area σ_o are identical, and the wanted substitute rigidity can be calculated without difficulties according to the slab theory.

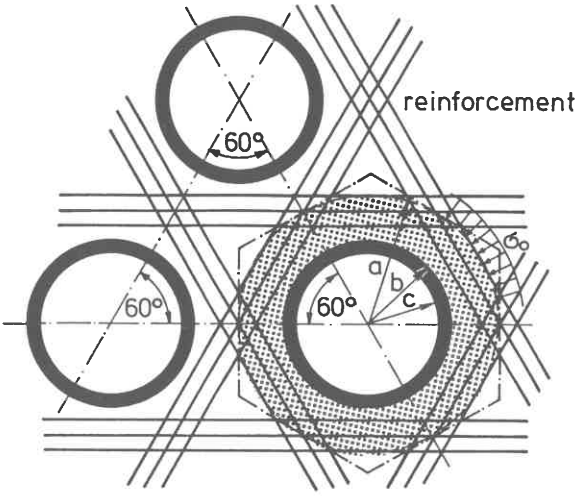

Figure 6. Standtube arrangement and symmetry conditions.

In the limit state of ultimate load the top cap subdivides in two areas with different material behaviour, that are the compression zone turned to the core cavity and the outside tension zone.

Concerning the compression zone, it is of interest to which extent substantial non-linear material behaviour arises, and how the above fictitious material law would have to be modified. On this score, first the function σ_o/σ_1 (see Fig. 7) describing the bound of stress states, beyond of which non-linear material behaviour of concrete is no more negligible has been determined. The criterion for this border between linear and non-linear material behaviour depicted in Figure 7 was constituted by the requirement that the distortion calculated with linear material parameters diverges less than 2 % from that calculated with non-linear parameters. This criterion was applied to the state of stress at the outer surface of a tube (not depicted), since the highest compressive stresses arise there. In order to determine the upper limit of the stress σ_o arising in the standtube area in the limit state of ultimate load, a calculation exemplary was carried out for the PCRV of the HTR 500. The result drawn in Figure 7 shows that this extreme state of stress is distinctly lying inside the range where assuming linear material behaviour gives a satisfying degree of accuracy. Hence, the above mentioned idealizing procedure for service load conditions is applicable to the ultimate load analysis, too, without more ado.

In the tension zone of the top cap, shown in Fig. 7, considerable cracking of concrete occurs hence the reinforcement running under 60^0 between the tubes becoming effective. For the purpose of determining the criterion for the formation of continuous cracks between the tubes, calculations of a cut off model with central tube under tensile load σ_o were carried out. The result was that the complete concrete section between the tubes will crack as soon as the tangential stress at the outer surface of a tube exceeds the concrete tensile strength β_z. Therefrom following formula as criterion for cracking in the standtube area can be derived:

(1) $\lim \sigma_o = \beta_z(a^2-b^2)/(2a^2)$ (see Fig. 6).

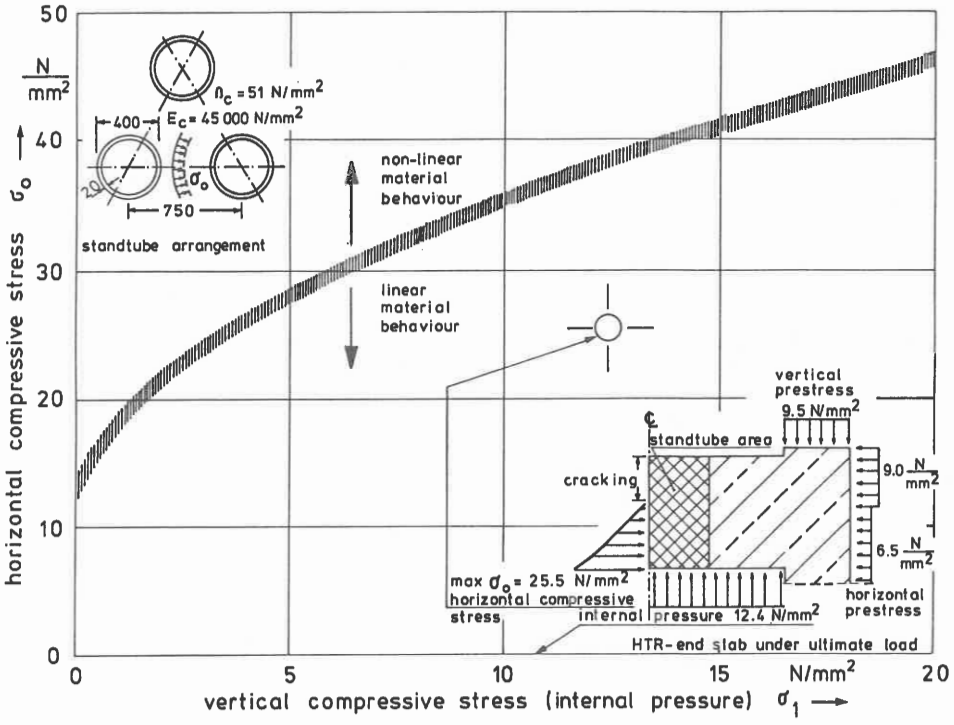

Figure 7. Typical maximum stress in PCRV standtube area (in comparison to bound of regarding non-linearity).

This cracking in radial direction of the single tubes is equivalent to both radial and tangential cracking with respect to the general PCRV coordinates, so that the whole reinforcement is activated. The transformation of the substitute rigidities of the three reinforcement directions - each characterized by the degree of reinforcement μ - to the radial and tangential directions of the overall PCRV results in an isotropic substitute rigidity in horizontal planes of the standtube area in cracked conditions characterized by the degree of reinforcement $1.5\,\mu$. Thereby, the boundary stress of the whole circular standtube area σ_o and the average reinforcement stress σ_s have following simple relation:

(2) $\sigma_s = \sigma_o / (1.5\,\mu)$.

Control calculations carried out with the above cut off model by definition of a tangential substitute rigidity in cracked condition related to the axis of a single tube have proved that the resulting average reinforcement stress calculated with the single tube section under lateral load σ_o is equal to that one calculated with the above mentioned isotropic substitute rigidity. Thus, a method is available by which the rigidity of the standtube area in cracked condition is well described and which permits the direct determination of the reinforcement stresses from the analysis of the top cap as a whole.

5 FINAL REMARKS

Based on some general considerations concerning the design principles of prestressed concrete structures of PCRVs, the present state of several investigations in order to establish or reconsider particular design criteria is described in this contribution. Since the research works on these topics are presently in hand, definite conclusions cannot yet be drawn. The presentation at the conference will give advanced information.

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